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Original Article

Estimation of radiostrontium, radiocesium and radiobarium transfer from arid soil to plant: A case study from Kuwait

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ABSTRACT

A technical approach to design and carry out an experiment to determine the uptake of selected radionuclides in site-specific conditions in Kuwait was developed and successfully executed for developing a radioecological decision support system. The radionuclides from soil-to-plant transfer factors have been obtained for leafy and non-leafy vegetables, and root crops cultivated in Kuwait. Two types of vegetated soils were selected and spiked with high concentrations of three relatively short-lived selected radionuclides (^{85}Sr, ^{134}Cs, and ^{133}Ba). The highest strontium and barium transfer factors were found in the order: leafy vegetables > root crops > non-leafy vegetables. The approximate range of radiocesium transfer factor was found to be low in all plant groups and was comparable to those reported elsewhere in different soil types of temperate and tropical environments. A strong negative correlation between the obtained transfer factors and the distribution coefficient of the radionuclide in soil was found. It is recommended to adopt the newly derived parameters for the sensitive areas in Kuwait and other Gulf countries instead of using the generic parameters, whenever dose calculation codes are used. This will help to more accurately assess and predict the end results of the committed effective dose equivalent through ingestion pathway.

1. Introduction

Significant quantities of long-lived radionuclides have been released into the atmosphere and deposited on the ground following nuclear weapons testing in the mid-sixties and the nuclear power accidents of Chernobyl and Fukushima, which occurred in 1986 and 2011, respectively [1–3]. Kuwait recognizes the risk related to embracing nuclear energy in the region, the possibility of nuclear accidents and the associated radionuclides leaching and being taken up by plants and grazing animals.

In general, the behavior of deposited radionuclides on the ground surface is controlled by their residence time in the topsoil. For example, the slow movement and low migration rate of radionuclides in the soil results in a long radionuclide residence time at the plant-rooting zone and, hence, increases the probability of radionuclide uptake by the plant. It will also pose additional hazards in terms of radiation exposure from the topsoil surface. Of principal interest in terms of environmentally significant long-lived radionuclides that might be released in significant quantities through severe nuclear/radiological accidents are radiocesium (^{137}Cs and ^{134}Cs) and radiostrontium (^{90}Sr) [4]. These long-lived radionuclides can be transported to the plant *via* root uptake and then to the food chain, causing an additional radiological dose.

The plant uptake of deposited radionuclides from the soil *via* plant roots is commonly expressed as the soil-to-plant Transfer Factor (TF) and is usually calculated as the ratio of the radionuclide concentration in plant and soil. However, the radionuclide content is usually expressed on a dry weight basis, as recommended by the IAEA [3], to decrease the data variability and to harmonize them for comparison purposes. In contrast, wet weights are usually used when estimating the committed effective dose through the ingestion of contaminated foodstuff.

The radionuclide TF is an important parameter that needs to be calculated for the site-specific conditions in order to estimate and predict the committed effective dose equivalent (CEDE) through the ingestion pathway [5]. Although the bulk of TF data in the ecological system has been collated in the IAEA technical report series No. 472 as a result of efforts in European, Nordic, and Northern American countries [3], limited data have been documented in arid and semi-arid areas in the Medill East region [6–10]

In general, many parameters control radionuclide migration into

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soil and uptake by the plant. It is a complicated process attributed to the physicochemical properties of the radionuclides and soil characteristics including, but not limited to, species/characteristics and contents of clay, cation exchange capacity (CEC), microorganisms, pH of the soil, the concentration of inorganic ions, and the concentration of organic substances. As such, the behavior of the relevant radionuclide in the soil is the major factor controlling its mobility [11]. The relationship between radionuclides' mobility and the parameters mentioned earlier are inversely proportional. For example, a low content of clay or CEC leads to high radionuclide mobility in the soil profile and vice versa. However, due to the complex process of the radionuclide uptake by the plant root, a wide range of TF values can be expected for the same plant species. This becomes clearer if we look into the large ranges of cesium TFs reported in the data worldwide. For example, the TF for leafy, non-leafy, and root crops varied from 0.00015 to 3, from 0.0008 to 11, and from 0.001 to 0.1, respectively [12].

The assessment of many relevant parameters affecting the radionuclides' movements is a long process and requires sufficient time and mathematical approximation to be performed. Conducting Lysimeter/field experiments to derive the radionuclides' movements and uptake parameters for the site-specific conditions is more realistic, since the most influencing parameters will be taken into consideration.

The present work aimed to evaluate the TFs of different plant groups (leafy and non-leafy vegetables and root crops) which are commonly cultivated outdoors in Kuwait, in addition to obtaining information on radionuclide translocations in the plant's compartment. These parameters are essential to estimate and predict the CEDE of the public due to the consumption of contaminated food in the case of nuclear/radiological accidents. A large amount of soil-to-plant TF data has already generated and reported for the temperate and tropical environments, yet no data are available in the arid region, in particular, for the Gulf countries. Thus, this study and the resulting outputs have great importance in terms of providing the TFs for such harsh conditions, which can be used in similar environments, especially the environment of the Arabian Gulf region. The newly derived parameters for the radioecologically sensitive areas in Kuwait, as well as in other Gulf countries, can be adopted instead of the accessible generic parameters whenever the dose calculation codes are used. This will help assess and predict the end results of the total effective dose equivalent more accurately.

2. Methods and materials

2.1. Vegetated soil sampling and characterization

Most of the land outside the urban area is owned by the State of Kuwait. The soil type representing the most common vegetated soil was selected, based on information on the soil survey for the State of Kuwait [13]. Data from existing studies were used to identify the soil types that were considered as radioecologically sensitive areas. About 24,000 ha of privately owned or controlled farms, used for agriculture, are located in the south and north of Kuwait; these are the Wafra and Abdaly farms. All agricultural land use relies on irrigation using groundwater and desalination water. Generally, peat moss and organic matter, such as cow compost as well as other fertilizer, are added to improve the poor soil quality. Such addition increases water-holding capacity and improves the soil structure.

Adequate quantity of bulk vegetated soil from the selected sites of the Abdaly (30.0235° N; 47.7046° E) and Wafra (28.5774° N; 48.1025° E) farms were excavated and transferred to a planter polyvinyl chloride box of about $100 \times 100 \times 50$ cm dimensions. This size is large enough to hold an adequate volume of soil and has enough space for proper root growth and development. According to the International Union of Radioecology (IRU) about 10–20 cm soil depth for grass and all other crops is sufficient for planting vegetables such as turnips, cucumbers, broccoli, beets, lettuce, and green onions. The IRU approach assumes that roots and all radionuclides present in the rooting zone are in that soil layer [14]. The general soil type properties and characteristics were adopted from the detailed report of the soil survey in Kuwait, 1999 [15], as presented in Table 1.

2.2. Spiking of soil with mixed gamma solution

About 1 L of a stock solution containing a high activity of ^{85}Sr and ^{134}Cs certified solutions was prepared. Although, ^{137}Cs is a gamma emitter and easy to be detected by conventional gamma spectrometry, yet ^{90}Sr is a beta emitter and needs a long procedure of radiochemistry separation and measurement. Therefore, ^{85}Sr and ^{134}Cs were used as tracers since they both can be easily determined by gamma spectrometry and have shorter physical half-lives than ^{90}Sr and ^{137}Cs, which facilitates the waste management of residual materials from the experiment. The arrangement of using shorter half-life radioisotopes was necessary to avoid accumulating large quantities of soil contaminated with long half-life radioisotopes. However, a low activity of ^{133}Ba certified liquid solution was added to the prepared gamma mixture solution as it is chemically similar to ^{226}Ra, which has a special radiological concern linked with the technologically enhanced naturally occurring radioactive materials. The radionuclide of ^{133}Ba is also easy to detect by gamma spectrometry.

Four plastic containers ($1 \times 1 \times 0.5$ m), filled with about 200 kg of soil, were hosted within a green shade. The containers were each filled with soil from one of the two farms (two containers for each farm). The soil in each container was wet and was mixed using an electric-powered, heavy-duty handheld mixer before spiking the radioactive materials. About 100 g of the prepared carrier-free radioactive mixture was transferred from the DURAN bottle to a garden presser sprayer, which was filled with 2 L distilled water using the remote handling tong. The garden presser sprayer was shielded with a 3 mm lead sheet and transported from the laboratory to the green shade by a trolley. Then, the radioactive solution was spread and mixed with the wet soil using the handheld mixer. The massic radioactivity and the associated uncertainty at the date of preparation were calculated in each soil container. The average concentrations of the contaminated soil at the date of executing the experiment were 12.3 ± 0.43 kBq.kg^{-1} for ^{85}Sr, 1659 ± 59 Bq.kg^{-1} for ^{134}Cs, and 42.6 ± 1.3 Bq.kg^{-1} for ^{133}Ba. The different radioactivity concentrations were selected according to the half-live of the radionuclides so that the concentration of the contaminated soil levels will be below the exemption levels adopted by the regulatory body in Kuwait after harvesting the plants.

2.3. Plant group selection and implantation

The selection of the plant groups and species was dependent on the most common vegetables cultivated in the open field and those most consumed by the Kuwaiti inhabitants [16]. Table 2 presents the plant species studied in the present work. Each plant species was cultivated in a green shed that could provide shelter for the plants from the cold winter in January and also from the very hot temperature in August. The plants were irrigated by plant sprayers; usually, a large volume of water is used for irrigation in Kuwait because of the high evaporation rate. Adequate quantities of water were frequently used to irrigate the plants according to the temperature, but enhanced wetting was avoided.

Two methods were applied for plant growing: young seedlings

Table 1
The physical and chemical soil characteristics and properties (soil survey in Kuwait, 1999).

Location	Type of Soil	Texture	pH	*Clay* (%)	OM (%)	Ca (%)	K (%)	CEC Meq 100 mg^{-1}
Wafra Farms (28.5774° N; 48.1025° E)	Very deep and well or excessively drained, moderate to rapid permeability, gradual wavy boundary	typic torripsamments hyperthermic coarse loamy, calcic horizon	8	5.3	0.22	0.18	21.7	4.9
Abdaly Farms (30.0235° N; 47.7046° E)	Very deep sandy clay loam or fine sandy loam, well-drained or moderately well-drained, permeability moderate or slow, abrupt or gradual smooth boundary	Gypsiargid-fine loam-hyper thermic fine-loamy-gypsic horizon	8	8.5	0.3	0.2	25.3	3.9

Table 2
Groups of plants and plant species.

Group of Plants	Plant
Non-leafy Vegetables	Paprika
	Tomato
	Cucumber
	Eggplant
Leafy Vegetables	Lettuce
	Parsley
	Spinach
	Eruca Sativa
Root crops	White Radish
	Carrot
	White Onion

for paprika, tomato, cucumber, eggplant, and lettuce, while seeds plants were planted for parsley, spinach, Eruca Sativa, white radish, carrot, and white onion. All plant groups were implanted in the two soil types (that is, Wafra and Abdaly soil) and only full fruit was harvested. The number of crops that were harvested during the study period (two years) depended on the ease and growth period of each type of plant. For example, six crops were harvested from tomatoes, while only one crop of eggplant was harvested.

During the execution of the TF experiment, we faced several difficulties relating to growing vegetables, such as eggplant and cucumber, due to the weather conditions and the whitefly infection and other plant diseases. Thus, for non-leafy vegetables to grow and harvest fruits, different pesticides were used.

2.4. Sample preparation and radioactivity measurements

The harvested plant species were first washed and dried in the laboratory atmosphere, and then the edible parts were cut into small pieces and left for 24 h before drying in an oven for 24 h at a temperature of 85 °C. In addition, the plant compartments (roots, stem, and leaves) of some species were prepared with the same procedure. Adequate quantities of the dried samples were then ground, bottled in calibrated counting geometries, and measured by gamma spectrometry systems. The lower detection limits of the method used to determine the massic activities of ^{85}Sr, ^{134}Cs, and ^{133}Ba for 80,000 s counting time were 4.1, 2 and 3.3 Bq kg^{-1} dry weights, respectively. Hence, a clear gamma spectrum showing the gamma lines of the three radionuclides was a success.

Two low background gamma spectrometry systems (Ortec Gem and Ortec Gmx model types) were used to measure the prepared samples. Both spectrometers were calibrated against the counting geometries used, and their performance was continuously ensured by applying an in-house prepared quality control sample [17]. An external assessment of the analytical performance is regularly monitored through participating in the IAEA worldwide proficiency testing exercises.

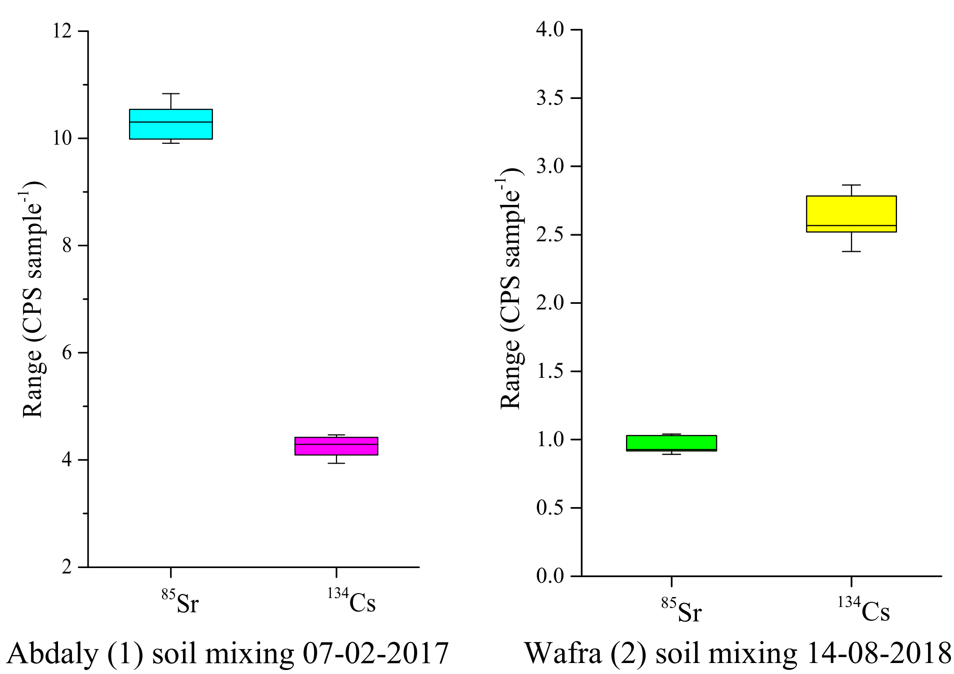

Fig. 1. Homogeneity testing of Abdaly (1) and Wafra (2) soil types.

The collected gamma spectra were analyzed by Genie 2000, and the necessary cascade summing correction of the ^{134}Cs and ^{133}Ba gamma lines were applied by LabSOCS software (Canberra Inc.). It should be emphasized that, due to the high concentration of ^{85}Sr in most of the samples, it was hard to resolve the ^{133}Ba peaks with excellent statistics. Therefore, the measurements were repeated after waiting for some time, to allow ^{85}Sr to have decayed and to decrease the effect of its interference (Compton scattering) (Fig. A. 5). All results were reported in Bq.kg^{-1} dry weight with the associated uncertainty. An uncertainty propagation algorithm was applied for the radioactivity calculation. Special attention was given to the sample homogeneity and the dryness factor estimation.

3. Results and discussions

3.1. Homogeneity testing of the spiked soil

To ensure the homogenous distribution of the radioactivity within the soil, six random samples, 300 g each, were taken, filled with the counting geometry, and counted at the laboratory for 300 s. Gamma spectra were analyzed, and the areas under the peaks of ^{85}Sr (514 keV) and ^{134}Cs (604 keV) were used to generate a box plot presentation that enabled us to observe if an outlier was presented.

An example of the homogeneity test results of Abdaly (first container) soil and Wafra (second container) at two different dates is shown (Fig. 1). Obviously, outliers should not be observed, provided that the soil mixing was acceptable, and there was no need for further mixing. It should be noted that the testing of the homogeneity process was performed after harvesting and new implantation was started.

3.2. Soil-to-plant transfer factors

As recommended by the IAEA [18], the TFs were calculated based on the dry mass weights of the plant/compartment and soil. All plant species were harvested when they attained the fruit growth stage to avoid any underestimation of the TFs; that is, the concentration of the radionuclides in the plant is proportional to that in the soil and the soil-plant system is in equilibrium.

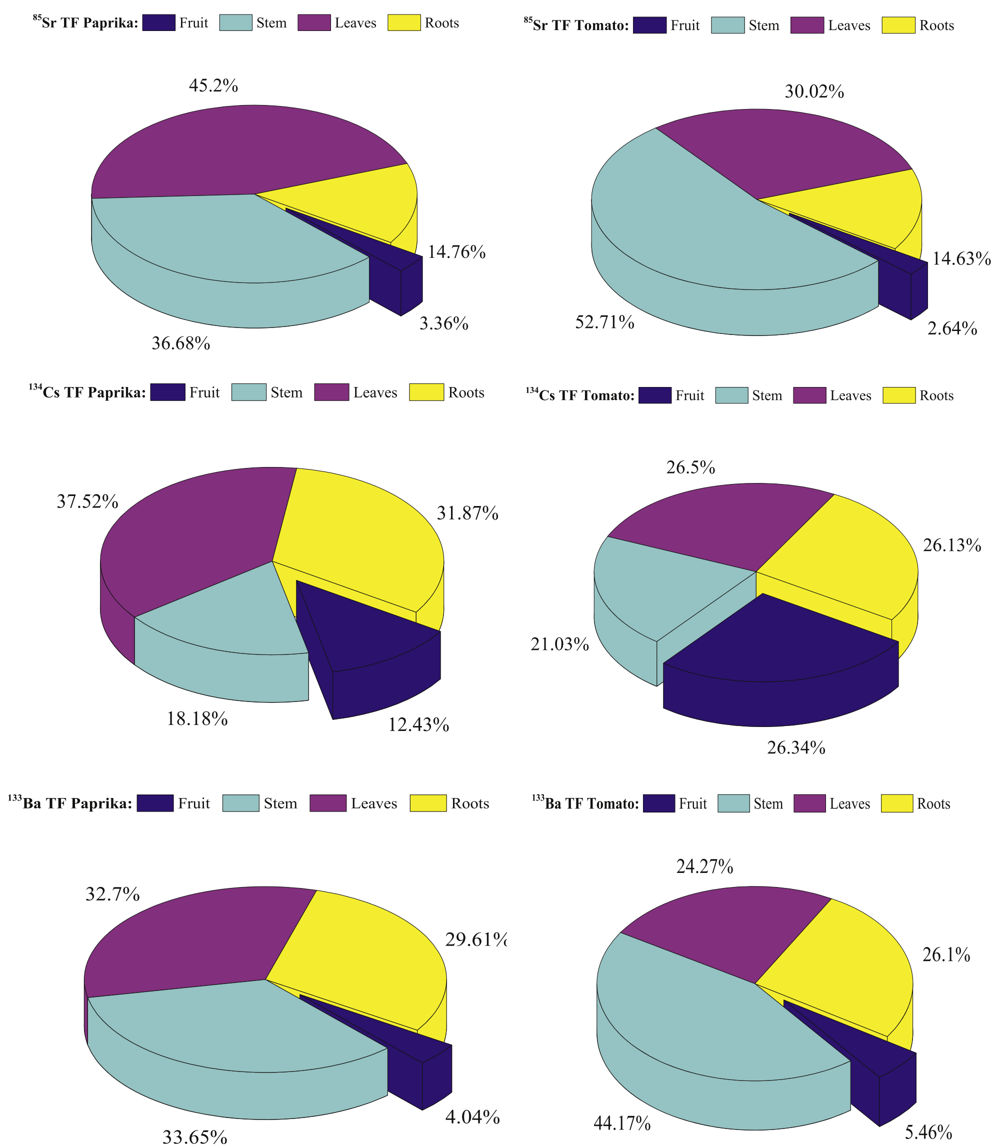

Fig. 2. Radionuclide translocation in tomato and paprika compartments.

Table 3
The experimentally derived TFs in Kuwaiti soil.

Plant Group	Plant Species	N	Transfer Factor (Sandy Soil) in Kuwait														
			^{85}Sr					^{134}Cs					^{133}Ba				
			Ave	±	STD	Min	Max	Ave	±	STD	Min	Max	Ave	±	STD	Min	Max
Non-Leafy Veg.	Paprika	4	1.43	±	0.24	1.15	1.67	0.11	±	0.05	0.06	0.15	0.53	±	0.48	0.20	1.24
	Tomato	6	1.04	±	0.48	0.48	1.90	0.28	±	0.13	0.13	0.54	0.50	±	0.17	0.35	0.69
	Cucumber	3	3.99	±	1.16	2.80	5.12	0.14	±	0.06	0.11	0.17	0.54	±	0.25	0.25	0.68
	Eggplant	2	1.60	±	0.74	0.93	2.59	0.13	±	0.07	0.01	0.17	0.10	±	0.09	0.04	0.20
Leafy Veg.	Lettuce	5	24.65	±	10.06	8.51	32.51	0.16	±	0.04	0.09	0.20	3.59	±	1.81	0.55	4.94
	Parsley	6	18.31	±	5.26	10.40	23.95	0.31	±	0.15	0.10	0.54	4.58	±	2.27	2.10	7.05
	Spinach	3	7.70	±	2.08	5.39	10.19	0.13	±	0.03	0.10	0.17	1.05	±	0.37	0.64	1.50
	Eruca Sativa	4	31.92	±	8.74	17.69	39.90	0.21	±	0.05	0.14	0.26	5.06	±	1.75	2.21	6.52
Root Crops	White Radish	2	10.54	±	7.81	5.02	16.07	0.22	±	0.26	0.04	0.41	1.10	±	0.87	0.49	1.71
	Carrot	2	4.22	±	1.20	3.37	5.07	0.07	±	0.03	0.06	0.09	2.28	±	1.18	1.45	3.12
	White Onion	1	4.45	±	0.52	3.93	4.97	0.13	±	0.01	0.12	0.26	0.47	±	0.46	0.01	0.93

The TFs of the plant species of the leafy, non-leafy, and root crops were calculated and presented according to the plant group and species of the site-specific conditions (Table 3). The detailed presentation of the individual plant group species TFs cultivated in Wafra and Abdaly soils are presented in Appendix A (Fig. A1, A2, A3). The TF values show no significant difference; therefore, the average TFs of the plant species and plant group were calculated and presented in Fig. A. 4 as the TF in sandy soil.

The TF ranges (Table 3) were presented based on the minimum and maximum TF values of the plant species cultivated in both vegetated soils; the range of the TF single value (white onion) was presented as the TF calculated value plus/minus its standard deviation. Broad TF ranges were observed; ^{85}Sr and ^{133}Ba were the highest in the order: leafy vegetables > root crops > non-leafy vegetables. However, the approximate range of cesium TF was found to be very low in all plant groups (from 0.01 to 0.54). The TFs results obtained in Table 3 are consistent with the experimental results of Bunzl and Schimmack (1988) [19] who showed that the sorption of radionuclides in agricultural soils increases in the following order: ^{85}Sr < ^{133}Ba < ^{134}Cs. Although the mechanisms of cesium uptake by the plant roots are not completely understood, there is evidence that cesium ions ($Cs+$) are absorbed by the potassium ions ($K+$) uptake system of the root [20]. It was also observed that the cesium absorption by the plant roots is less efficient than its analogous, potassium. The replacement process of cesium ions with potassium is increased as long as the wetting and drying cycles are continued; leading to enhancing the strong fixation and prevented it to be untaken by the plant roots [21]. As such, the TF of cesium from soil to all plant types was very low compared with radiostrontium and radiobarium.

Clearly, the selectivity and the ability of the plant to retain a large amount of water by absorbing dissolved elements plays a major role in accumulating high radionuclide concentrations and, hence, obtaining high TF values. This can be seen, for example, in the leafy vegetable group where the range of ^{85}Sr TFs varied from 5.4 to 39.9. In contrast, the same leafy group showed lower ^{134}Cs TF ranges, which varied from 0.09 to 0.54. The low ^{134}Cs TF values obtained indicated that cesium is strongly adsorbed on the clay particles, where the Kuwaiti soils contain about 5–8% clay (Table 1). This is true even for small clay contents (1–6%) which can bind cesium effectively [22–24].

Moreover, the derived radionuclide TFs of the plant species in each group showed remarkable variations as the radionuclide transfer from soil to plant is a complex process and is affected by many variables. Therefore, the obtained results for the site-specific conditions in Kuwait should be considered valid and can be used instead of the IAEA or other generic values for the dose estimation. In other words, the TF is explicit to the system studied, which includes the soil texture, the radionuclides' physiochemical properties, and the plant species.

A comparison between the obtained ^{85}Sr and ^{134}Cs TFs and the IAEA collated data for sandy soil [17] are presented in Table 4. The average TF data for the site-specific conditions in Kuwait (arid environment) are much higher than those reported by the IAEA for the temperate environment, yet the ranges of the radiocesium are comparable. In contrast, the experimentally derived ^{85}Sr TFs in Kuwait were much higher than those of reported by the IAEA. This is most likely due to the irrigation system applied in Kuwait where the large volume of water used for irrigation enhances transporting of the dissolved ^{85}Sr from soil water to the plant through root uptake.

As stated previously, there are no significant differences in the studied vegetated soil texture; therefore, the TFs of the site-specific values are mostly governed by the physicochemical properties of the radionuclides and the plant selectivity towards adsorption of some specific minerals. The variables mentioned earlier are embedded in the distribution coefficient variable Kd (the ratio of the mass of solute adsorbed or precipitated on the soil per unit of dry mass to the solute concentration in the liquid) of the mineral in the specific soil texture. As such, the Kd can be used as an indicator to estimate the leachability of a specific radionuclide from the soil; that is, high Kd values refer to considerable retention of the radionuclide in the soil, which leads to low root uptake, and vice versa.

A strong negative correlation between the Kd and the TF has been recognized by Sheppard and Thibault (1990) [25] as follows:

Table 4
Comparison of the experimentally derived TFs for strontium and cesium in Kuwait and the IAEA reported data (the average presented in brackets).

Plant Group	IAEA 472 (Temperate environment)		Present Work (Arid environment)	
	Sr	Cs	Sr	Cs
Leafy	$6.4\ 10^{-2}$ – 7.8 (1.7)	$2.0\ 10^{-3}$ – $9.8\ 10^{-1}$ ($1.2\ 10^{-1}$)	2.1–40 (20.6)	$1.0\ 10^{-1}$ – $5.4\ 10^{-1}$ ($2.0\ 10^{-1}$)
Non-Leafy	$2.0\ 10^{-1}$ – 7.9 ($8.7\ 10^{-1}$)	$1.2\ 10^{-2}$ – $7.3\ 10^{-1}$ ($3.5\ 10^{-2}$)	$4.8\ 10^{-1}$ – 5.1 (2.0)	$7.0\ 10^{-2}$ – $5.4\ 10^{-1}$ ($1.6\ 10^{-1}$)
Root Crops	$3.0\ 10^{-2}$ – 4.8 (1.1)	$8.0\ 10^{-3}$ – $4.0\ 10^{-1}$ ($6.2\ 10^{-2}$)	3.37–16.1 (6.41)	$4.0\ 10^{-2}$ – $4.1\ 10^{-1}$ ($1.4\ 10^{-1}$)

Table 5
Range of the distribution coefficients (L/kg) for strontium, cesium, and barium in the sand (values in brackets were based on the mean value).

Reference	Kd-Sr	Kd-Cs	Kd-Ba
Present work	6.9–14.6	50.2–67.3	16.8–31.2
IAEA 472 (2010)	0.4–2400	9.6–35,000	–
Isherwood (1981)	13–43	(100)	–
Kennedy and Strenge (1992)	(15)	–	(52)

$$\mathrm{Ln}\ (\mathrm{Kd}) = a + b\ [\ln(\mathrm{TF})] \tag{1}$$

where a and b are constants derived from experimental data a = 2.11 for sandy soil; and b = −0.56 [25,26] and the TF used is based on the weights of the dry soil and the wet plants.

The Kd values were calculated for all plant groups by adopting the average TFs of the site-specific conditions in Kuwait, based on wet weight, and compared with the reported Kd values (Table 5). The experimentally derived Kd for the site-specific conditions can be accepted and used for modeling the leaching and uptake of the radionuclides in arid-soil regions.

3.3. Translocation of ^{85}Sr, ^{134}Cs, and ^{133}Ba in plants

Besides the TF estimation, the translocation of the radionuclides in different plant compartments (roots, stem, leaves, and fruits) was calculated in dry weight and presented as a percentage in pie charts. Once the radionuclides enter the body of the plant through the root uptake, they may accumulate in various compartments of

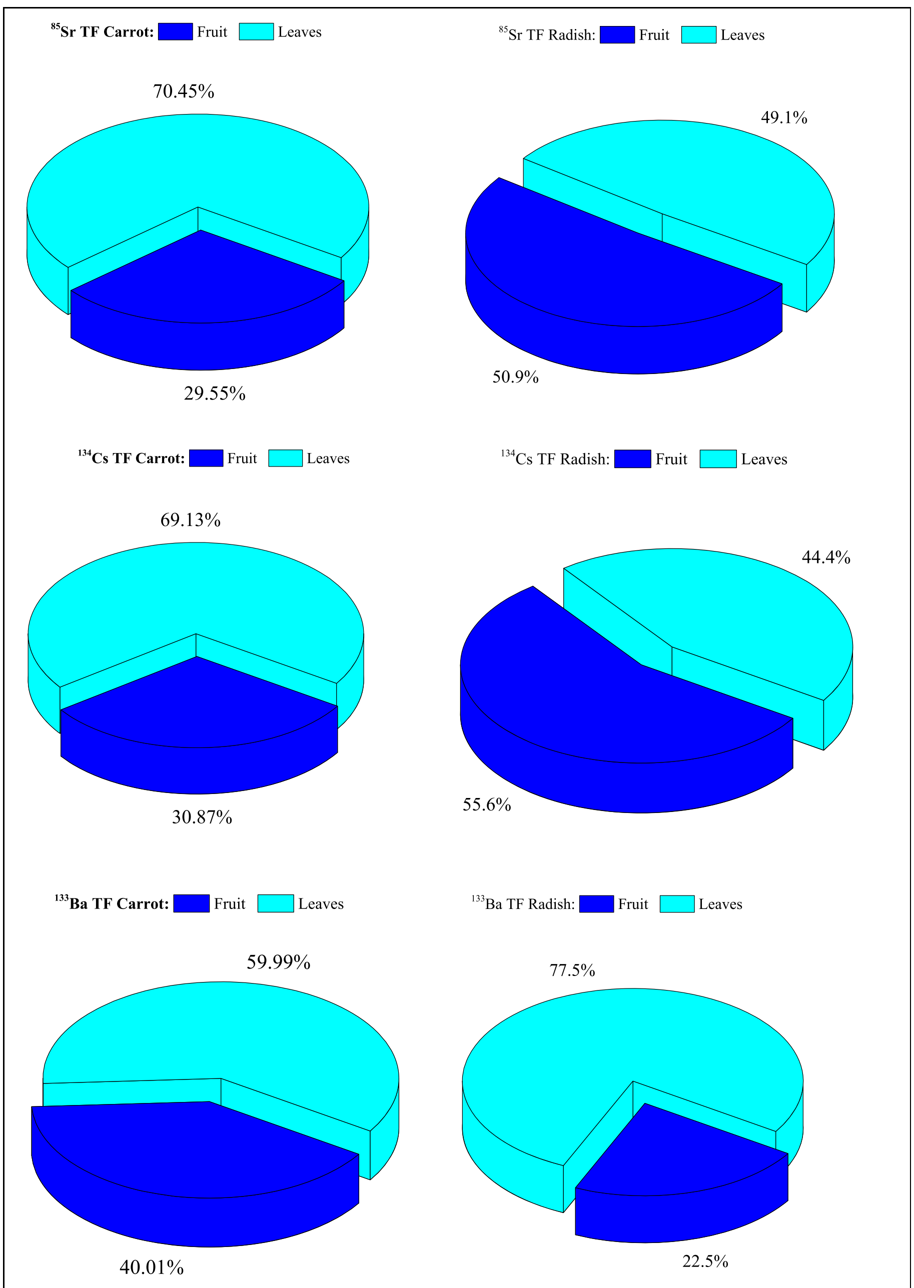

Fig. 3. Radionuclide translocation in carrot and radish compartments.

the plant with different concentrations (roots, stem, leaves, and fruits). The radionuclides' translocation in the non-leafy plant group (tomato and paprika) and root crops (radish and carrot) are presented in Figs. 2 and 3. Clearly, the concentration of the studied radionuclides in leaves and stems was higher than the roots and fruits, reflecting the radionuclides' solubility and elemental composition, and their concentration in the plant species. In contrast, other research has observed that the accumulation of the radionuclides was low in fruits compared with the other plant compartments [27].

Although the alkaline earth metals (for example, Magnesium, Barium, Calcium, and Radium) have similar chemical behavior to strontium, a complex physiochemical process still occurred and resulted in different concentrations of the same element in the plant's compartments. The same occurred for the group elements of cesium. In addition, competition between the elements exists in the soil and the plant, and their chemical forms play a major role in the element accumulation in a certain species [5,28]. As such, the obtained results are still valid for the site-specific conditions and the studied plant groups. The lower concentration of the radionuclide in the edible parts of the fruits will lead to lower CEDE to the population due to consuming non-leafy vegetables, such as tomato and paprika (Fig. 2).

4. Conclusions

A technical approach to design and carry out an experiment to determine radionuclide transfer from soil to plant was developed and successfully executed to generate data on the time-dependent uptake of cesium, strontium, and barium radioisotopes for site-specific conditions in Kuwait. The key success of the experiment is considered to be the homogeneity of the radionuclides in the soil and the prepared samples for gamma spectrometry measurements, in addition to taking account of all possible related uncertainties.

Major outcomes of the soil-to-plant TFs have been obtained for the leafy and non-leafy vegetables, and root crops of the most common plant species in Kuwait. The highest strontium and barium TFs were found in the order: leafy vegetables > root crops > non-leafy vegetables. The obtained TFs of the studied radionuclides for the site-specific conditions in Kuwait were higher than those reported for temperate and tropical environments. The major factor affecting the transfer of radionuclide from sandy soil to the plant was the distribution coefficient (Kd) in the soil-plant system, whereas the irrigation system in the arid-regions enhances the radionuclides' leaching processes. The obtained TFs for the studied plant groups can be utilized by the scientific community in the Gulf region to examine the radiological consequences of the nuclear/radiological events.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2020.08.023.

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