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ORIGINAL PAPER

Transfer Factors and Effective Dose Evaluation Due to Natural Radioactivity in Staple Food Grains from the Vicinity of Proposed Nuclear Power Plant

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Abstract This study focused on quantification of radioactivity concentration of naturally occurring radioactive materials ^{40}K, ^{226}Ra and ^{232}Th in most staple food grain i.e. wheat of the study area using gamma spectrometry for two years. ^{40}K, ^{226}Ra and ^{232}Th activities were detectable in most of the wheat grain samples and ranged 111.3–245.7, <0.04–0.37 and <0.015–0.11 Bq kg^{-1} respectively. Effective dose due to the consumption of radionuclides via wheat grains was calculated on its estimated annual intake by the local populace. Also to evaluate transfer factors of radionuclide's, corresponding fields' soils were collected and assessed for their radioactivity content. Measured average radioactivity levels in soils from the site were in order: ^{40}K (544.7 ± 14.6 Bq kg^{-1}) > ^{226}Ra (41 ± 1.6 Bq kg^{-1}) > ^{232}Th (32.3 ± 1.2 Bq kg^{-1}) and comparable to the corresponding levels obtained worldwide. The geometric mean transfer factors of studied NORMs in wheat grains were in order: ^{40}K (0.371 ± 0.07) > ^{226}Ra (0.003 ± 0.002) > ^{232}Th (0.001 ± 0.001). Significant positive dependencies of transfer factors of ^{40}K, ^{226}Ra and ^{232}Th in wheat grains were observed with total organic carbon content of soil. Estimated annual effective doses from ingestion of the wheat were 1.37E−01 mSv year^{-1} for ^{40}K, 4.14E−03 mSv year^{-1} for Ra^{226} and 1.10E−03 mSv year^{-1} for ^{232}Th, well under the permissible cumulative global average.

Keywords Annual effective dose · Natural radionuclides · Transfer Factor · HPGe detector · Wheat

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Introduction

^{238}U, ^{232}Th, and ^{40}K are the naturally occurring radionuclides (NORMs) which are present in all compartments of environment. The average activities of ^{40}K, ^{238}U, and ^{232}Th permissible in soil are 400, 35, and 30 Bq kg^{-1}, respectively (UNSCEAR 2000). These radionuclides get incorporated into vegetation either through activity interception by external plant surfaces, i.e., through foliar uptake of suspended materials from the atmosphere or through soil to plant transfer via root system. Although soil acts as a natural buffer system, controlling the transport of chemical elements and substances into various components of biosphere (Yadav et al. 2017; Smuc et al. 2012), plants may uptake toxic substances including radionuclides along with nutrients which may subsequently get transferred to the food chain (Rattan et al. 2005). The mobility of bioavailable fraction of radionuclides from rhizospheric soil to plants is influenced by several factors (Ravi et al. 2014) such as climatic conditions, physico-chemical properties of soil, degree of plants maturity at harvesting, chelating ions outside plant roots and sub-cellular compartmentalization, controlled influx through plasma membranes, binding of ions to cell walls, and selective uptake by plant.

Accumulation of radionuclides in soils and their uptake by crop plants followed by their subsequent movement in food chain are a matter of concern for radio-ecologists.

Higher concentrations of radionuclides in crop grains may cause toxicity to human beings or other living species feeding on them (Alloway and Ayres 1997). Agricultural soil to plant transfer of contaminants can be an important pathway of human exposure assessment, as the soil is an imperative resource that is used for food production (Al-Kharouf et al. 2008). A number of studies have been conducted in the preceding two decades to explore the transfer factor of radionuclides from soil to crops. Site-specific baseline values of radioactivity concentration in different matrices are important information to understand the status of NORMs in a typical location and to assess the impact of anthropogenic activities.

Baseline studies are mandatorily carried out at all proposed nuclear facility sites. Radionuclides activity varied from 0.002–10.6 Bq kg^{-1} (^{238}U), 0.002–2.8 Bq kg^{-1} (^{232}Th), 0.1–7.2 Bq kg^{-1} (^{226}Ra), 3.0–110.8 Bq kg^{-1} (^{40}K), and 0.03 to 3.0 Bq kg^{-1} (^{137}Cs) in different food matrices collected from vicinity of proposed nuclear facilities, near Vizag, India (Patra et al. 2014). The activity concentrations of ^{40}K, ^{228}Ra, and ^{226}Ra were quantified in pulses, cereals, and vegetables cultivated around Kudankulam, India (Ross et al. 2013). Mean ^{40}K, ^{228}Ra, and ^{226}Ra activities in pulses were 294.3, 1.07, 0.15 Bq kg^{-1}, while 70.78, 0.47, and 0.09 Bq kg^{-1}, respectively, in cereals. Reported activity concentrations were higher in pulses as compared to other studied food categories. The concentrations of ^{232}Th, ^{238}U, ^{226}Ra, and ^{40}K were determined in staple cereals (rice and wheat), pulses, and drinking water consumed by the population residing around high background radiation area located in Chhatrapur, Odisha, India (Lenka et al. 2013). ^{232}Th, ^{238}U, ^{226}Ra, and ^{40}K activities in the collected samples were in the range of 0.3–2.0, 0.3–32.0, 0.4–28.2, and 14.3–957 Bq kg^{-1}, respectively. Kumar et al. (2009) analyzed uranium content in food samples including wheat and *Brassica* grains from different areas of the district Bathinda, Punjab. The uranium content was 0.38 Bq kg^{-1} in *Brassica* grains and 4.60 Bq kg^{-1} in wheat grains.

Nuclear power Corporation of India (NPCIL), India has proposed a nuclear power plant (2800 MW capacity, 700 × 4) at Village Gorakhpur, Fatehabad district, Haryana, India. Uranium concentration in water has been reported for urban and rural areas of the district (Singh et al. 2014a, b). Wheat is the staple food and major crop cultivated in this area in *rabi* season. Keeping this in view, this study was conducted to quantify ^{40}K, ^{232}Th, and ^{226}Ra radioactivity in agricultural field soil, wheat crop grains, their transfer factor (TF), and natural internal dose imparted from consumption of wheat grown within 30-km radius area of the proposed site. These basic radiometric data generated in the study might be useful especially with regard to food policy and other administrative functions.

Materials and Methods

Study Area

This study has been conducted within 30-km radius area of the proposed Gorakhpur Haryana Anu Vidyut Pariyojana (GHAVP), and the study area stretches into Fatehabad and Hisar districts of Haryana, India.

Climate of the area is tropical with significant variations in ambient temperature from 47 °C in summer to 2 °C in winter. The area receives an annual average rainfall of 395.6 mm of which about two third is received during the short southwest monsoon period from July to September. Study area is an alluvial plain of Indo-Gangetic basin having flat plain topography with an average elevation 215 m, gently sloping from northeast to southwest. A total of 23 sampling locations were established in the study (Fig. 1). All sampling locations were geo-referenced using Global Positioning System (Table 1).

Sampling and Sample Processing

A total of 46 agricultural field soil and 46 wheat grain samples ($\approx$1.0 kg each) from identified sampling stations were collected during wheat harvesting season (April–May) for two years, i.e., 2011 and 2012. Soil samples from wheat crop-cultivated agricultural fields were collected with the help of a wooden spade from a sub-surface depth level of 5–10 cm. To obtain a representative sample, four sub-samples of soil from rectangular grid of 0.5 m^2 area were collected and then mixed together to have a composite sample. After dehusking the wheat grains and removing debris from the soil samples, they were packed in plastic containers and transported to the laboratory.

Soil samples after removing foreign materials, pebbles, etc. were first air dried and then kept in oven to achieve a constant sample weight, ground and passed through a 2.0 mm sieve and stored in cylindrical plastic containers. Grain samples were dried in drying oven at 110 °C until constant weight was attained. Dried sub-samples were ashed in muffle furnace at $\approx$350 °C till the ash was completely white. The ashed samples after being homogenized were kept in cylindrical plastic containers, tightly sealed with adhesive tape. Both grain and soil samples packed in cylindrical vials were left for a minimum of 28 days for secular equilibrium to be established between ^{226}Ra and its short-lived daughters before gamma spectrometry measurements (Singh et al. 2005).

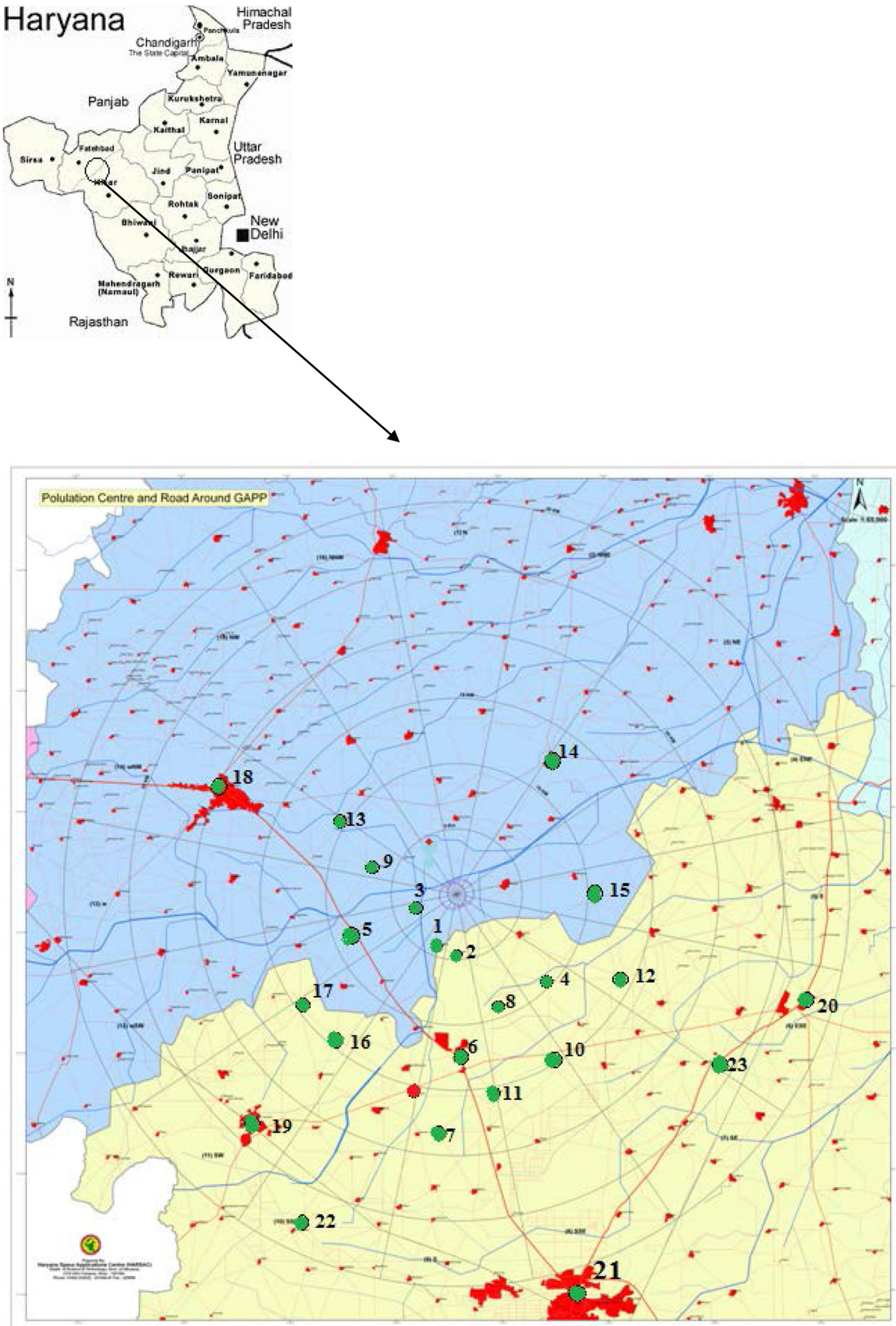

Fig. 1 Map of the study area showing different wheat grain sampling locations

Table 1 Sampling locations detail in the study area

Village and sample ID	Wheat-2011[a]		Sample ID	Wheat-2012[a]	
	Latitude	Longitude		Latitude	Longitude
Kumharia/KUMH	29°24′33.7″N	75°36′42.1″E	KUMH	29°24′28.3″N	75°37′32.1″E
Sabarwas/SAB	29°11′54.4″N	75°30′12.3″E	SAB	29°23′54.6″N	75°37′42.5″E
Kajalheri/KAJL	29°25′44.5″N	75°35′22.0″E	KAJL	29°26′16.5″N	75°35′58.7″E
Kirmara KIR	29°22′28.5″N	75°42′22.6″E	KIR	29°23′02.7″N	75°41′37.3″E
Badopal/BDPL	29°24′47.4″N	75°33′20.7″E	BDPL	29°25′18.7″N	75°33′04.5″E
Agroha/AGH	29°18′40.5″N	75°38′13.0″E	AGH	29°20′22.0″N	75°37′44.2″E
Jagan/JGN	29°16′41.0″N	75°37′38.1″E	JGN	29°16′27.5″N	75°37′02.4″E
Kuleri KUL	29°22′36.7″N	75°41′19.2″E	KUL	29°22′06.3″N	75°39′28.4″E
Muhmmadpur/MPUR	29°27′51.2″N	75°33′35.6″E	MPUR	29°27′33.6″N	75°34′14.9″E
Nangthala/NGTH	29°19′22.0″N	75°41′53.9″E	NGTH	29°19′57.8″N	75°42′41.2″E
Landhri/LNDH	29°18′26.4″N	75°39′33.0″E	LNDH	29°18′01.4″N	75°39′04.3″E
Knoh/KNH	29°23′31.4″N	75°45′21.7″E	KNH	29°23′23.6″N	75°45′10.9″E
Dhani majra/DM	29°30′21.0″N	75°31′47.3″E	DM	29°29′46.3″N	75°32′14.3″E
Bhuna/BHU	29°31′29.9″N	75°41′40.7″E	BHU	29°31′17.1″N	75°40′54.1″E
Nehla/NHLA	29°26′03.4″N	75°44′32.0″E	NHLA	29°26′03.4″N	75°45′05.9″E
Sarangpur/SPUR	29°20′51.9″N	75°31′40.8″E	SPUR	29°20′44.0″N	75°32′33.9″E
Bhoda Hoshnak/BHN	29°21′12.2″N	75°30′36.2″E	BHN	29°22′00.4″N	75°30′54.9″E
Fatehabad/FTB	29°29′31.4″N	75°29′18.7″E	FTB	29°29′14.4″N	75°29′24.5″E
Adampur/APUR	29°16′27.7″N	75°28′24.0″E	APUR	29°17′13.8″N	75°29′27.6″E
Barwala/BAR	29°21′10.7″N	75°53′13.9″E	BAR	29°20′53.4″N	75°52′45.2″E
Hisar/HSR	29°11′39.6″N	75°40′40.3″E	HSR	29°11′40.2″N	75°40′42.8″E
Siswal/SISL	29°11′54.4″N	75°30′12.3″E	SISL	29°12′33.4″N	75°30′59.0″E
Badon/BDN	29°17′01.7″N	75°48′27.4″E	BDN	29°17′02.1″N	75°48′28.1″E

[a] Composite soil samples from the same agricultural field were also collected

Radionuclides' Quantification

^{40}K, ^{226}Ra, and ^{232}Th were quantified using High-purity Germanium detector (HPGe, Baltic scientific instruments, Latvia) in ashed wheat grains and dried soil samples. Co-axial p-type HPGe detector was connected to preamplifier, amplifier, ADC converter, and acquisition interface module (Orion, Itech Instruments). A cylindrical-shaped special heavy-lead shield (^{210}Pb < 50 Bq kg^{-1}) of about 100 mm thickness with outer jacket of 1.5 mm of low Carbon steel, inner diameter (with copper lining) of 200 mm, and inner height (with copper lining) of 330 mm surrounded the detector to minimize the background radiation. Characteristic X-rays from lead were reduced using a 9.0-mm-thick layer of copper lined with 1.0-mm tin. Detector output was connected to an Amplifier (Model GCD 50 190). To maintain measurement quality, energy and efficiency calibration of the spectrometer were carried out using a standard mixed multi-nuclide source, traceable to the U. S. National Institute of Standard and Technology (NIST) standard. The standards and samples were prepared with a uniform geometry and counted for a period of 80,000 s in order to get sufficient counts at desired peaks. The activity of ^{40}K was evaluated using the photo peak of its characteristics gamma line at 1460 keV. However, the activities of ^{232}Th and ^{226}Ra (^{238}U) can be determined using their short-lived decay products, i.e., of ^{232}Th from 583 keV gamma-ray of ^{208}Tl and ^{226}Ra from 609 keV γ-ray of ^{214}Bi (Mehra 2009). The instrument had energy resolution (FWHM) of 0.90 keV for energy 122 keV(Co-57) and 2.0 keV for energy 1332 keV(Co-60), and relative efficiency (w.r.t. 3″ × 3″ NaI detector and Co-60 source mounted 25 cm above the detector) at 1332 keV γ-photon is $\geq$50%. Qualitative and quantitative analyses of gamma spectra were processed using INTERWINNER 7.0 program. Detector was attached with cryocan of liquid nitrogen of 30 L capacity to keep it cool continuously for avoiding any change in crystal structure.

Transfer Factor Analysis

Transfer factor of NORMs from soil to wheat grains was calculated using Eq. 1 (Singh et al. 2014c).

$$TF = \frac{C_{\text{Grain}}}{C_{\text{Soil}}}, \tag{1}$$

where C_{grain} and C_{soil} are the radioactivity concentration of radionuclides in grains and respective agricultural field soils, respectively, expressed in Bq kg^{-1} (On dry weight basis).

Annual Effective Dose

Annual effective dose (AED) received by the adult population due to ingestion of ^{40}K, ^{232}Th, and ^{226}Ra through dietary intake of wheat grains cultivated in the vicinity study area were calculated using Eq. 2 (Patra et al. 2014).

$$\mathrm{AED(Sv)} = \mathrm{CR} \times \mathrm{FI} \times \mathrm{DCF}, \quad (2)$$

where CR is the activity of radionuclide in wheat grains (Bq kg^{-1}); FI is the food ingestion rate (0.295 kg day^{-1} for wheat grains) for an adult person living in the study area; DCF is the dose conversion factors (ICRP 2012) for calculations of effective dose due to ^{40}K, ^{232}Th, and ^{226}Ra, which were 6.2E−09, 2.3E−07, and 2.8E−07 Sv Bq^{-1}, respectively.

Results and Discussion

^{40}K, ^{232}Th, and ^{226}Ra Activity in Soil Samples of Wheat Fields

Activity concentration of naturally occuring radionuclides in the soils of wheat fields was detectable in all the samples and varied from 445.4–708.7 Bq kg^{-1} for ^{40}K, 31.9–50.9 Bq kg^{-1} for ^{226}Ra, and 24.2–39.0 Bq kg^{-1} for ^{232}Th (Table 2). ^{226}Ra, ^{232}Th, and ^{40}K activities in the soil of the study are comparable to the global average concentrations of these radionuclides in soils reported by United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2000). Geometric mean activity concentrations of NORMs (Bq kg^{-1}) in the soil samples of wheat fields were in the following order: ^{40}K (544.7 ± 14.6 Bq kg^{-1}) > ^{226}Ra (41 ± 1.6 Bq kg^{-1}) > ^{232}Th (32.3 ± 1.2 Bq kg^{-1}). Activity concentrations of NORMs in different types of soils from Indian subcontinent have been reported by several authors. Pulhani et al. (2005) reported ^{226}Ra, ^{238}U,

Table 2 Naturally occurring radionuclides' activity (Bq kg^{-1} DW) in wheat fields' soil around GHAVP site during 2011 and 2012

Sample ID	2011 NORMs activity (Bq kg^{-1} DW)			Sample ID	2012 NORMs activity (Bq kg^{-1} DW)		
	^{40}K	^{226}Ra	^{232}Th		^{40}K	^{226}Ra	^{232}Th
KUMH-WS-1	644.0 ± 17.3	46.9 ± 1.8	37.8 ± 1.4	KUMH-WS-2	455.4 ± 12.5	36.6 ± 1.4	30.0 ± 1.1
SAB-WS-1	585.2 ± 15.3	40.6 ± 1.6	33.2 ± 1.2	SAB-WS-2	458.3 ± 12.5	36.2 ± 1.4	30.7 ± 1.1
KAJL-WS-1	489.7 ± 14.0	41.1 ± 1.6	33.5 ± 1.2	KAJL-WS-2	488.1 ± 12.8	37.6 ± 1.4	30.9 ± 1.1
KIR-WS-1	612.8 ± 15.7	46.5 ± 1.7	36.8 ± 1.3	KIR-WS-2	551.8 ± 14.2	42.7 ± 1.6	29.1 ± 1.1
BDPL-WS-1	543.9 ± 14.2	42.4 ± 1.5	31.5 ± 1.1	BDPL-WS-2	445.4 ± 12.7	31.9 ± 1.3	26.7 ± 1.0
AGH-WS-1	643.0 ± 17.4	48.5 ± 1.9	35.9 ± 1.4	AGH-WS-2	474.0 ± 13.3	37.6 ± 1.5	27.9 ± 1.1
JGN-WS-1	581.0 ± 15.6	42.0 ± 1.6	34.8 ± 1.3	JGN-WS-2	471.9 ± 13.4	32.0 ± 1.4	24.2 ± 1.0
KUL-WS-1	626.0 ± 16.9	44.4 ± 1.7	35.2 ± 1.3	KUL-WS-2	585.5 ± 14.8	43.2 ± 1.6	30.0 ± 1.1
MPUR-WS-1	555.2 ± 14.4	39.1 ± 1.5	30.0 ± 1.1	MPUR-WS-2	548.6 ± 14.2	42.2 ± 1.6	33.7 ± 1.2
NGTH-WS-1	610.4 ± 16.1	42.2 ± 1.6	33.1 ± 1.2	NGTH-WS-2	525.6 ± 14.5	40.1 ± 1.6	33.1 ± 1.2
LNDH-WS-1	506.6 ± 14.1	37.3 ± 1.5	30.3 ± 1.1	LNDH-WS-2	538.8 ± 14.9	42.9 ± 1.7	33.8 ± 1.2
KNH-WS-1	529.4 ± 14.1	38.6 ± 1.5	29.7 ± 1.1	KNH-WS-2	463.9 ± 13.1	36.4 ± 1.4	27.6 ± 1.1
DM-WS-1	572.5 ± 15.0	44.8 ± 1.6	34.8 ± 1.2	DM-WS-2	532.6 ± 14.4	40.2 ± 1.6	31.0 ± 1.2
BHU-WS-1	532.0 ± 14.5	45.9 ± 1.7	35.3 ± 1.2	BHU-WS-2	502.7 ± 13.7	41.8 ± 1.5	33.1 ± 1.2
NHLA-WS-1	667.8 ± 17.3	49.4 ± 1.8	39.0 ± 1.4	NHLA-WS-2	518.6 ± 14.5	44.7 ± 1.7	33.4 ± 1.2
SPUR-WS-1	507.5 ± 13.5	36.0 ± 1.4	29.2 ± 1.1	SPUR-WS-2	580.8 ± 15.4	44.1 ± 1.7	34.4 ± 1.2
BHN-WS-1	494.4 ± 13.4	35.4 ± 1.4	29.0 ± 1.1	BHN-WS-2	493.0 ± 13.7	38.7 ± 1.5	32.2 ± 1.2
FTB-WS-1	540.5 ± 14.8	42.8 ± 1.6	35.2 ± 1.3	FTB-WS-2	546.0 ± 15.0	42.1 ± 1.6	33.5 ± 1.2
APUR-WS-1	541.6 ± 14.2	34.8 ± 1.4	29.7 ± 1.1	APUR-WS-2	509.7 ± 13.3	41.0 ± 1.5	31.9 ± 1.1
BAR-WS-1	708.7 ± 18.3	50.9 ± 1.9	38.7 ± 1.4	BAR-WS-2	548.0 ± 15.3	44.6 ± 1.7	35.4 ± 1.3
HSR-WS-1	604.9 ± 15.1	41.6 ± 1.5	33.0 ± 1.2	HSR-WS-2	522.9 ± 14.8	33.6 ± 1.5	27.0 ± 1.1
SISL-WS-1	581.8 ± 14.8	42.9 ± 1.6	31.6 ± 1.2	SISL-WS-2	554.8 ± 14.5	46.6 ± 1.7	36.2 ± 1.2
BDN-WS-1	682.4 ± 17.0	43.8 ± 1.7	34.5 ± 1.3	BDN-WS-2	528.9 ± 14.4	41.7 ± 1.6	35.5 ± 1.2

Table 3 Naturally occurring radionuclides' activity (Bq kg^{-1} DW) in wheat grains grown around GHAVP site during 2011 and 2012

Sample ID	2011 NORMs activity (Bq kg^{-1} DW)			Sample ID	2012 NORMs activity (Bq kg^{-1} DW)		
	^{40}K	^{226}Ra	^{232}Th		^{40}K	^{226}Ra	^{232}Th
KUMH-W-1	121.2 ± 3.0	0.05 ± 0.06	<0.015[b]	KUMH-W-2	212.9 ± 3.7	0.09 ± 0.04	0.05 ± 0.02
SAB-W-1	245.7 ± 4.3	0.14 ± 0.05	0.05 ± 0.03	SAB-W-2	220.7 ± 4.1	0.19 ± 0.05	0.03 ± 0.03
KAJL-W-1	233.7 ± 4.0	0.07 ± 0.05	0.03 ± 0.03	KAJL-W-2	218.2 ± 3.6	0.05 ± 0.04	0.02 ± 0.02
KIR-W-1	194.7 ± 3.1	0.08 ± 0.04	0.03 ± 0.02	KIR-W-2	196.8 ± 3.3	0.19 ± 0.05	0.07 ± 0.03
BDPL-W-1	207.0 ± 3.1	0.07 ± 0.04	0.02 ± 0.02	BDPL-W-2	166.6 ± 3.1	0.10 ± 0.04	0.04 ± 0.02
AGH-W-1	210.7 ± 4.2	0.14 ± 0.06	0.06 ± 0.03	AGH-W-2	203.8 ± 3.2	0.15 ± 0.05	0.07 ± 0.03
JGN-W-1	186.8 ± 3.9	0.06 ± 0.05	<0.015[b]	JGN-W-2	212.2 ± 2.9	0.16 ± 0.04	0.04 ± 0.02
KUL-W-1	221.4 ± 3.1	0.20 ± 0.04	0.05 ± 0.02	KUL-W-2	227.1 ± 4.0	0.11 ± 0.05	0.05 ± 0.03
MPUR-W-1	125.6 ± 3.2	0.13 ± 0.07	0.03 ± 0.04	MPUR-W-2	206.8 ± 3.2	0.22 ± 0.05	0.06 ± 0.03
NGTH-W-1	213.0 ± 4.4	<0.04[a]	0.04 ± 0.03	NGTH-W-2	211.9 ± 3.8	0.19 ± 0.05	0.07 ± 0.03
LNDH-W-1	175.6 ± 3.4	0.08 ± 0.04	0.06 ± 0.03	LNDH-W-2	234.7 ± 4.0	0.09 ± 0.05	<0.015[b]
KNH-W-1	169.1 ± 3.2	0.07 ± 0.04	0.02 ± 0.02	KNH-W-2	204.6 ± 3.8	0.25 ± 0.05	0.05 ± 0.03
DM-W-1	111.3 ± 2.9	<0.04[a]	<0.015[b]	DM-W-2	216.6 ± 3.4	0.37 ± 0.05	0.11 ± 0.02
BHU-W-1	202.0 ± 3.3	0.23 ± 0.05	0.04 ± 0.03	BHU-W-2	225.3 ± 3.6	0.25 ± 0.06	0.04 ± 0.03
NHLA-W-1	228.1 ± 4.6	0.11 ± 0.06	0.03 ± 0.03	NHLA-W-2	175.4 ± 3.5	0.05 ± 0.04	0.04 ± 0.03
SPUR-W-1	196.3 ± 3.3	0.08 ± 0.05	0.02 ± 0.03	SPUR-W-2	197.1 ± 3.2	0.15 ± 0.05	0.06 ± 0.03
BHN-W-1	198.3 ± 4.0	0.06 ± 0.05	0.03 ± 0.03	BHN-W-2	196.0 ± 3.9	0.03 ± 0.05	0.02 ± 0.03
FTB-W-1	244.9 ± 4.2	0.20 ± 0.05	0.02 ± 0.03	FTB-W-2	233.9 ± 4.0	0.14 ± 0.05	0.02 ± 0.02
APUR-W-1	230.8 ± 4.9	0.19 ± 0.07	0.02 ± 0.04	APUR-W-2	218.5 ± 4.0	0.22 ± 0.06	0.06 ± 0.03
BAR-W-1	188.3 ± 3.8	0.19 ± 0.06	0.08 ± 0.03	BAR-W-2	232.1 ± 4.5	0.19 ± 0.06	0.07 ± 0.03
HSR-W-1	214.6 ± 4.1	0.23 ± 0.06	0.10 ± 0.03	HSR-W-2	220.4 ± 4.1	0.19 ± 0.06	0.04 ± 0.03
SISL-W-1	198.3 ± 3.9	0.04 ± 0.05	0.03 ± 0.03	SISL-W-2	211.0 ± 3.1	0.18 ± 0.04	0.06 ± 0.02
BDN-W-1	221.9 ± 4.0	0.14 ± 0.05	0.03 ± 0.03	BDN-W-2	225.2 ± 3.8	0.05 ± 0.04	0.04 ± 0.02

[a] Minimum detectable limit for ^{226}Ra in wheat grains

[b] Minimum detectable limit for ^{232}Th in wheat grains

^{232}Th, and ^{40}K activities from two morphologically different regions, viz., Punjab and Mahabaleshwar, India. ^{226}Ra, ^{238}U, ^{232}Th, and ^{40}K activities were in the range of 45.2–53.6 Bq kg^{-1}, 11.2–46.2 Bq kg^{-1}, 46.5–78.5 Bq kg^{-1}, and 394–579 Bq kg^{-1} respectively in Punjab and in the range of 16.01–20.9 Bq kg^{-1}, 9.4–20.5 Bq kg^{-1}, 10.4–19.6 Bq kg^{-1}, and 32–52 Bq kg^{-1} respectively in Mahabaleshwar. Authors concluded that the activity of radionuclides is higher in cultivated soils, which may be due to mineral inputs from regular irrigation and fertilizer application. In the soils of Kaiga region, Karnataka, India, ^{40}K and ^{210}Pb activities were in the range of 57.8–227.2 Bq kg^{-1} and 10.4–75.9 Bq kg^{-1}, respectively (Karunakara et al. 2013). In one another study, ^{226}Ra activity in the soils of Kaiga region has been reported in the range of 5.1–51.6 Bq kg^{-1} (James-Joshy et al. 2011). ^{40}K, ^{226}Ra, and ^{232}Th activities in soil and beach sand samples of Kalpakkam, India were in the range of 38–760 Bq kg^{-1}, 7.0–81 Bq kg^{-1}, and 14–160 Bq kg^{-1}, respectively (Kannan et al. 2002). ^{40}K, ^{238}U, and ^{232}Th in the soil of Agastheeswaram taluk, Kanyakumari district, India were in the range of BDL–613.24 Bq kg^{-1}, BDL–229.86 Bq kg^{-1}, and 32.03–567.76 Bq kg^{-1}, respectively (Khanna et al. 2005). The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K have been reported to be in the range of 18.2–90.3 Bq kg^{-1}, 34.8–124.7 Bq kg^{-1}, and 80.4–181.4 Bq kg^{-1} from some areas of Punjab and Himachal Pradesh, India (Singh et al. 2005). ^{40}K, ^{232}Th, and ^{238}U activities in the soils of Kotagiri Taluk, Nilgiri biosphere, India were 229.2, 102 Bq kg^{-1}, and 41.4 Bq kg^{-1}, respectively, (Selvasekarapandian et al. 2002). A comparison of these studies showed that activity of NORMs in the soil is variable at different regions. This variation may be attributed to soil origin, soil type, landuse pattern, agronomic practices used by the farmers, etc.

^{40}K, ^{232}Th, and ^{226}Ra Activity in Wheat Grain Samples

All the collected wheat grain samples were quantified for ^{40}K, ^{226}Ra, and ^{232}Th. ^{40}K activity was detectable in all the samples and ranged from 111.3 to 245.7 Bq kg^{-1} with a geometric mean of 202 ± 3.7 Bq kg^{-1}. ^{226}Ra and ^{232}Th activities were detectable in most of the wheat grain samples and ranged from <0.04 to 0.37 Bq kg^{-1} and <0.015 to 0.11 Bq kg^{-1} with geometric mean values of 0.12 ± 0.05 Bq kg^{-1} and 0.04 ± 0.03 Bq kg^{-1}, respectively (Table 3).

Activity of NORMs reported in various types of grains by various authors from different parts of the world is given in Table 4. The activity concentration in wheat flour samples collected from the local markets in Iraq ranged from 1.08 to 12.53 Bq kg^{-1} with an average 6.60 Bq kg^{-1} for ^{238}U, 0.12–4.30 Bq kg^{-1} with an average 1.95 Bq kg^{-1} for ^{232}Th, and 41.84 to 264.73 Bq kg^{-1} with an average 133 Bq kg^{-1} for ^{40}K (Abojassim et al. 2014). This study concluded that consumption of wheat flour as foodstuff is safe for target population. Changizi et al. (2013) quantified ^{226}Ra, ^{232}Th, and ^{40}K activities in wheat and corn grains collected from Iran. Mean activities of ^{226}Ra, ^{232}Th, and ^{40}K were 1.67 Bq kg^{-1}, 0.5 Bq kg^{-1}, and 91.73 Bq kg^{-1} respectively, in wheat grains and 0.81 Bq kg^{-1}, 0.85 Bq kg^{-1}, and 101.5 Bq kg^{-1} respectively, in corn grains. Other studies have reported higher activity concentrations of ^{226}Ra and ^{232}Th and lower activity concentration of ^{40}K in both the matrices compared to the present study. Organically and conventionally grown winter wheat from Belgium was monitored for the distribution of natural radionuclides, and no significant difference between two were observed (Lindahl et al. 2011). Overall average activity concentrations in wheat grains obtained for ^{40}K, ^{226}Ra, ^{228}Ra, and ^{228}Th were 115 ± 22 Bq kg^{-1}, 0.10 ± 0.05 Bq kg^{-1}, 0.15 ± 0.05 Bq kg^{-1}, and 0.04 ± 0.03 Bq kg^{-1}, respectively.

Pulhani et al. (2005) measured ^{226}Ra, ^{238}U, ^{232}Th, and ^{40}K activity in wheat grain samples collected from two geographically different provinces (Punjab and Maharashtra) in India. ^{226}Ra, ^{238}U, ^{232}Th, and ^{40}K activities in wheat grain samples collected from Punjab were in the range of 0.4–0.8 Bq kg^{-1}, 0.02–0.06 Bq kg^{-1}, 0.6–1.2 Bq kg^{-1}, and 79.1–110 Bq kg^{-1}, respectively. ^{226}Ra, ^{238}U, ^{232}Th, and ^{40}K activities in wheat grain samples collected from Mahabaleshwar, Maharashtra were in the range of <0.2 Bq kg^{-1}, 0.03–0.04 Bq kg^{-1}, 0.1–0.2 Bq kg^{-1} and 116–130 Bq kg^{-1}, respectively. ^{226}Ra, ^{232}Th, and ^{40}K were higher in wheat grains in the present study than those from Punjab, while reported ^{226}Ra and ^{40}K activities were lower and ^{232}Th activity was higher in wheat grains from Maharashtra.

Transfer Factor of ^{40}K, ^{232}Th, and ^{226}Ra from Soil to Wheat Grains

The mobility of NORMs from rhizospheric zone of soils to the harvestable, edible part of the wheat plant, i.e., grains, was evaluated in terms of transfer factors (Fig. 2a, b). Transfer factors of ^{226}Ra and ^{232}Th were not countable for

Table 4 Globally measured naturally occurring radionuclides' activity in different food and grain matrices

S. no.	Location	Food item	^{40}K (Bq kg^{-1})	^{226}Ra (Bq kg^{-1})	^{232}Th (Bq kg^{-1})	^{238}U (Bq kg^{-1})	References
1	Punjab, India	Wheat grains	86.1–109.9	0.4–0.8	0.8–1.2	0.03–0.06	Pulhani et al. (2005)
2	Mahabaleshwar, India	Wheat grains	116–130	<0.2	0.1–0.2	0.03–0.04	Pulhani et al. (2005)
3	Vizag, India	Mixed foods	3–110.8	0.1–7.2	0.002–2.8	0.002–10.6	Patra et al. (2014)
4	Odisha, India	Cereals, pluses	14.3–957	0.4–28.2	0.3–2.0	0.3–32.0	Lenka et al. (2013)
5	Kudankulam, India	Mixed crops	36–380.6	0.02–0.23	0.09–4.59	–	Ross et al. (2013)
6	Lebanon	Mixed foods	6.9–868	–	–	–	El Samad et al. (2013)
7	Tehran, Iran	Mixed foods	–	6.0–1153	–	0.6–15.6	Hosseini et al. (2006)
8	Tenerife, Spain	Mixed foods	35–380	0.03–0.47	–	<0.09	Hernandez et al. (2004)
9	Tanzania	Maize and rice	24.67–48.79	–	3.82–4.08	5.02–13.23	Mlwilo et al. (2007)
10	Punjab, India	Wheat and mustard	–	–	–	0.38–4.6	Kumar et al. (2009)
11	Jos Plateau, Nigeria	Vegetables and cereals	BDL–684.5	BDL–83.5	BDL–89.8	–	Jibiri et al. (2007)
12	Nigeria	Cereals and tubers	9.9–298	–	3.5–10.5	1.47–39.5	Arogunjo et al. (2005)
13	Kanyakumari	Rice and blackgram	120.2–482.7	3.07–7.52	–	–	Shanthi et al. (2010)
14	GHAVP site, India	Wheat grains	111.3–245.7	<0.04–0.37	<0.015–0.11	–	Present study

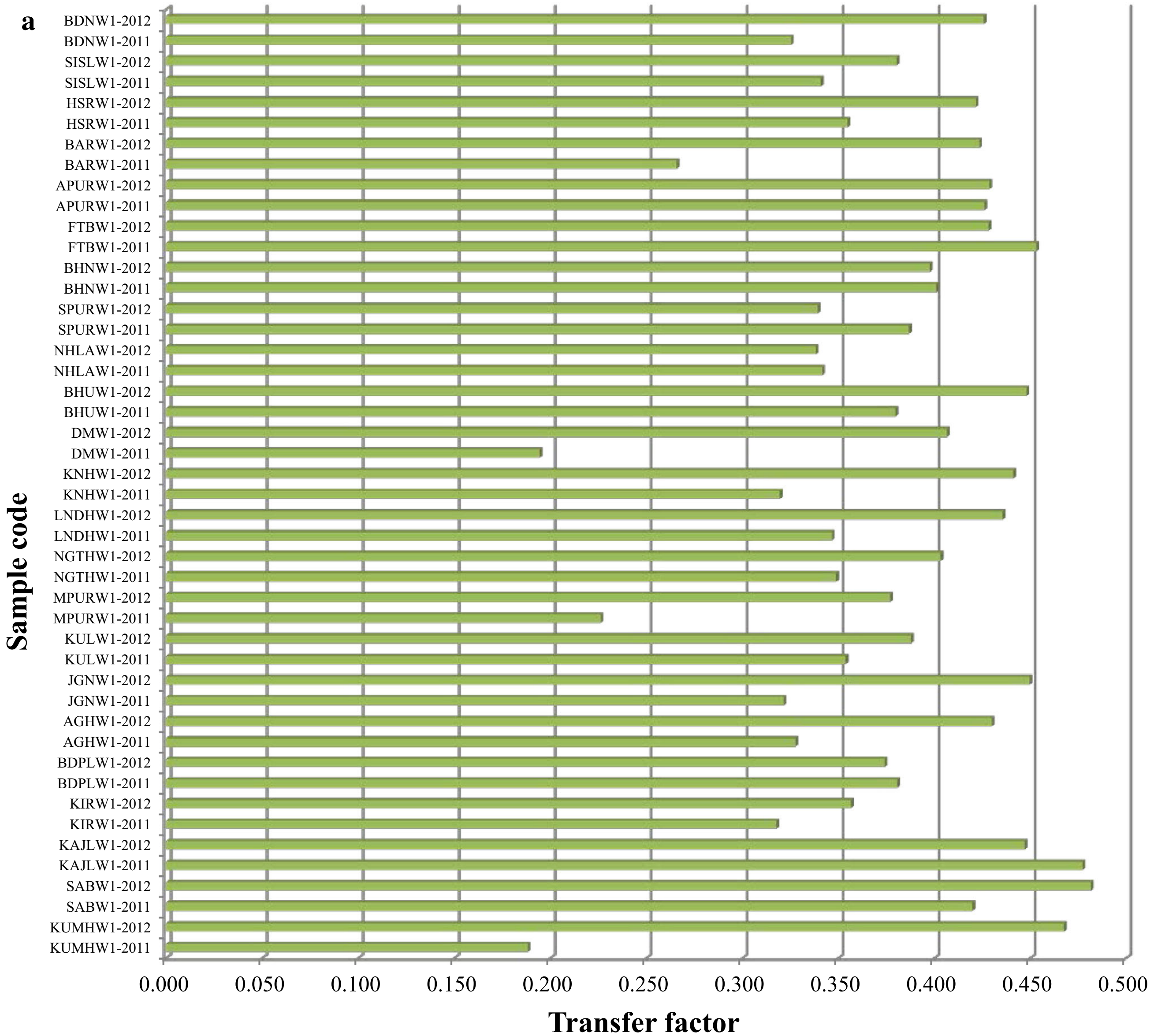

Fig. 2 **a** Transfer factors of ^{40}K from soil to wheat grains collected from GHAVP vicinity. **b** Transfer factors of ^{226}Ra and ^{232}Th from soil to wheat grains collected from GHAVP vicinity

some of the wheat grain samples as radionuclides activity in one of the matrices was below detection limit (BDL). Soil to wheat grains TF of ^{40}K, ^{226}Ra, and ^{232}Th were in the range of 0.19–0.48, BDL–0.01, and BDL–0.004, respectively. The geometric mean TF of studied NORMs was in the following order: ^{40}K (0.37) > ^{226}Ra (0.003) > ^{232}Th (0.001). The soil to plant transfer factor is one of the important parameters to estimate the probable uptake and subsequent ingestion of radiation dose from radionuclides through food (IAEA 1982, 1994). Factors likely to affect radionuclide transfer from soil to plants may include soil characteristics, soil management practices, climatic conditions, type of plants, parts of the plant concerned, physico-chemical form of the radionuclides, and the effect of the competitive species (Bettencourt et al. 1988).

Transfer factors of radionuclides in the crops cultivated in different soil types may vary up to one or two orders of magnitude, and this variability may be attributed to genetic variability intrinsic in plants and distinctiveness among species besides the soil characteristics affecting the mobility of nutrients. ^{40}K shows maximum transfer factor due to its monovalent nature and higher solubility resulting in higher mobility and uptake. Also, K is an essential nutrient, and therefore plant will seek K according to its requirement. In addition to stable K, ^{40}K

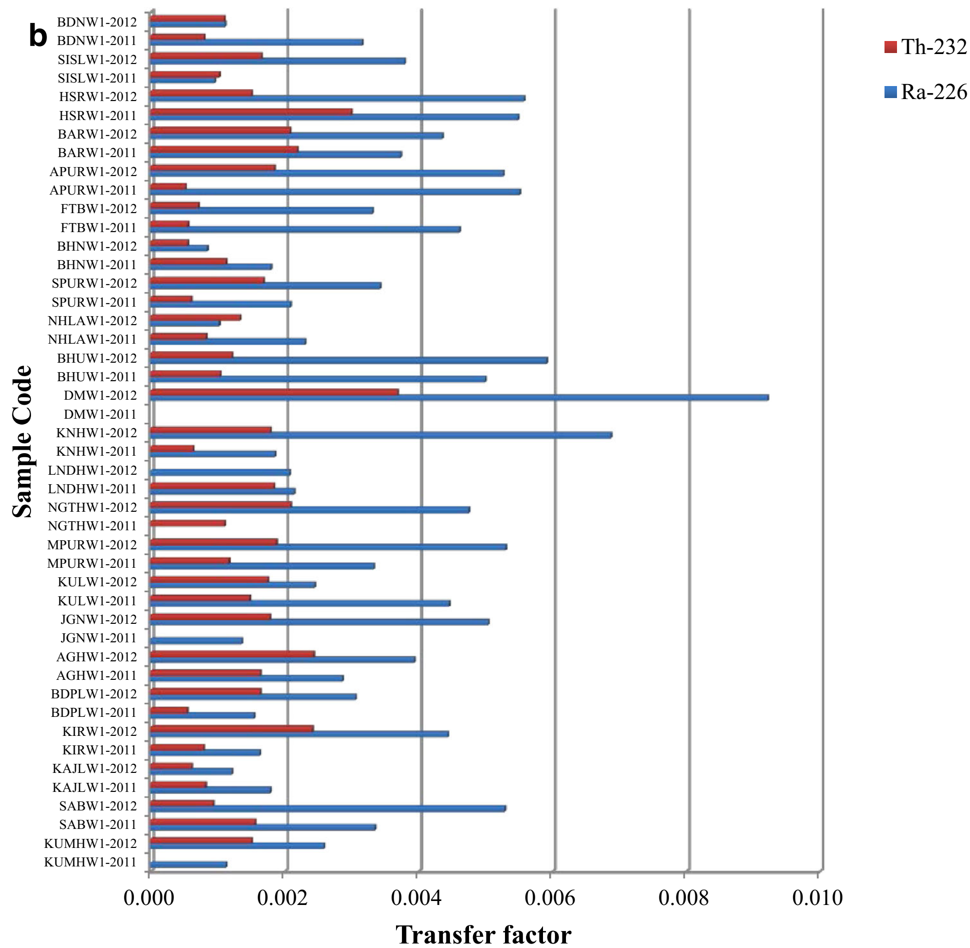

Fig. 2 continued

is also taken up by the plants. Radium is divalent and also has good solubility, but can be retarded by adsorption on hydroxides or by competition with calcium which will be in large excess in the soil. So, its uptake is less than potassium or ^{40}K. Thorium is highly insoluble in soil water and so has minimum uptake.

In different agricultural systems, fecundity of the plant cultivated soil and crop cultivation techniques like soil processing; application of agrochemicals, including pesticides and fertilizers, enhanced irrigation in drought affected areas, and water drainage from marshy territories may results in redistribution of radionuclides in the rhizospheric zone, consequently altering the radionuclide uptake by crops (IAEA 2006). Speciation of the radionuclides and their bio-available fraction present in rhizospheric soil may also influence radionuclide transfer within the same plant (IAEA 2009).

Radionuclide concentration in phosphate fertilizers, field soil, and their uptake by wheat grains grown at Faisalabad, Pakistan was determined by Tufail et al. (2010). Soil to wheat grain transfer factor of ^{40}K (0.12 ± 0.02) was lower, while that of ^{226}Ra (0.02 ± 0.004) and ^{232}Th (0.04 ± 0.007) were higher than that of the present study. Akhter et al. (2007) reported that soil to grain transfer factors of ^{40}K were the highest and that of ^{226}Ra were the lowest in wheat grown at agricultural farms in two districts in Pakistan. Transfer factors of natural radionuclides in wheat grains grown under natural field conditions on two morphologically different soils, from India varied from 6.0×10^{-3} to 2.4×10^{-2} for ^{232}Th, 4.0×10^{-4} to 2.1×10^{-3} for ^{238}U, 9.0×10^{-3} to 1.6×10^{-2} for ^{226}Ra, and 0.14 to 3.1 for ^{40}K (Pulhani et al. 2005). About 54–75% of total ^{238}U, ^{232}Th, and ^{226}Ra activity was concentrated in the roots of the wheat plants and only 1–2% was found distributed in grains. On the other hand, 57% of ^{40}K activity accumulated in the shoots and 16% in the grains.

Effect of Soil Parameters on Transfer Factor of Natural Radionuclides

Uptake of elements from the soil is influenced by physico-chemical properties of soil in the agricultural field, age and part of the bio-available concentration, and nature of the species (Sharma et al. 2007). Therefore, different soil properties of collected soil samples were determined. Transfer factors were calculated per soil group and evaluation of dependency of transfer factor on specific soil properties was performed, following correlation analysis and principal component analysis (PCA). Wheat grain TF of ^{40}K was negatively correlated with available K ($r = -0.47^{**}$, $p \leq 0.01$) and total Ca content ($r = -0.35^{*}$, $p \leq 0.05$) of soil. Decreased uptake of ^{40}K may be attributed to increased Ca content of the soil, as the cation contributes greatly to cation potential of the soil and may interfere with ion uptake by plants leading to their decreased transfer factor (Anke et al. 2004). Transfer factors of ^{40}K, ^{226}Ra, and ^{232}Th were positively correlated with total organic carbon content ($r = 0.49^{**}$, $p \leq 0.01$; $r = 0.32^{*}$, $p \leq 0.05$; $r = 0.36^{*}$, $p \leq 0.05$) of soil. Increased transfer factor of these radionuclides with increasing organic carbon content of the soil may be due to their higher bio-available fraction present in soil solution at higher TOC. Higher the TOC content of the soil, more will be the retention of different ions on its surface against the leaching, and thus greater the uptake by plants. On the contrary, Hunsen and Huntington (1969) suggested that the mobility of thorium in soil is strongly affected by soil organic matter as the radionuclide may get strongly complexed with soil organic matter. Transfer factor of ^{232}Th in wheat grains were positively correlated with CEC ($r = 0.35^{*}$, $p \leq 0.05$) content of the soils of corresponding fields.TF of ^{226}Ra of wheat grain was positively correlated with the TF of ^{40}K ($r = 0.32^{*}$, $p \leq 0.05$) and TF of ^{232}Th ($r = 0.59^{**}$, $p \leq 0.01$) (Table 5).

Principal component analysis with Varimax normalization (PCA-V) was applied for qualitative evaluation of correlation matrix results. Three factors loaded with TF of different NORMs in wheat grains and corresponding fields' soil physico-chemical parameters, explaining a total variance 66.1%, were obtained. Factor-1 contributed 26.57% to the total variance, a high loading on K ($r = 0.83$) and Ca

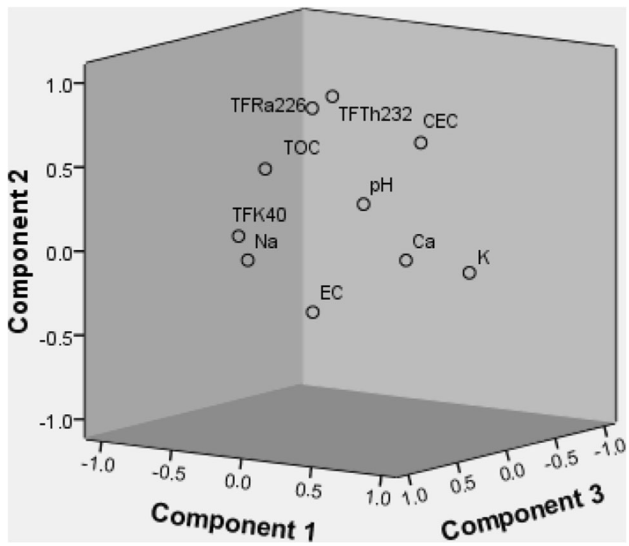

Fig. 3 Principal component plot in rotated space (PCA) for transfer factor of *NORMs* in wheat grains and physico-chemical parameters of the soil of the corresponding fields

Table 5 Correlation among transfer factor of *NORMs* in wheat grains and parameters of rhizospheric soils of the corresponding fields

	TF-K^{40}	TF-Ra^{226}	TF-Th^{232}	pH	EC	Na	K	Ca	TOC	CEC
TF-K^{40}	1.00									
TF-Ra^{226}	0.32*	1.00								
TF-Th^{232}	−0.06	0.59**	1.00							
pH	−0.19	0.14	0.10	1.00						
EC	−0.13	−0.24	−0.26	0.23	1.00					
Na	0.09	0.09	0.02	0.18	0.73**	1.00				
K	−0.47**	−0.12	−0.22	0.26	0.32*	0.06	1.00			
Ca	−0.35*	−0.05	−0.14	0.48**	0.34*	0.12	0.39**	1.00		
TOC	0.49**	0.32*	0.36*	−0.24	−0.30*	0.03	−0.55**	−0.47**	1.00	
CEC	−0.15	0.17	0.35*	0.07	−0.06	−0.16	0.08	−0.02	0.05	1.00

* Correlation is significant at the 0.05 level (2-tailed)

** Correlation is significant at the 0.01 level (2-tailed)

Table 6 Annual effective dose of NORMs from consumption of wheat grains cultivated in the vicinity of proposed GHAVP site, Haryana, India

Dose	Statistics	^{40}K	Ra^{226}	^{232}Th
Annual effective dose (mSv year^{-1})	Min	7.43E−02	<1.21E−03	<4.95E−04
	Max	1.64E−01	1.12E−02	2.83E−03
	Mean	1.37E−01	4.14E−03	1.10E−03
	GM	1.35E−01	3.51E−03	9.75E−04

($r = 0.64$) supporting correlation between two soil cations. With high loading on TF- ^{232}Th ($r = 0.75$), TF- ^{226}Ra ($r = 0.67$), and CEC ($r = 0.61$), Factor-2 contributed 20.22% to the total variance. Factor-3 accounting for 19.29% of the total variance was highly loaded with different soil properties, supporting associations among them (Fig. 3).

Annual Effective Dose from the Ingestion of ^{40}K, ^{232}Th, and ^{226}Ra Via Dietary Intake of Wheat Grains Grown in the Study Area

Radionuclide exposure in foodstuffs depends upon their uptake by specific plants and consumption level of specific foodstuffs, soil type, and soil physico-chemical characteristics. Calculated annual effective dose rates due to ingestion of ^{40}K, ^{232}Th, and ^{226}Ra through dietary intake of wheat grains grown in the vicinity of proposed site are given in Table 6. The annual effective dose incorporated due to ingestion of ^{40}K via dietary intake of wheat grains to the residents of study area varied from a minimum of 0.0743 mSv year^{-1} at *Dhani majra-1* location to a maximum of 0.164 mSv year^{-1} at *Sabarwas-1* location. The spatial variation in radioactivity dose from ^{40}K was low with arithmetic and geometric mean doses of 0.137 and 0.135 mSv year^{-1}, respectively.

The annual effective dose incorporated due to ingestion of ^{226}Ra via dietary intake of wheat grains to residents of study area varied from minimum of <1.21E−03 mSv year^{-1} at *Nangthla-1* location to a maximum of 1.12E−02 mSv year^{-1} at *Dhani majra-2* location. The spatial variation in radioactivity dose from ^{226}Ra was moderate with arithmetic and geometric mean dose values of 4.14E−03 and 3.51E−03 mSv year^{-1}, respectively.

The annual effective dose incorporated due to ingestion of ^{232}Th via dietary intake of wheat grains to residents of study area varied from a minimum of <4.95E−04 mSv year^{-1} at *Kumharia-1* location to a maximum of 2.83E−03 mSv year^{-1} at *Dhanimajra-2* location. The spatial variation in radioactivity dose from ^{232}Th was moderate with arithmetic and geometric mean dose values of 1.10E−03 and 9.75E−04 mSv year^{-1}, respectively. The annual ingestion dose incorporated due to studied radionuclides varied by one order of magnitude. The intake of radionuclides by consumption of wheat grains from the cultivated in study area contribute a small fraction of the total annual ingestion dose received by man due to naturally existing radioactivity in the environment.

The total cumulative annual effective dose from the ingestion of ^{40}K, ^{232}Th and ^{226}Ra through dietary intake of wheat grains varied from 0.07 to 0.17 mSv year^{-1}. Total radioactivity dose from ingestion of ^{40}K, ^{232}Th and ^{226}Ra via ingestion of wheat grains in present study was found to be in magnitude order of 10^{-2} to 10^{-1} mSv year^{-1}; well under the global average permissible limits for general public (UNSCEAR 2000). At this magnitude order, the dose to general public is negligible to be effective.

Lenka et al. (2013) estimated the annual effective dose from the ingestion of ^{232}Th, ^{238}U, ^{226}Ra, ^{40}K, and ^{137}Cs in staple cereal (rice and wheat) grains, pulses, and drinking water in high background radiation area located in Chhatrapur, Odisha, India. The annual effective doses from cereals, pulses, and drinking water varied in the range of 0.11–0.94, 0.10–0.31, and 0.005–0.003 mSv year^{-1}, respectively with an estimated total average annual effective dose of 0.53 mSv year^{-1}. The dose from the cereals was highest due to their higher consumption. Shanthi et al. (2010) estimated the annual effective dose with highest contribution of 0.66 mSv year^{-1} by ^{228}Ra followed by 0.47 mSv year^{-1} by ^{228}Th, 0.46 mSv year^{-1} by ^{40}K and 0.20 mSv year^{-1} by ^{226}Ra ingestion via consumption of south Indian foods with total annual effective dose of 1.79 mSv year^{-1}. Akhter et al. (2007) measured the annual committed effective doses to be 0.008, 0.005 and 0.178 mSv year^{-1} for ^{232}Th, ^{238}U and ^{40}K, respectively, through ingestion of daily diets to Pakistani population. The total annual committed effective dose impact of these radionuclides was 0.18 mSv year^{-1}. Total annual effective dose due to ^{40}K, ^{238}U, and ^{232}Th activity ingestion via different foodstuffs in tin mining area of Jos Plateau, Nigeria individuals was reported in the range of 0.0002 mSv year^{-1} in Sword beans to 0.22 μSv year^{-1} in Yam (Jibiri et al. 2007). Hosseini et al. (2006) reported annual effective dose of 2.88×10^{-2} μSv due to ^{238}U and 2.15 μSv due to ^{226}Ra ingestion via wheat grains intake collected from markets in Tehran. Mlwilo et al. (2007) reported total annual effective doses due to total ^{232}Th and ^{238}U activity ingestion via staple food grains (maize and rice) from various localities of Tanzania. Estimated total annual effective doses were 0.16 mSv year^{-1} for infants, 0.29 mSv year^{-1} for children, and 0.36 mSv year^{-1} for adults respectively.

Conclusion

In the present study, naturally occurring radioactive materials (^{40}K, ^{226}Ra, and ^{232}Th) activities have been quantified in wheat grains, the major widely consumed foodstuff in North India. Dosimetry analysis revealed that ingestion of wheat grains cultivated in the study area is radiologically safe for general public. ^{40}K is the main contributor to total cumulative annual effective dose, but the radionuclide is of limited interest in dose calculations because this is an essential isotope of the element remains under homeostatic control in the human cells. Therefore, ^{40}K content in human body is regulated and determined largely by its physiological characteristics rather than its intake. Also, the measured activity concentrations of terrestrial radionuclides in the soils of wheat crop fields were comparable to the global averages. Correlation analysis revealed that total organic carbon is the major factor governing the transfer of radionuclides from soil to wheat grains. The study gives the baseline information of soil and wheat grains' natural radioactivity contents and uptake under specific conditions around GAHVP site, which will be useful for assessing the impact of operations of nuclear power plant in future.

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