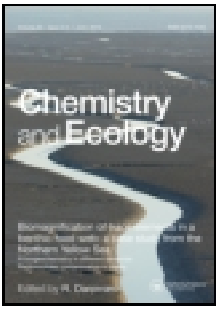

Chemistry and Ecology
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gche20

Soil characteristics influence the radionuclide uptake of different plant species

A. K. Hegazy [a] [b] , S. Y. Afifi [c] , A. A. Alatar [a] , H. A. Alwathnani [a] & M. H. Emam [b]

[a] Department of Botany and Microbiology, College of Science, King Saud University, Riyadh, Saudi Arabia

[b] Department of Botany, Faculty of Science, Cairo University, Giza, Egypt

[c] Nuclear Materials Authority, Anshas, Cairo, Egypt

Published online: 23 Nov 2012.

Chemistry and Ecology, 2013
Vol. 29, No. 3, 255–269, http://dx.doi.org/10.1080/02757540.2012.744827

Soil characteristics influence the radionuclide uptake of different plant species

A.K. Hegazy[a,b]*, S.Y. Afifi[c], A.A. Alatar[a], H.A. Alwathnani[a] and M.H. Emam[b]

[a]*Department of Botany and Microbiology, College of Science, King Saud University, Riyadh, Saudi Arabia;* [b]*Department of Botany, Faculty of Science, Cairo University, Giza, Egypt;* [c]*Nuclear Materials Authority, Anshas, Cairo, Egypt*

(*Received 4 February 2012; final version received 11 October 2012*)

The key point of food plant agriculture is how to regulate the harmonious relationship between the soil and the plant environment. This study deals with radionuclide uptake by two food plant and two fruit tree species in relation to the geochemical characteristics of the soil. Uranium and thorium content was determined in coastal black sand and inland cultivated soils. Four commonly cultivated species *Eruca sativa*, *Lycopersicon esculentum*, *Psidium guajava* and *Mangifera indica* were investigated. Physical and chemical properties of the soil were analysed in relation to uranium and thorium uptake by plants. The results revealed the ability of plants to accumulate uranium and thorium in their edible portions. The absorbed radionuclides were positively correlated with their concentrations in the soil and the geochemical characteristics of the soil. The transfer of radioactive elements from soil to plant is a complex process that can be regulated by controlling the geochemical characteristics of the soil, including pH, clay, silt and organic matter content that reduce the bioavailability of soil radionuclides to plants, and in turn reduce the risks of biota and human exposure to radionuclide contamination.

Keywords: radionuclides; uranium; thorium; soil characteristics; transfer factor; Egypt

1. Introduction

Black sand deposits are extensive along the Mediterranean coast of the Nile Delta and Sinai, Egypt. These black sands contain some important minerals such as zircon, magnetite, garnet, rutile and monazite; some of which contain uranium and thorium (hereafter U and Th) in their chemical structures [1–4]. Abnormal occurrences of U and its decay products in rocks and soils, and Th in monazite sands are the main sources of the high natural background activity that has been identified in several areas of the world [5].

Trace elements are essential to all living organisms when present in small amounts. However, an excessive concentration of any trace element in the environment can cause severe toxic effects in exposed plants, animals and humans [6]. Evidence shows that the deposition of radiotoxic elements such as I, Cs, Th, U, Sr, K in critical organs and body fluids, even at trace levels, is likely to cause a wide variety of physiological disorders [7].

Natural radionuclides entering the food chain are mostly derived from the soil and depend on radionuclide enrichment and soil characteristics [4,8]. Radionuclide uptake by plants varies from species to species, where such variability affects the different food products [9]. An understanding

*Corresponding author. Email: aheagazy@ksu.edu.sa

of the mobility of U and Th in soils and their transfer to different plants requires a knowledge of the interactions of U and Th with abiotic and biotic components [10]. Soil solution composition is affected by different soil properties including pH, organic matter and clay contents, and microbial activity in the soil. Changes in soil physico-chemical properties and biological processes are likely to affect the amount of radionuclide in the soil solution that is available for root uptake [4,11,12].

In environmental samples with a harmful concentration of U and Th, determination of radionuclides is important from the view of protection against radiation [13]. The occurrence of radioactive elements in the uppermost soil layers represents a problem for the environment and human health due to the possibility of their integration into the food chain. As a consequence, there is a possible risk for coastal agro-systems and human health [14]. For environmental and human safety, assessment of the impact of a given contaminant in the ecosystem usually includes an estimation of the radionuclide concentration taken up by plants from the soil [15,16].

Food plants cultivated in Mediterranean black sand rich in radionuclides may take up and accumulate radioactive elements in their edible portions. Radionuclide availability and uptake are dependent on the radionuclide concentrations in the rhizosphere soil, the plant species and soil properties. This study was conducted to determine the radionuclide uptake by two food plants, rocket (*Eruca sativa* Mill.) and tomato (*Lycopersicon esculentum* L.), and two fruit trees, guava (*Psidium guajava* L.) and mango (*Mangifera indica* L.), commonly cultivated in the coastal black sand and inland River Nile Delta. Geochemical characteristics of the soil and the relationship to radioactive element uptake by the four study plant species are considered.

2. Material and methods

2.1. *Study species*

Two food plant species, *viz.*, rocket (*Eruca sativa* Mill.) and tomato (*Lycopersicon esculentum* L.) and two common fruit trees, guava (*Psidium guajava* L.) and mango (*Mangifera indica* L.) commonly cultivated in the coastal black sand soils were used.

2.2. *Study site*

The study was conducted at cultivated coastal black sand and inland agricultural sites, River Nile Delta. The coastal site is located around Lake El- Burullus between 31°5′E and 31°35′N. The inland sites were selected where the target crop plant is commonly cultivated. *E. sativa* material was taken from Giza, *L. esculentum* from Kafr El Sheikh, *P. guajava* from El Dakahlia and *M. indica* from El Nubaria. Black sand deposits are rich in heavy minerals, e.g. zircon ($ZrSiO_4$), rutile (TiO_2) and ilmenite ($FeTiO_3$) [4]. Black sands are economically important and are characterised by high concentrations of U and Th in their crystalline structure [1,4].

2.3. *Geochemical characteristics of the soil*

Soil samples were collected from the coastal black sand and inland agricultural land sites. Samples were taken from a depth of 30 cm for the fruit tree species guava and mango, and from rhizosphere soil of the two species rocket (10–20 cm depth) and tomato (20–30 cm depth). Five samples were taken randomly from each site and pooled into one composite sample. Soil samples were collected in paper bags and transported to the laboratory, air dried, sieved through a 2-mm sieve before analysis. For soil texture analysis, the coarse fractions were estimated by pipette methods [17]. Organic matter was determined using the loss on ignition method [18]. The percentage of $CaCO_3$ was estimated by titration against 1 N HCl [19].

Soil/water (1:5) extracts were prepared and used to determine total dissolved salts, soil reaction (pH), bicarbonates (HCO_3^-), chlorides (Cl^-) and sulfates (SO_4^{2-}). Total dissolved salts were measured using a conductivity meter (Model-DAI Lamotte Chemicale). Soil reaction was determined by a glass electrode pH meter (Model 206 Lutron Corporation). Bicarbonates were estimated by titration with 0.1 N HCl using methyl orange as indicator [19]. Determination of chlorides was carried out by titration against silver nitrate using a potassium chromate indicator [20]. Sulfates were determined turbidimetrically as barium sulfate at 470 nm [21].

To determine trace elements and major oxides, the collected soil samples were prepared for analysis by crushing ~2 kg of each sample into pea-size granules using a laboratory jaw crusher, followed by grinding using a blending mill. The pulverised soil samples were then used for subsequent analyses. The major oxides SiO_2, Al_2O_3, TiO_2 and P_2O_5 were measured spectrophotometrically. The Na and K contents were determined using flame photometric techniques. Fe_2O_3, MgO and CaO were determined using a titration method. The trace elements Cr, Ni, Cu, Zn, Zr, Rb, Y, Ba, Pb, Sr, Ga, V and Nb were determined by X-ray fluorescence analysis using a Phillips Unique II unit with automatic sample changer PW1510 (30 position). Results for measured trace elements and major oxides were obtained from the nuclear materials laboratory as mean values without standard deviation as there was no significant difference between replicates.

2.4. *Determination of radionuclides content*

To estimate the soil radionuclide content, the concentrations of U and Th were determined chemically using a spectrophotometric technique [22] at U & Th Laboratory, Central Labs, Nuclear Materials Authority, Anshas. Leaves of *E. sativa* and fruits of *L. esculentum*, *P. guajava* and *M. indica* collected from the coastal black sand and inland agricultural land sites were thoroughly washed free of soil particles under a light flow of distilled water. The concentrations of U and Th in the collected edible portions of study plants were determined using an inductively coupled plasma mass spectrometer (ICP-MS technique) model Jeol-JMS-PLASMAX2 high resolution ICP-MS. In the ICP technique, detection limits are generally based on at least three determinations of the signal produced by a blank. Two or three sigma standard deviations calculated from data were expressed as equivalent limits. The measured U and Th concentrations in soil and plant samples were obtained in mg kg^{-1} and converted to Bq kg^{-1} dry weight by multiplying the value of ^{238}U by 12.34 and the value of Th by 4.04. From the measured U and Th contents in the soil and plant samples, the transfer factor was determined as follows:

$$\text{Transfer factor} = \text{element concentration in plant/element concentration in soil.}$$

2.5. *Statistical analysis*

Data were analysed by analysis of variance (ANOVA; SPSS 15 for Windows) to test the significance of differences among species and sites. The relationship between soil characteristics and radionuclide uptake of U and Th were analysed by Pearson correlation coefficient.

3. Results

3.1. *Geochemical characteristics of soil*

Physical and chemical properties of the soil samples are summarised in Table 1. The percentage of coarse sand was highest in the coastal black sand soil compared with the inland clayey soil.

Table 1. Soil characteristics of the cultivated coastal black sand and the inland clayey soils.

	Eruca sativa		*Lycopersicon esculentum*		*Psidium guava*		*Mangifera indica*	
Soil Variable	Black sand	Clay soil	Black sand	Clay soil	Black sand	Clay soil	Black sand	Clay soil
Coarse sand (g%)	78.12 ± 2.74***	54.57 ± 2.52	67.56 ± 3.41***	2.53 ± 0.85	82.20 ± 1.48***	25.66 ± 1.86	75.29 ± 1.53	73.81 ± 1.59
Fine sand (g%)	2.38 ± 2.69*	11.80 ± 2.23	30.33 ± 3.09**	19.15 ± 1.28	15.34 ± 1.63*	20.89 ± 2.15	18.62 ± 1.60	21.40 ± 1.18
Silt (g%)	0.21 ± 0.00**	6.46 ± 0.85	0.55 ± 0.12***	20.61 ± 0.47	0.41 ± 0.00***	18.34 ± 0.21	1.76 ± 0.28*	0.73 ± 0.13
Clay (g%)	1.30 ± 0.11***	27.18 ± 1.21	1.57 ± 0.27***	57.71 ± 1.67	2.05 ± 0.40***	35.11 ± 0.37	4.34 ± 0.34	4.06 ± 0.55
pH	7.41 ± 0.02***	7.74 ± 0.01	7.27 ± 0.02**	7.67 ± 0.07	7.79 ± 0.06	7.75 ± 0.01	7.71 ± 0.01	7.71 ± 0.05
EC (dS m^{-1})	0.36 ± 0.01**	0.43 ± 0.02	0.09 ± 0.00***	0.76 ± 0.02	0.29 ± 0.01***	3.38 ± 0.06	0.26 ± 0.01**	0.18 ± 0.01
Cl^- (g%)	0.01 ± 0.00***	0.02 ± 0.00	0.01 ± 0.00**	0.01 ± 0.00	0.02 ± 0.00***	0.09 ± 0.00	0.01 ± 0.00	0.00 ± 0.00
SO_4^- (g%)	0.01 ± 0.00***	0.02 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00***	0.02 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
HCO_3^- (g%)	0.02 ± 0.00***	0.05 ± 0.00	0.02 ± 0.00***	0.06 ± 0.00	0.07 ± 0.00***	0.05 ± 0.00	0.07 ± 0.00***	0.05 ± 0.00
$CaCO_3$ (g%)	3.47 ± 0.20***	7.11 ± 0.34	3.24 ± 0.20***	8.47 ± 0.00	0.24 ± 0.00**	1.13 ± 0.14	0.24 ± 0.00**	1.05 ± 0.14
Oraganic matter (g%)	0.24 ± 0.00***	3.66 ± 0.05	0.19 ± 0.00***	5.56 ± 0.06	0.66 ± 0.01***	7.39 ± 0.07	1.33 ± 0.02**	0.97 ± 0.01

Notes: Values are given as mean ± SD and rounded to two decimal places. Significant at $^{***}p \leq 0.001$; $^{**}p \leq 0.01$; $^{*}p \leq 0.05$.

Table 2. Trace element concentrations (ppm) in cultivated coastal black sand and inland clayey soils.

			Trace element (ppm)												
Species	Study site	Locality	Cr	Ni	Cu	Zn	Zr	Rb	Y	Ba	Pb	Sr	Ga	V	Nb
Eruca sativa	Black sand	Baltim	98	19	9	33	1969	22	1222	3215	u.d.	70	23	70	41
	Clay soil	Giza	50	45	21	105	411	49	234	1768	u.d.	14	22	72	42
Lycopersicon esculentum	Black sand	Baltim	98	18	9	37	2528	25	1578	3332	u.d.	90	22	67	34
	Clay soil	Kafr Elshikh	67	52	21	72	324	55	221	2473	u.d.	11	21	106	36
Psidium guajava	Black sand	Baltim	49	16	10	27	844	31	513	1245	u.d.	30	24	30	39
	Clay soil	El Dakahlia	60	54	20	76	361	53	245	2613	u.d.	12	22	112	37
Mangifera indica	Black sand	Baltim	91	23	10	48	1707	31	1069	2445	u.d.	61	20	61	34
	Clay soil	El Nubaria	25	13	26	48	1160	29	725	518	u.d.	42	24	13	40

Notes: Data were obtained from the nuclear material laboratory as mean values without standard deviations as there was no significant difference between replicates. u.d., below the limit of detection.

Table 3. Major oxides (wt%) in the cultivated coastal black sand and in the inland clayey soils.

			Major Oxides (%)										
Species	Study site	Locality	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	L.O.I.	Total (%)
Eruca sativa	Black sand	Baltim	63.69	6.38	3.69	9.58	11.2	2.0	1.55	0.33	0.66	0.9	99.98
	Clay soil	Giza	57.67	8.95	1.28	7.99	7.0	1.0	1.08	0.67	0.39	13.48	99.51
Lycopersicon esculentum	Black sand	Baltim	68.62	5.89	5.49	8.78	5.6	1.0	2.22	0.46	0.74	0.61	99.41
	Clay soil	Kafr Elshikh	52.17	11.76	1.72	9.18	5.6	1.0	1.62	0.79	0.40	14.91	99.15
Psidium guajava	Black sand	Baltim	57.87	5.34	1.98	7.99	7.0	2.0	2.09	0.60	0.55	14.49	99.91
	Clay soil	El Dakahlia	50.45	10.43	1.99	10.38	8.4	1.0	1.62	0.79	0.38	14.04	99.30
Mangifera indica	Black sand	Baltim	71.42	5.25	1.82	5.59	5.6	2.0	2.09	0.53	0.42	4.35	99.07
	Clay soil	El Nubaria	78.87	4.76	0.54	2.39	4.2	1.0	1.48	0.46	0.42	5.6	99.72

Notes: Data were obtained from the nuclear material laboratory as mean values without standard devaitions as there was no significant difference between replicates. L.O.I., loss on ignition.

Table 4. Uranium and thorium radionuclide concentrations ($Bq\,kg^{-1}$ dry weight) in the edible portions of the study plant species, and in the cultivated coastal black sand and inland clayey soils.

			Uranium			Thorium		
Species	Study site	Locality	Soil ($Bq\ kg^{-1}$)	Plant ($Bq\ kg^{-1}$)	Transfer factor	Soil ($Bq\ kg^{-1}$)	Plant ($Bq\ kg^{-1}$)	Transfer factor
Eruca sativa	Black sand	Baltim	76.92 ± 3.11***	12.96 ± 2.23**	0.17 ± 0.03**	32.46 ± 0.62***	1.66 ± 0.36**	0.05 ± 0.01
	Clay soil	Giza	45.25 ± 1.89	4.20 ± 0.49	0.09 ± 0.01	16.03 ± 0.62	0.53 ± 0.01	0.03 ± 0.00
Lycopersicon esculentum	Black sand	Baltim	95.43 ± 3.11***	16.66 ± 1.97***	0.18 ± 0.02*	31.25 ± 1.02***	1.54 ± 0.16***	0.05 ± 0.01*
	Clay soil	Kafr Elshikh	46.89 ± 2.47	2.22 ± 0.86	0.05 ± 0.02	11.45 ± 0.62	0.49 ± 0.04	0.04 ± 0.00
Psidium guajava	Black sand	Baltim	86.79 ± 1.89***	16.17 ± 1.73*	0.19 ± 0.02	20.07 ± 0.62***	1.46 ± 0.04***	0.07 ± 0.00
	Clay soil	El Dakahlia	60.88 ± 1.43	11.48 ± 1.36	0.19 ± 0.03	7.95 ± 0.62	0.57 ± 0.00	0.07 ± 0.01
Mangifera indica	Black sand	Baltim	81.86 ± 1.89***	14.31 ± 1.36**	0.18 ± 0.02***	24.24 ± 0.81***	0.97 ± 0.02***	0.04.00***
	Clay soil	El Nubaria	9.75 ± 0.45	9.39 ± 0.99	0.97 ± 0.15	01.91 ± 0.10	0.49 ± 0.04	0.25 ± 0.03

Notes: Values are given as mean ± SD and rounded to two decimal places. Significant at $^{***}p \leq 0.001$; $^{**}p \leq 0.01$; $^{*}p \leq 0.05$.

The percentage of fine sand was generally higher in the inland soil than in coastal black sand soil. In contrast to coarse sand, silt and clay contents were lowest in the coastal black sand and highest in the inland clayey soil.

With respect to the chemical properties of the soil, the reaction was slightly alkaline with a pH from 7.27 ± 0.02 and 7.41 ± 0.02 in black sand to 7.67 ± 0.07 and 7.75 ± 0.01 in the inland clayey soil (Table 1). Electric conductivity (EC) was mostly higher in the inland soil than in the coastal black sand, as also indicated by the percentage content of Cl^- and SO_4^{2-} ions. Similarly, carbonates and organic matter contents showed maximum values in the inland soil and minimum values in the coastal black sand soil. For example, the coastal black sand in which *E. sativa* was cultivated contained 3.47 ± 0.20 and 0.24 ± 0.00% of carbonates and organic matter, respectively. The inland clayey soil in which *E. sativa* was cultivated contained significantly higher values of carbonates and organic matter, amounting to 7.12 ± 0.34 and 3.66 ± 0.05%, respectively.

Trace elements in the coastal black sand and inland clayey soil are shown in Table 2. Barium (Ba), zirconium (Zr) and yttrium (Y) were the most detected trace elements in the coastal black sand. Trace element concentrations were generally higher in the coastal black sand than in the inland soil with the exception of zinc (Zn), rubidium (Rb) and vanadium (V) content, which were

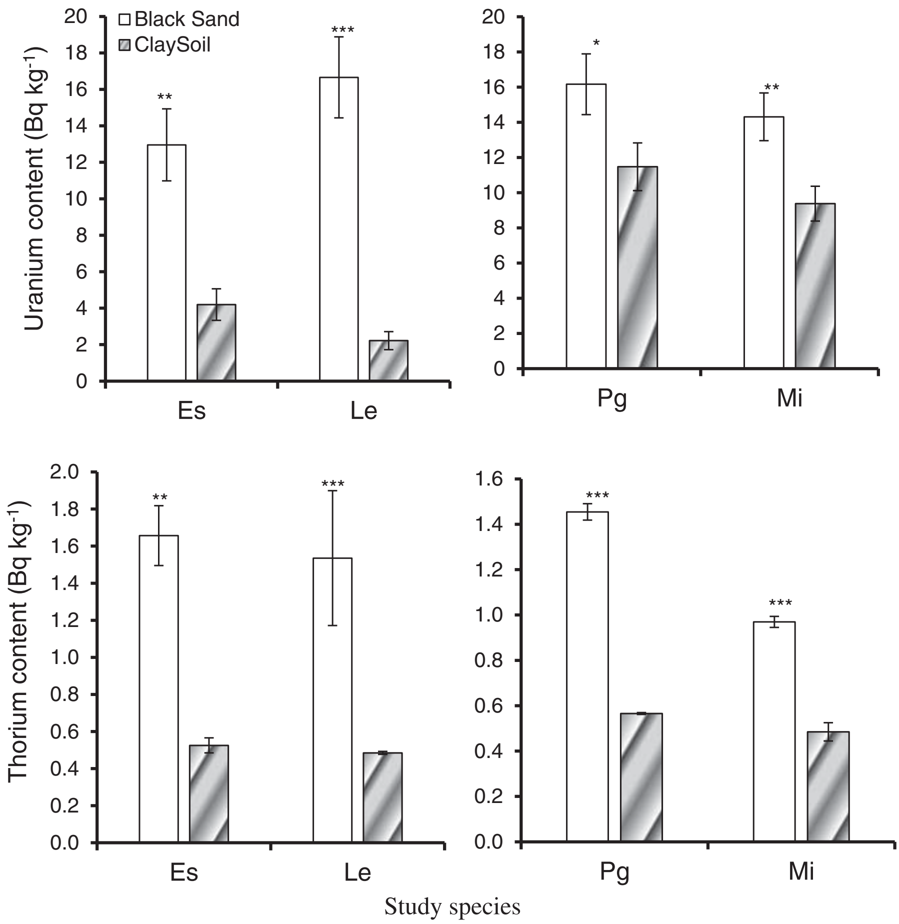

Figure 1. Radionuclide concentration (Bq kg^{-1} dry weight) in the edible portions of the study crop plants (Es = *Eruca sativa* and Le = *Lycopersicon esculentum*) and study fruit trees (Pg = *Psidium guajava* and Mi = *Mangifera indica*) cultivated in coastal black sand and inland clayey soils. The vertical bar around the mean is the standard deviation. Results are significant at $^{***}p \leq 0.001$; $^{**}p \leq 0.01$ and $^{*}p \leq 0.05$.

higher in the inland soil than in coastal black sand soil. Lead (Pb) was not detected in coastal black sand and inland soil. Silicon oxide (SiO_2) was the major oxide constituent in coastal and inland soil types (Table 3). The most commonly detected major oxides following SiO_2 were: iron oxide (Fe_2O_3), CaO and aluminum oxide (Al_2O_3). Titanium oxide (TiO_2) was relatively higher in the coastal black sand than in the inland soil. Potassium oxide (K_2O) and phosphorus oxide (P_2O_5) were detected the least in both coastal and inland soils.

3.2. *Radionuclide content and transfer factor*

The concentrations of U and Th in the study soil are summarised in Table 4. The values of U and Th were significantly higher in the coastal black sand than in the inland clayey soil. The U concentrations in the coastal black sand soil where *E. sativa* and *L. esculentum* cultivated were significantly higher than that in the coastal black sand soil where *P. guajava* was growing. The same trend of results was observed for the Th concentration in the same soil.

For the plants cultivated in the coastal black sand soil, U and Th concentrations were higher than in the plants cultivated in the inland clayey soil (Figure 1). In the leaves of *E. sativa* cultivated in the inland clayey soil, U and Th concentrations were 4.20 and 0.53 Bq kg^{-1} dry weight respectively, but these concentrations increased significantly to 12.96 and 1.66 Bq kg^{-1} dry weights respectively, in plants cultivated in the coastal black sand. Similarly, U and Th concentrations

Table 5. Pearson's correlation coefficient between U and Th concentrations and the various soil characteristics, assuming a linear relation.

	Radionuclide concentration (Bq kg^{-1} dry weight)			
	Uranium		Thorium	
Characteristic	Soil	Plant	Soil	Plant
U in soil (Bq kg^{-1})	1.00	0.68***	0.84***	0.78***
Th in soil (Bq kg^{-1})	0.84***	0.54**	1.00	0.85***
U in plant (Bq kg^{-1})	0.68***	1.00	0.54**	0.78***
Th in plant (Bq kg^{-1})	0.78***	0.78***	0.85***	1.00
Coarse sand (g%)	0.29	0.68***	0.46*	0.61***
Fine sand (g%)	0.26	0.40*	0.27	0.31
Clay (g%)	−0.36*	−0.78***	−0.50**	−0.66***
Silt (g%)	−0.27	−0.62***	-0.51**	−0.62***
$CaCO_3$ (g%)	−0.25	−0.78***	−0.03	−0.32
HCO_3^- (g%)	−0.17	−0.16	−0.47*	−0.44*
Cl^- (g%)	−0.02	−0.03*	−0.39	−0.33
Organic matter (g%)	−0.32	−0.58**	−0.58***	−0.69***
pH	−0.44*	−0.36*	−0.69***	−0.61***
H_2SO_4 (g%)	−0.16	−0.33	−0.26	−0.40*
EC (dS m^{-1})	−0.08	−0.10	−0.42*	−0.37*

Notes: Values are rounded to two decimal places. Correlations significant at $^{***}p \le 0.001$; $^{**}p \le 0.01$; $^{*}p \le 0.05$.

Table 6. Multiple regressions of the data showing R^2 values indicating the variation in U and Th radionuclide concentrations in plant tissues with their concentration in soil, together with and other soil characteristics of clay, silt and coarse sand.

Radionuclide	R^2	Equation
Uranium	0.91***	$U_{plant} = 9.73 + 0.07^{***}\ U_{Soil} - 0.47^{***}\text{Clay} + 0.85\text{Silt} - 0.22\ \text{OM} + 0.0\ \text{Coarse Sand}$
Thorium	0.87***	$Th_{plant} = 0.60 + 0.03^{***}\ Th_{Soil} - 0.02\text{Clay} + 0.13^{*}\text{Silt} - 0.18\ \text{OM} + 0.02^{*}\text{Coarse Sand}$

Notes: OM, organic matter. $^{***}p \le 0.001$; $^{**}p \le 0.01$; $^{*}p \le 0.05$.

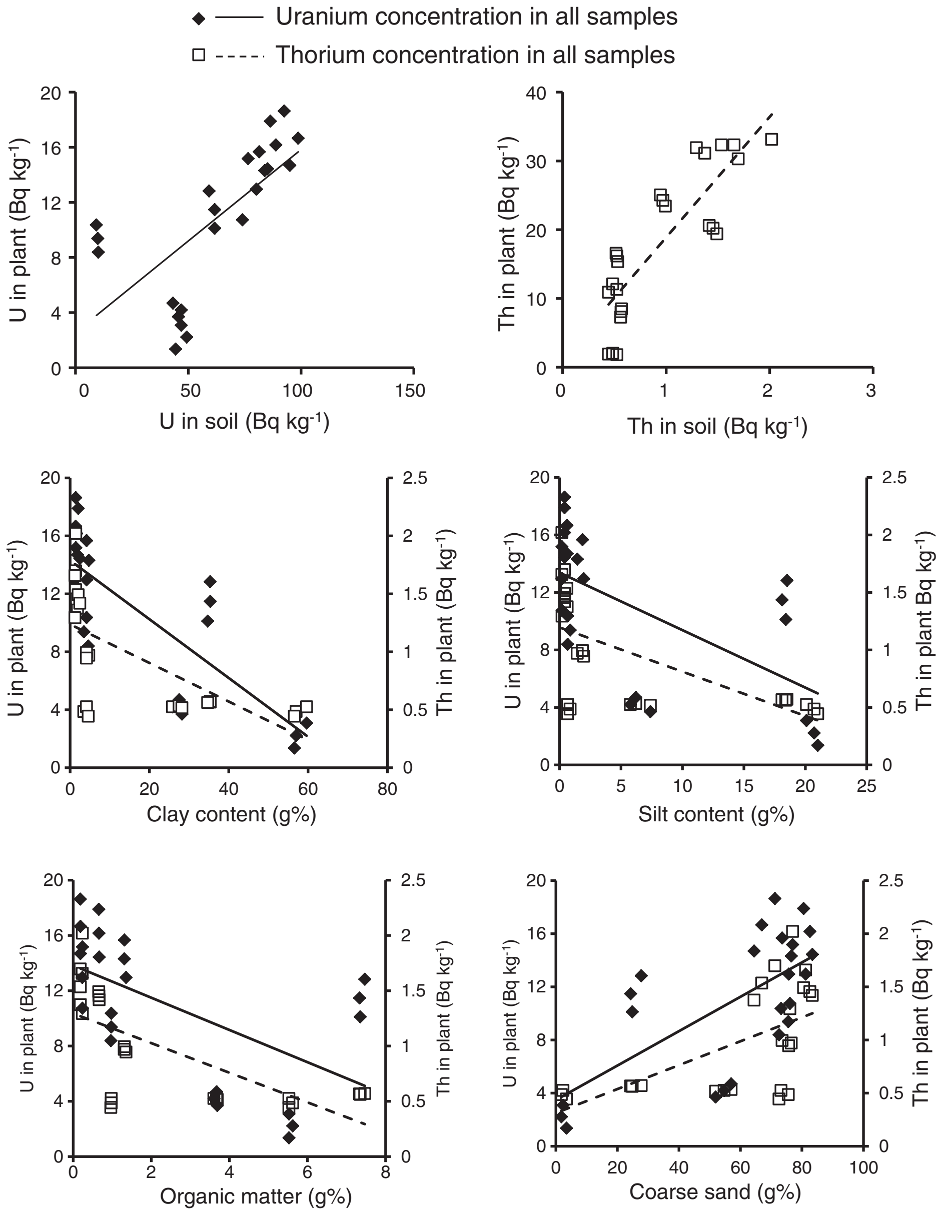

Figure 2. Relationships between U and Th concentration in plants and their concentrations in soil against the soil properties clay, silt, organic matter and coarse sand contents.

in fruits of *L. esculentum*, *P. guajava* and *M. indica* cultivated in coastal black sand soil were significantly higher than the concentrations in the plants collected from inland clayey soil site.

Transfer factors from soil to edible portions of the study plant species were calculated and are shown in Table 4. Transfer factors for U from coastal black sand soil to the study plant species were generally higher than in the inland clayey soil. Alternatively, with respect to the transfer factor for Th to the study plant species, there was no significant difference between both coastal black sand and inland clayey soils.

3.3. *Soil characteristics–radionuclide uptake relationship*

The relationship between the physical and chemical properties of the soil and both U and Th uptake by plants are summarised in Table 5. There is a strong positive correlation between radionuclides concentrations in soil and the concentrations absorbed by plants. The correlation coefficient between U in soil and U in plants was 0.68, whereas between U in soil and Th in plants was 0.78. The correlation coefficient between Th in soil and in plants was 0.85. Most soil characteristics showed strong correlation with U and Th uptake by plants. The correlation coefficient between coarse sand and U content in the plants was 0.68 and that between coarse sand and Th in plants was 0.61. Alternatively, a strong negative correlation was found between clay, silt and organic matter content in the soil and U and Th uptake by plants. pH showed a negative correlation with radionuclides content of plants for both U and Th. The correlation between uptake of the two radioactive elements by plants and other soil characteristics showed a weak negative correlation. The variation in U and Th content in plant tissues with their content in soil and some soil characteristics, particularly clay, silt, organic matter and coarse sand content, is shown by multiple regression of the data, giving R^2 and is explained by an equation for each radionuclide (Table 6). The R^2 values for U and Th are 0.91 and 0.87, respectively. There is a strong positive and linear relationship

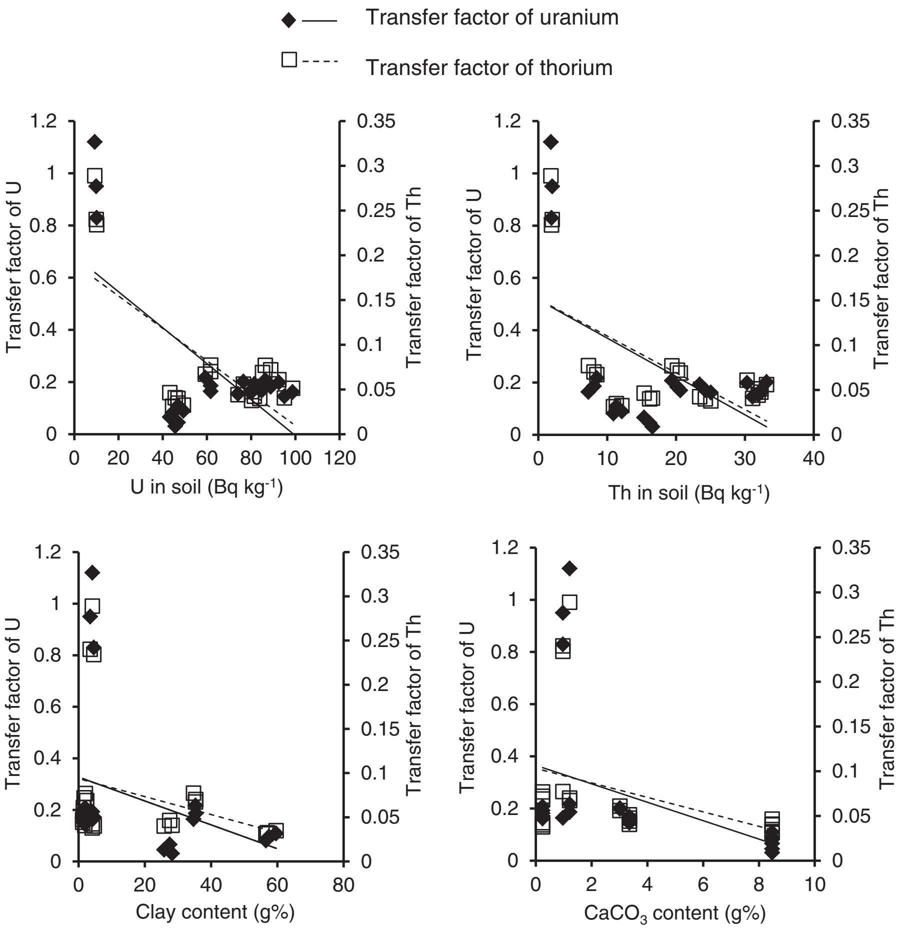

Figure 3. Relationships between U and Th transfer factors and their concentrations against clay and $CaCO_3$ content in soil.

Table 7. Pearson's correlation coefficient between U and Th transfer factor (TF) and various soil characteristics, assuming a linear relation.

	Transfer factor	
Soil characteristics	Uranium	Thorium
Uranium in soil ($Bq\,kg^{-1}$)	−0.65***	−0.69***
Thorium in soil ($Bq\,kg^{-1}$)	−0.53**	−0.61***
Coarse sand (g%)	0.33	0.24
Fine sand (g%)	0.16	0.14
Clay (g%)	−0.36*	−0.26
Silt (g%)	−0.34	−0.24
$CaCO_3$ (g%)	−0.41*	−0.37*
HCO_3 (g%)	0.02	0.06
Cl (g%)	−0.19	−0.12
Organic matter (g%)	−0.29	−0.20
pH	0.12	0.18
H_2SO_4 (g%)	−0.28	−0.26
EC ($dS\,m^{-1}$)	−0.16	−0.09
TF uranium	1.00	0.99***
TF thorium	0.99***	1.00

Notes: Values are rounded to two decimal places. Correlations significant at $^{***}p \leq 0.001$; $^{**}p \leq 0.01$; $^{*}p \leq 0.05$.

between the absorbed radionuclide and its concentration in soil (Figure 2). A positive relationship occurs with coarse sand content, whereas clay, silt and organic matter contents demonstrate a strong negative linear relationship with U and Th content in plants. Soil-to-plant transfer factors for U and Th showed a strong negative correlation with U and Th concentrations in soil (Table 7). As observed from correlation coefficient values, the relationship between the transfer factors of U and Th and some major soil characteristics is negative, particularly with clay and $CaCO_3$ content, which showed a strong negative correlation (Figure 3).

4. Discussion

Study of geochemical characteristics of soil revealed that coastal black sand soil is rich in coarse sand with relatively low clay, silt, carbonates and organic matter contents. Black sand soil contains several trace elements and major oxides that were detected with higher concentrations than in the inland clayey soil. The elements Zr, Y and Ba were the most detectable trace elements, whereas SiO_2 and Fe_2O_3 were the most detectable oxides in the coastal black sand soil. Therefore, these elements are easily precipitated as sulfates and carbonates during weathering. As pointed out previously [23,24], Zn, Ba, Mn and P are fixed by the organic matter and adsorbed onto the oxides and hydroxides. A study of the major oxides in the soil revealed that SiO_2, Fe_2O_3, CaO and Al_2O_3 are the most detected oxides in both coastal black sand and inland clayey soils, whereas K_2O and P_2O_5 are the least detected oxides. SiO_2 is the most resistant oxide to weathering, and hence become concentrated in sandy, silty and loamy soil [23].

Radionuclide concentrations in the coastal black sand and in the inland clayey soils revealed that the U concentration is generally higher than that of Th. Concentrations of U and Th in soil depend mainly on the soil type, parent rock, climate, vegetation and season [16]. The slightly high U concentration in the cultivated soils is explained by the use of phosphate fertilisers in the agriculture practices. This may interpret the high concentrations of U and Th accumulated in the edible portions of the plants cultivated in the coastal black sand soil compared with plants cultivated in the inland clayey soil. Similarly, Hegazy and Emam [4] revealed that U and Th concentrations in the tissues of wild plants grown in natural coastal black sand soil were higher than in plants grown in inland uncultivated soils. It has also been reported [4,16] that concentrations of U and

Th are species dependent. Differences in uptake between species suggest that U is strongly related to the plant's ability to regulate uptake of the element [25]. The transfer factor for U showed high values compared with the transfer factor for Th from the coastal black sand and inland clayey soil. This is in agreement with Martínez-Aguirre et al. [26] who reported that Th exhibits a much lower mobility than U, and is also consistent with the results of Chen et al. [27] who observed that Th has lower transfer factor values than U.

The relationship between radionuclides in plant tissues and their concentrations in soil revealed a strong positive correlation. This is supported by a study by Al-Masri et al. [28], who reported the increase of radionuclide concentrations in plant tissues with the increased amounts in soil. It is known that the soil-to-plant transfer of naturally occurring radionuclides is affected by both soil characteristics and concentrations of radionuclides in the soil [4,29]. Soil properties such as pH, clay mineral, Ca, K and organic matter contents, and soil amendments such as fertiliser application have been reported [5,30] to strongly affect the uptake, retention and distribution profile of radionuclides in plants. As indicated by the results, there was a strong negative correlation between U and Th uptake by plant and clay, silt, organic matter content and pH of the soil. These findings are in accordance with previous studies [4,31] that revealed a negative correlation between U and Th uptake by some wild plant species and clay and organic matter content of soil. pH has been reported to influence the mobility of radionuclides in the soil as it affects the adsorption and the solubilisation of radionuclides [32,33]. Organic matter content has been reported to affect the retention and migration of the fallout radionuclides in the environment [34,35], as it can be associated with higher levels of soluble humic acids due to formation of U complex and render it unavailable for plant uptake [36]. The effects of soil texture on the movement of radionuclides appear to be similar to the effects on the divalent cations Ca and Mg, which are adsorbed by soil clay particles through ion exchange mechanisms. The relative rates of radioactive element adsorption have been reported to increase with the increase of soil clay content [37].

The transfer factor for U and Th from soil to plant and their concentrations in the soil, particularly clay and $CaCO_3$ content, revealed a strong negative correlation. This seems to be attributed to inherent plant complexity, special variability in the plant–soil system, and the uptake and accumulation of radionuclides in plants [38]. The transfer factor is a useful parameter, which is used to evaluate the impact of radionuclide release into the environment. The transfer factor depends on the vegetation type, soil properties and the type of radionuclides [39]. As pointed previously [38], the uptake of isotope from soil to plants depends upon various interrelated soil properties including texture, clay content, dominant clay minerals, cation exchange capacity, exchangeable cations, pH and organic matter contents. It also varies with physical and chemical forms of the radionuclides, plant species, plant part and stage of growth. Use of the transfer factor assumes a linear relationship between the concentrations of a certain element in the plant and in the soil [15]. This is shown in the current study where linear relationship was observed between U and Th concentrations in soil and plant tissues. Non-essential elements or elements that are not physiologically regulated by plants typically follow a linear curve model [40]. This proved true in the current study, where U and Th demonstrated a linear curve model, indicating that the two elements may act as non-essential elements.

5. Conclusions

The study of radionuclide concentrations in the four crop plant species in the coastal black sand soil, revealed an ability to accumulate U and Th in their edible portions. Radionuclide accumulation occurs at higher concentrations in coastal black sand soils than in cultivated inland soils. Soil-to-plant transfer of U was significantly higher than the transfer of Th. The uptake of U and Th by plants was strongly correlated with the radionuclide content and the geochemical characteristics of the soil. This correlation was positive with radionuclide concentration and coarse sand content, whereas a negative correlation was observed with pH, clay, silt and organic matter content of the soil. Cultivation of food plants in soils rich in clay, silt and organic matter minimises the absorption of radioactive elements due to the reduced soil-to-plant transfer of radionuclides.

Acknowledgements

The authors acknowledge the deanship of scientific research at King Saud University for funding the work through the research group project No. RGP-VPP-175 on plant ecology and biotechnology. We appreciate the two anonymous reviewers and editorial comments which greatly improved the manuscript.

References

[1] A.A.H. Hassan, *Ground magnetic and spectrometric exploration of the black sand deposits in Abu Khashaba district, Rosetta area, Egypt*, M.Sc. diss., Cairo University, 1993.
[2] A.F.A. El-Hadry, *Geological, sedimentological and radiometric studies in black sand deposits, west Rosetta beach which emphasis a heavy economic minerals*, Ph.D. diss., Cairo University, 1998.
[3] A. El-Gamal, M. Rashad, and Z. Ghatass, *Radiological responses of different types of Egyptian Mediterranean coastal sediments*, Radiat. Phys. Chem. 79 (2010), pp. 831–838.
[4] A.K. Hegazy and M.H. Emam, *Accumulation and soil-to-plant transfer of radionuclides in the Nile delta coastal black sand habitats*, Int. J. Phytoremediat. 13 (2011), pp. 140–155.
[5] M. Bolca, M.M. Saçb, B. Çokuysala, T. Karalıb, and E. Ekdalb, *Radioactivity in soils and various foodstuffs from the Gediz River Basin of Turkey*, Radiat. Meas. 42 (2007), pp. 263–270.
[6] A. Poli, A. Salerno, G. Laezza, P. di Donato, S. Dumontet, and B. Nicolaus, *Heavy metal resistance of some thermophiles: Potential use of α-amylase from* Anoxybacillus amylolyticus *as a microbial enzymatic bioassay*, Res. Microbiol. 160 (2009), pp. 99–106.
[7] P. Akhterb, S.D. Orfi, and N. Ahmad, *Caesium concentration in the Pakistani diet*, J. Environ. Radioactiv. 67 (2003), pp. 109–118.
[8] N.N. Jibiri, I.P. Farai, and S.K. Alausa, *Estimation of annual effective dose due to natural radioactive elements in ingestion of foodstuffs in tin mining area of Jos-Plateau, Nigeria*, J. Environ. Radioactiv. 94 (2007), pp. 31–40.
[9] P.W. Abrahams, *Soils: Their implications to human health*, Sci. Total Environ. 291 (2002), pp. 1–32.
[10] X. Hou and P. Roos, *Critical comparison of radiometric and mass spectrometric methods for the determination of radionuclides in environmental, biological and nuclear waste samples*, Anal. Chem. Acta 608 (2008), pp. 105–139.
[11] M. Gavrilescu, L.V. Pavel, and I. Cretescu, *Characterization and remediation of soils contaminated with uranium*, J. Hazard. Mater. 163 (2009), pp. 475–510.
[12] C. Tamponnet, A. Martin-Garin, M.A. Gonze, N. Parekh, R. Vallejo, T. Sauras-Year, J. Casadesus, C. Plassard, S. Staunton, M. Norden, R. Avila, and G. Shaw, *An overview of BORIS: Bioavailability of radionuclides in soils*, J. Environ. Radioactiv. 99 (2008), pp. 820–830.
[13] W. Gang, W. Zhen-Kuan, W. Yong-Xiang, C. Li-Ye, and S. Hong-Bo, *The mutual responses of higher plants to environment: Physiological and microbiological aspects*, Colloid Surface B 59 (2007), pp. 113–119.
[14] M.D. Sztajnkrycer and E.J. Otten, *Chemical and radiological toxicity of depleted uranium*, Mil. Med. 169 (2004), pp. 212–216.
[15] P. Blanco Rodriguez, F. Vera Tomé, and J.C. Lozano, *About the assumption of linearity in soil-to-plant transfer factors for uranium and thorium isotopes and ^{226}Ra*, Sci. Total Environ. 284 (2002), pp. 167–175.
[16] I. Shtangeeva, S. Ayrault, and J. Jain, *Thorium uptake by wheat at different stages of plant growth*, J. Environ. Radioactiv. 81 (2005), pp. 283–293.
[17] W.P. Miller and D.M. Miller, *A micro-pipette method for soil mechanical analysis*, Commun. Soil Sci. Plan Anal. 18(1) (1987), pp. 1–15.
[18] S.E. Allen, H.M. Grimshaw, J.A. Parkinson, and C. Quarmby, *Chemical Analysis of Ecological Materials*, Blackwell, Oxford, 1974.
[19] M.L. Jackson, *Soil Chemical Analysis*, Constable, London, 1962.
[20] A. Hazen, *On the determination of chloride in water*, Am. J. Chem. 2 (1989), pp. 409–425.
[21] C.V. Balbir, K. Swaminathan, and K.C. Sud, *An improved turbidimetric procedure for the determination of sulphate in plants and soils*, Talanta 24 (1977), pp. 49–50.
[22] Z. Marczenko, *Separation and Spectrophotometric Determination of Elements*, Harwood, New York, 1986.
[23] S.Y. Afifi, F.A. Moawad, N.E. Ali, and M.A. Ahmed, *Impact of radioactive elements on the biochemical constituents of some wild plants, West Central Sinai, Egypt*, Bull. Fac. Sci. Cairo Uni. 72 (2004), pp. 1–21.
[24] A. Kabata-Pendias and H. Pendias, *Trace elements in soil and plants*, 3rd ed, CRC Press, Boca Raton, FL, 2000.
[25] A.C. Hakonson-Hayes, P.R. Frsquez, and F.W. Whicker, *Assessing potential risks from exposure to natural uranium in well water*, Environ. Radioact. 59 (2002), pp. 29–40.
[26] A. Martínez-Aguirre, M. Garcia-León, and M. Ivanovich, *U and Th speciation in river sediments*, Sci. Total Environ. 173 (1995), pp. 203–209.

[27] S.B. Chen, Y.G. Zhu, and Q.H. Hu, *Soil to plant transfer of* ^{238}U*,* ^{226} *Ra and* ^{232} *Th on a uranium mining-impacted soil from southeastern China*, J. Environ. Radioactiv. 82 (2005), pp. 223–236.
[28] M.S. Al-Masri, B. Al-Akel, A. Nashawani, Y. Amin, K.H. Khalifa, and F. Al-Ain, *Transfer of* ^{40}K*,*^{238} *U*,^{210} *Pb, and* ^{210} *Po from soil to plant in various locations in south of Syria*, J. Environ. Radioactiv. 99 (2008), pp. 322–331.
[29] V.A. Pulhani, S. Dafauti, A.G. Hegde, R.M. Sharma, and U.C. Mishral, *Uptake and distribution of natural radioactivity in wheat plants from soil*, J. Environ. Radioactiv. 79 (2005), pp. 331–346.
[30] M.S.A. Soliman, A.K. Hegazy, S.K, Goda, M.H. Emam, and A.A. Alatar, *Cytotoxicity and mutagenic effects of soil radionuclides on some black sand*, J. Mediterr. Ecol. 11(2011), pp. 5–20.
[31] A.K. Hegazy, M.H. Emam, and A.A. Alatar, *Growth and reproductive attributes of radionuclides phytoremediators in the Mediterranean coastal black sands*, Afr. J. Biotech. 10 (2011), pp. 16781–16792.
[32] M.K. Seddeek, H.M. Badran, T. Sharshar, and T. Elnimr, *Characteristics, spatial distribution and vertical profile of gamma-ray emitting radionuclides in the coastal environment of North Sinai*, J. Environ. Radioactiv. 84 (2005), pp. 21–50.
[33] A. Savinkov, N. Semioshkina, B.J. Howard, and G. Voigt, *Radiostrontium uptake by plants from different soil types in Kazakhstan*, Sci. Total Environ. 373 (2007), pp. 324–333.
[34] S. Staunton, C. Dumat, and A. Zsolnay, *Possible role of organic matter in radiocaesium adsorption in soils*, J. Environ. Radioactiv. 58 (2002), pp. 163–173.
[35] I. Shtangeeva, *Uptake of uranium and thorium by native and cultivated plants*, J. Environ. Radioactiv. 101 (2010), pp. 458–463.
[36] D.C. Lauria, F.C.A. Ribeiro, C.C. Conti, and F.A. Loureiro, *Radium and uranium levels in vegetables grown using different farming management systems*, J. Environ. Radioactiv. 100 (2009), pp. 176–183.
[37] J.J. Mortvedt, *Plant and soil relationships of uranium and thorium decay series radionuclide. A review*, J. Environ. Qual. 23 (1994), pp. 643–650.
[38] A. Jabbara, M. Tufailc, W. Arshedb, A.S. Bhattia, S.S. Ahmadd, P. Akhterb, and M. Dilband, *Transfer of radioactivity from soil to vegetation in Rechna Doab, Pakistan*, Isotope Environ. Health Sci. 46 (2010), pp. 495–505.
[39] H. Velasco, J.J. Ayub, and U. Sansone, *Analysis of radionuclide transfer factors from soil to plant in tropical and subtropical environments*, Appl. Radiat. Isotope. 66 (2008), pp. 1759–1763.
[40] M.I. Sheppard and S.C. Sheppard, *The plant concentration ratio concept as applied to natural U*, Health Phys. 48 (1985), pp. 494–500.