Soil-to-Plant Transfer Factors for Natural Radionuclides in the Brazilian Cerrado Region

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ABSTRACT

Large amounts of phosphogypsum produced have been attracting attention of Radiological Protection institutions and Environmental Protection agencies worldwide, given its high potential for environmental contamination. In Brazil, this material has been used for several decades, especially for agricultural purposes. Due to the presence of radionuclides in its composition, it is necessary to understand the mechanisms for natural radionuclide transfer in the soil/plant system and to evaluate if the use of phosphogypsum in soil contributes to increased exposition of humans to natural radioactivity. Experiments were accomplished in a greenhouse with lettuce cultivation in two types of soil (sandy and clayey) fertilized with four different amounts of phosphogypsum. Samples of phosphogypsum, soil, lettuce and drainage water were then analyzed for key radionuclides. 238U and 232Th analyses were carried out by Neutron Activation Analysis; 226Ra, 228Ra, and 210Pb by analyzed by Gamma Spectrometry; and 210Po by Alpha Spectrometry Technique. Finally, Transfer Factors of soil-plant were calculated as well as annual contribution to the effective dose due to the ingestion of lettuces. 226Ra average specific activity in phosphogypsum samples (252 Bq kg⁻¹) was below the maximum level recommended by USEPA, which is 370 Bq kg⁻¹ for agricultural use. Although most of the results for mean specific activity of radionuclides in lettuce presented values below the Minimum Detectable Activity (MDA), Transfer Factors were estimated for those conditions in which the mean specific activity proved to be superior to MDA. Values ranged from 1.8 \times 10^{-3} to 2.3 \times 10^{-2} for 232Th; 3.5 \times 10^{-2} to 4.1 \times 10^{-2} for 226Ra, 2.4 \times 10^{-1} to 3.2 \times 10^{-1} for 228Ra, and 3.5 \times 10^{-2} to 8.5 \times 10^{-2} for 210Po, depending on the type of soil used for planting vegetables. In general, results obtained in the present study indicated that mobility of radionuclides was low in both soils studied. Calculated effective doses committed were well below the 1 mSv year⁻¹ limit established by ICRP, for the public in general (4.3 \times 10^{-3} mSv year⁻¹ for the experiments in clayey soil and 7.5 \times 10^{-3} mSv year⁻¹ for the experiments in sandy soil).
1. INTRODUCTION

Apatite is the main raw material in Brazilian phosphoric fertilizer industries. It is present in rocks, of which approximately 80% are of igneous origin [1]. The most common process used in the production of phosphoric fertilizers is the attack of the phosphate rock with concentrated sulfuric acid and water. In this case, main products from chemical reactions are phosphoric acid (H₃PO₄), simple super-phosphate (SSP), and triple super-phosphate (TSP). Dehydrated calcium sulphate (phosphogypsum) and hydrofluoric acid are by-products of phosphate rock processing.

Phosphogypsum (PG) generation rate is approximately 4.8 tons per 1.0 ton of produced phosphoric acid. Annual world production is estimated to be 150 million tons, of which approximately 6 million tons are generated in Brazil [2]. At present, this material is stored in piles located near factories. However, this practice may represent a potential contamination risk, mainly to organisms and hydrological systems located close to the pile.

The possibility of using PG in agriculture [3, 4, 5] has been the focus of research in several countries and in Brazil, especially in Cerrado agriculture [6, 7], where soils have characteristics which are compatible to the use of PG. In this system, fast mineralization of organic matter, associated with intense leaching, produces soils with naturally low fertility. These are acidic soils (pH between 4.3 and 6.2) with high levels of exchangeable aluminum and low levels of phosphorus available to plants; they are also poor in calcium and magnesium, elements involved in root development [8].

Toxic concentrations of soluble aluminum in soils that negatively influence crops can be avoided with addition of acidity correctives, which buffer the soil pH over 5.0. Rocks that contain alkaline constituents such as oxides, hydroxides, carbonates, and silicates of calcium, and/or magnesium are commonly employed to neutralize soil acidity [9]. Calcareous materials are included in this category and are known as limestone, containing calcium and/or magnesium carbonates. However, it is more difficult and expensive for farmers to obtain limestone, mainly due to its use in more profitable industrial sectors, such as cement production, metallurgic sites, building sites, etc.

Various residues generated by industries have been studied as possible substitutes for limestone. Among them, the industrial waste phosphogypsum (PG), or “agricultural gypsum” (AG), has been considered mainly to be applied in conjunction with limestone in order to improve the effects of the sub-superficial acidity on root growth. In Brazil, the application of PG as a soil conditioner has been practiced for several years [7, 10]. Nevertheless, due to the presence of radionuclides in PG and taking into account the environmental aspects related to reuse of residues in agriculture [11, 12], a study has been carried out to evaluate whether its application to improve soil fertility can result in a radiological impact to human health and the environment.

Migration and accumulation of contaminants in cultivated soils is complex, involving processes such as leaching, capillary rise, runoff, sorption, root uptake, and re-suspension into the atmosphere. Assessment models normally make use of a plant/substrate concentration ratio, referred to as a transfer factor (TF) to estimate the transport of radionuclides and other elements of interest through the food [13]. This ratio describes the amount of element expected to enter a plant from its substrate under equilibrium conditions.
Factors such as soil characteristics, climatic conditions, type of plants, part of the plant concerned, physical-chemical form of the radionuclides and the effect of the competitive species can influence TF values [15].

The main objective of this work was to present chemical and radiological parameters obtained in a set of greenhouse experiments, which were carried out for determination of natural radionuclide Transfer Factors to lettuce plants (\(^{238}\)U, \(^{232}\)Th, \(^{226}\)Ra, \(^{228}\)Ra, \(^{210}\)Pb, and \(^{210}\)Po) cultivated in two typical soils (clayey and sand) from the Cerrado region, fertilized with different doses of PG.

2. MATERIALS AND METHODS

2.1. Sample Collection and Pre-Treatment

Samples of PG were collected in a fertilizer facility that produces phosphoric acid through a wet method. The phosphate rock used at the industrial site has igneous origin and comes from the Alkaline-Carbonate site in Tapira, MG, Brazil [1]. Thirty samples were collected from the surface of the piles at different locations, according to Environmental Protection Agency guidelines [16]. PG samples were then dried in the laboratory at 60°C for 48 hours and sieved through 30 and 60 mesh (590 and 250 µm). Afterwards, small fractions of the samples were mixed and divided, in order to form a composed sample.

Soil samples were collected from two different locations in the Sete Lagoas municipal district (clayey yellow rhodic ferralsol (hapludox) - LVSL) and in the João Pinheiro municipal district (sandy rhodic ferralsol (hapludox) - LVTM), that represented typical soils from the Cerrado region. Soil samples were air dried and sieved through 2 mm mesh.

Chemical characterization of soil samples was done through the following analyses: pH in water (1:2.5); P and K extractable by Mehlich 1; exchangeable Ca, Mg, and Al by extraction with 1 mol L\(^{-1}\) KCl; Sum of Exchangeable Bases (SB); Cationic Exchange Capacity at pH 7.0 (CEC); Index of Bases Saturation (V); Index of Aluminum Saturation (m), and Organic Matter Content (OM).

2.2. Greenhouse Experiments

Greenhouse experiments were carried out at an experimental area owned by Viçosa Federal University’s Soil Department (Viçosa, MG), in a metallic structure without temperature control.

Lettuce was chosen to perform the experiment (Lactuca sativa). The selection of this green-leaf species was due to its short cycle, great volume in the market, commercialization, and nutritional value. Besides this, it is a nutrient demanding green-leaf.

In order to facilitate collection of drainage water, 0.5 dm\(^3\) of Zero Type gravel, 0.5 dm\(^3\) of One Type gravel, and 0.5 dm\(^3\) of washed sand were placed in the bottom of the vessels. Mixtures were then prepared with soil, with recommended phosphogypsum dosages (1 NG), double dosage (2 NG), and half dosage (0.5 NG) in order to verify the effect of this practice on bioavailability of key radionuclides, in both types of soils studied (sandy and clayey). Seven dm\(^3\) of soils corrected and treated with phosphogypsum were then placed in appropriate vessels.
Phosphogypsum dose (recommended mass) equivalent to 1 NG (gypsum need) was of 0.5 g.dm$^{-3}$ for clayey soil and 0.2 g.dm$^{-3}$ for sandy soil, [15]. Each experiment was done in triplicate vessels for each type of soil in order to guarantee reliable results, with one vessel without phosphogypsum. Three lettuce seedlings were planted per vessel. Figure 1 shows a picture of an experiment carried out in the greenhouse.

Water drainage was accomplished by employing hoses connected to the inferior part of each vessel, which were directed to appropriate reservoirs. Irrigation was kept daily in order to reestablish soil field capacity, evaluated previously in the lab and equivalent to the humidity of grinded and sieved samples. Leached water samples were collected in polyethylene containers every fifteen days. Samples were acidified to pH 2 with concentrated nitric acid for preservation. At the end of the collection period, a 5 L composed water sample was sent for analysis and determination of concentration for key elements.

After harvest, lettuce samples were washed with public supply water in order to remove impurities, washed with distilled water, and then dried in a muffle furnace with air circulation. Samples were weighted for humid mass determination, lyophilized in a LABCONCO equipment at -40 ºC and 133µBAR for approximately 48 hours, weighted for determination of dried mass, and transferred to a grinder to be processed. Later on, they were weighted, stored in polyethylene containers, and shipped for analysis. A total of 9 g was obtained from each lettuce vessel.

![Figure 1. Experiments with Lettuce Cultivated with Phosphogypsum Waste.](image-url)

2.3. **Determination of Radionuclide Activity Concentrations**
2.3.1. PG and soil samples

$^{226}$Ra, $^{228}$Ra, and $^{210}$Pb activity concentrations in PG and soil samples were determined by Gamma Spectrometry using an HPGe detector (45% relative efficiency). Samples were sealed in plastic containers for 30 days, which was the time needed to assure radioactive equilibrium between $^{226}$Ra and its daughters, $^{214}$Pb and $^{214}$Bi. Energy photopeaks at 609 keV and 1,020 keV, and 351 keV were used to determine $^{226}$Ra, corresponding to $^{214}$Bi and $^{214}$Pb, respectively. A 911 keV energy photopeak for $^{228}$Ac ($T_1/2 = 6.12$ hours) was used to determine $^{228}$Ra. A 46.5 keV energy photopeak was used for $^{210}$Pb determination.

$^{210}$Po activity concentration measurement was performed using an Alpha Spectrometry system, through determination of the powder deposited in a silver plate, using a reducing HCl and ascorbic acid medium. Matrix purification was done by a specific SR-Spec chromatographic resin from Eichrom.

$^{232}$Th activity concentration in PG and soil samples was determined by Neutron Activation Analysis technique (AAN), $k_0$ method [17]. In this case, 200 mg of each sample was weighed in polyethylene tubes, sealed, and irradiated in a TRIGA MARK I IPR-R1 reactor located at CDTN/CNEN, using 100 kW with a thermal neutron flow equivalent to $6.35 \times 10^{11}$ neutrons cm$^{-2}$ s$^{-1}$, for 8 hours. After irradiation and an appropriate time for decline, the procedure followed medium and long half-life radionuclide determination. Gamma Spectrometry was done using an HPGe detector with 15% efficiency. KAYZERO/SOLCO software was used for calculating element concentration.

$^{238}$U activity concentration was determined through retarded neutron fission activation method, and samples were irradiated with a flow of thermal neutrons. This method uses fast irradiation followed by a reading of retarded neutrons. Samples were irradiated for 50 seconds, 30 seconds were allowed for decline time, and counting took 60 seconds. The irradiation process and counting employed an automated pneumatic system. A $^{10}$BF$_3$ detector was used to count retarded neutrons. Uranium concentration was calculated through linear regression, adjusted according to established patterns.

2.3.2. Lettuce and Drainage Water Samples

The method employed for determination of $^{226}$Ra and $^{228}$Ra concentrations in lettuce and leached water was based on Total Alpha and Beta Counting of Ba(Ra)SO$_4$ (a precipitate containing radium), performed in a Proportional Gas Flow Counter model ESM-Eberline FHT 770T of ultra low background. Counting efficiencies were determined through standards of $^{226}$Ra and $^{228}$Ra with known activity. Background was obtained by counting an empty stainless steel planchet. $^{210}$Pb concentration measurement was also carried out at LAPOC. For both samples, lead was recovered in the supernatant after separation of radium.

$^{210}$Po activity concentration measurement was performed using an Alpha Spectrometry system, through determination of the powder deposited in a silver plate, using a reducing HCl and ascorbic acid medium. Matrix purification was done by using a specific SR-Spec chromatographic resin from Eichrom.
\(^{232}\)Th and \(^{238}\)U concentrations in the lettuce samples were determined by Neutron Activation Analysis technique (AAN), \(k_0\) method, and through retarded neutron fission activation method, respectively, as described before.

The method to measure \(^{238}\)U concentration in samples of leached water was based on the separation of uranium from impurities through extraction with tri-n-butyl-phosphate (TBP) from a solution containing the saline agent Al\((\text{NO}_3\))\(_3\), EDTA, and tartaric acid [18]. For such procedure, 150 mL of leached water was treated with nitric and perchloric acids until formation of humid salts, followed by addition of 10 mL of nitric acid and re-extraction with arsenazo III solution in a pH 3 buffer containing sodium fluoride. A red-violet stable complex was formed and measured at 650 nm in a Spectrophotometer equipped with a glass cell of 01 cm optical path.

For determination of \(^{232}\)Th in leached water samples, aliquots of 300 mL were attacked with nitric and perchloric acids until formation of humid salts, followed by addition of 10 mL nitric acid, with thorium extraction by tri-n-octil fosfinoxide (TOPO), and re-extraction with oxalic acid. A colorimetric reaction was carried out with arsenazo III and the complex was spectrophotometrically measured at 665 nm [18].

### 3. RESULTS AND DISCUSSIONS

Chemical characterization revealed that both soils were acidic and possessed low fertility levels (see Table 1). This is related to low levels of nutrients (Ca, Mg, K, and P), as well as low CEC values. Low base saturation indexes (V) indicated that small proportions of exchangeable Ca\(^{2+}\), Mg\(^{2+}\), and K\(^+\) are occupying negative charged sites of the colloids. Conversely, exchangeable Al\(^{3+}\) ions are dominant, as indicated by relatively high Al saturation index \((m > 30\%)\). Clayey soil presented slightly higher fertility, with higher Ca and organic matter (OM) levels. In general, both soils had high Al levels and potential acidity. These are typical characteristic of acidic Cerrado soils, where exchangeable Al is considered toxic for most cultivated plants.

Figure 1 presents results for natural radionuclide activity concentrations in soil and PG samples. As it can be verified, \(^{238}\)U concentration in PG was well below the concentration found in the clayey soil. It is important to mention that: (1) PG samples usually have low \(^{238}\)U concentration compared to other natural radionuclides. In phosphoric rock, members of the \(^{238}\)U and \(^{232}\)Th natural series are in radioactive equilibrium. During acid attack to phosphoric rocks, phosphoric acid is enriched with \(^{238}\)U, while \(^{232}\)Th, radium isotopes, and \(^{210}\)Pb tend to concentrate in PG; (2) Brazilian phosphoric rock has igneous origin, with smaller \(^{238}\)U concentrations than \(^{232}\)Th concentrations; and (3) clayey soil used in this study was developed from weathering of granite rocks over 2,700 million years, typically presenting \(^{238}\)U contents from 5 to 10 ppm.

In general, the PG generated by phosphoric acid industries in Brazil has natural radionuclide activity concentrations well below those observed in other countries [19, 5]. The largest \(^{232}\)Th activity concentration in relation to \(^{238}\)U activity concentration can be explained by the rock igneous origin.
Figure 2 presents results of average specific activity for radionuclides measured in mixtures of soil samples treated with recommended doses of phosphogypsum (1 NG), double (2 NG) and half (0.5), and one non-treated soil sample (without phosphogypsum). The average of triplicate measurements was considered for each condition. For sandy soil, results for $^{238}\text{U}$, $^{226}\text{Ra}$, $^{210}\text{Pb}$, and $^{210}\text{Po}$ were below the Minimum Detectable Activity (MDA). Only $^{232}\text{Th}$ and $^{228}\text{Ra}$ had values above the MDA.

Leached water presented average activity values below MDA for all radionuclides studied.

Table 1. Chemical characterization of soil samples.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>pH</th>
<th>P</th>
<th>K$^+$</th>
<th>Ca$^{2+}$</th>
<th>Mg$^{2+}$</th>
<th>Al$^{3+}$</th>
<th>H$^+$ Al</th>
<th>SB</th>
<th>CEC</th>
<th>V m</th>
<th>OM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(mg dm$^{-3}$)</td>
<td>(cmol$_c$ dm$^{-3}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>clay</td>
<td>5.18</td>
<td>1.5</td>
<td>0.02</td>
<td>0.90</td>
<td>0.06</td>
<td>0.48</td>
<td>8.3</td>
<td>0.97</td>
<td>1.45</td>
<td>10.5</td>
<td>33.1</td>
</tr>
<tr>
<td>sand</td>
<td>5.32</td>
<td>0.4</td>
<td>0.041</td>
<td>0.11</td>
<td>0.02</td>
<td>0.1</td>
<td>3.2</td>
<td>0.17</td>
<td>0.27</td>
<td>5.0</td>
<td>37</td>
</tr>
</tbody>
</table>

Figure 1. Activity Concentration of the PG and soil samples.
Table 1 presents results for average specific activity of each natural radionuclide present in lettuce samples cultivated in soil mixtures with recommended doses of phosphogypsum and soil without phosphogypsum. As verified, average specific activities for $^{238}\text{U}$, $^{226}\text{Ra}$, and $^{210}\text{Pb}$ in samples cultivated with sandy soil, as well as specific activities for $^{238}\text{U}$, $^{210}\text{Pb}$, and $^{232}\text{Th}$ (phosphogypsum doses equivalent to 0.5 and 1.0 NG) in clayey soil, were below the MDA.
As mentioned previously, most samples of fertilized soil and lettuce presented activities below Minimum Detectable Activity. Still radionuclide Transference Factors were calculated for those conditions in which the specific activity was above the MDA. Results obtained are presented on Table 2.

There is a trend to have a higher FT for experiments in sandy soil (at least for $^{232}$Th, which is the only radionuclide that allowed a comparison). As mentioned earlier, sandy soil with a low concentration of organic matter and CTC, has low capacity to retain radionuclides, making them easily available to plants. It is interesting to observe that it was only possible to calculate transfer factors for elements from the $^{232}$Th series for sandy soil, since most values for average specific activity were below the MDA.

In order to estimate the annual contribution to the effective dose that comes from chronic ingestion of green leaves analyzed in this study, a research was initially conducted to know the amount of lettuce consumed by an individual from the studied population. In Brazil, this information is provided by POF (Family Budget Research), which belongs to the Brazilian Geography and Statistics Institute [20]. Data from the last Census (2002/2003) was employed in this work, which described annual domestic food acquisition per capita (kg); an equivalent of 0.822 kg.yr$^{-1}$ for lettuce in Minas Gerais State. The effective committed dose determined in this study was well below the 0.3 mSv yr$^{-1}$ limit for the general public [21], indicating that phosphogypsum application did not result in a significant increase of human exposure to natural radioactivity, in the experimental conditions of this study.

<table>
<thead>
<tr>
<th>Radionuclides</th>
<th>$^{238}$U (Bq.kg$^{-1}$)</th>
<th>$^{232}$Th (Bq.kg$^{-1}$)</th>
<th>$^{226}$Ra (Bq.kg$^{-1}$)</th>
<th>$^{228}$Ra (Bq.kg$^{-1}$)</th>
<th>$^{210}$Pb (Bq.kg$^{-1}$)</th>
<th>$^{210}$Po (Bq.kg$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clayey Soil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 NG</td>
<td>&lt; 1.25</td>
<td>0.2 ± 0.05</td>
<td>&lt; 3.6</td>
<td>&lt; 8.0</td>
<td>&lt; 8.0</td>
<td>3.0 ± 1.0</td>
</tr>
<tr>
<td>0.5 NG</td>
<td>&lt; 1.25</td>
<td>&lt; 0.07</td>
<td>2.0 ±1.0</td>
<td>1.5 ± 0.6</td>
<td>&lt; 3.0</td>
<td>2.0 ± 0.6</td>
</tr>
<tr>
<td>1.0 NG</td>
<td>&lt; 1.25</td>
<td>&lt; 0.07</td>
<td>&lt; 2.2</td>
<td>&lt; 4.0</td>
<td>&lt; 3.0</td>
<td>1.0 ± 0.6</td>
</tr>
<tr>
<td>2.0 NG</td>
<td>&lt; 1.25</td>
<td>0.4 ± 0.2</td>
<td>2.0 ±1.0</td>
<td>&lt; 2.0</td>
<td>&lt; 3.0</td>
<td>2.0 ± 0.6</td>
</tr>
<tr>
<td>Sandy Soil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 NG</td>
<td>&lt; 1.25</td>
<td>0.7 ± 0.2</td>
<td>&lt; 2.0</td>
<td>&lt; 6.4</td>
<td>&lt; 7.0</td>
<td>3.0 ± 1.0</td>
</tr>
<tr>
<td>0.5 NG</td>
<td>&lt; 1.25</td>
<td>0.5 ± 0.2</td>
<td>&lt; 4.0</td>
<td>6.0 ± 2.0</td>
<td>&lt; 4.0</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>1.0 NG</td>
<td>&lt; 1.25</td>
<td>0.6 ± 0.3</td>
<td>&lt; 3.0</td>
<td>8.0 ± 3.0</td>
<td>&lt; 3.0</td>
<td>1.3 ± 0.6</td>
</tr>
<tr>
<td>2.0 NG</td>
<td>&lt; 1.25</td>
<td>0.7 ± 0.3</td>
<td>&lt; 2.0</td>
<td>7.0 ± 2.0</td>
<td>&lt; 5.0</td>
<td>1.5 ± 0.4</td>
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Table 2. Soil-plant transfer factors.

Clayey Soil

<table>
<thead>
<tr>
<th>PG doses</th>
<th>$^{238}$U</th>
<th>$^{232}$Th</th>
<th>$^{226}$Ra</th>
<th>$^{228}$Ra</th>
<th>$^{210}$Pb</th>
<th>$^{210}$Po</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 NG</td>
<td>-</td>
<td>$1.8 \times 10^{-3}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$8.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>0.5 NG</td>
<td>-</td>
<td>-</td>
<td>$3.6 \times 10^{-2}$</td>
<td>-</td>
<td>-</td>
<td>$5.3 \times 10^{-2}$</td>
</tr>
<tr>
<td>1.0 NG</td>
<td>-</td>
<td>-</td>
<td>$4.1 \times 10^{-2}$</td>
<td>-</td>
<td>-</td>
<td>$3.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>2.0 NG</td>
<td>-</td>
<td>$3.7 \times 10^{-3}$</td>
<td>$3.5 \times 10^{-2}$</td>
<td>-</td>
<td>-</td>
<td>$4.8 \times 10^{-2}$</td>
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</tbody>
</table>

Sandy Soil

<table>
<thead>
<tr>
<th>PG doses</th>
<th>$^{238}$U</th>
<th>$^{232}$Th</th>
<th>$^{226}$Ra</th>
<th>$^{228}$Ra</th>
<th>$^{210}$Pb</th>
<th>$^{210}$Po</th>
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</thead>
<tbody>
<tr>
<td>0 NG</td>
<td>-</td>
<td>$2.3 \times 10^{-2}$</td>
<td>-</td>
<td>$2.4 \times 10^{-1}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.5 NG</td>
<td>-</td>
<td>$1.6 \times 10^{-2}$</td>
<td>-</td>
<td>$2.0 \times 10^{-1}$</td>
<td>-</td>
<td>-</td>
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<tr>
<td>1.0 NG</td>
<td>-</td>
<td>$2.0 \times 10^{-2}$</td>
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<td>$3.2 \times 10^{-1}$</td>
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</tr>
<tr>
<td>2.0 NG</td>
<td>-</td>
<td>$2.3 \times 10^{-2}$</td>
<td>-</td>
<td>$2.4 \times 10^{-1}$</td>
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</table>

4. CONCLUSIONS

This study was conducted mainly due to the concern regarding risks involved with an increase of exposure to natural radioactivity related to application of a NORM type material in agriculture. As mentioned earlier, industrial processes to which these materials are submitted may increase concentration of radioactive elements (levels of emitted radiation) and exposure of workers and public individuals to radioactivity.

Soils employed in this experiment were analyzed for fertility, revealing that both soils are acid and have low level of fertility. This can be proved by low concentrations of available nutrients (Ca, Mg, K, and P), as well as low effective CTC value.

Analyses results for determination of natural radionuclide concentration in phosphogypsum samples indicated that the average specific activity for $^{226}$Ra (252 Bq.kg$^{-1}$) was below the limit recommended by the US Environmental Protection Agency (USEPA, 1988) for employment of phosphogypsum in agriculture, which is 370 Bq.kg$^{-1}$.

Specific activity for each key radionuclide present in clayey soil samples were superior to those obtained for sandy soil. Such findings can be explained by clayey soil’ mineralogical characteristics, which have a higher ion retention capacity in their surface, greater organic matter content as well as superficial area.

Even though most results for radionuclide concentration in lettuce samples were below MDA, transfer factors (FT) were estimated for those conditions in which specific activity was above the MDA. Values obtained ranged from $1.8 \times 10^{-3}$ to $2.3 \times 10^{-2}$ for $^{232}$Th; $3.5 \times 10^{-2}$ to $4.1 \times 10^{-2}$ for $^{226}$Ra, $2.4 \times 10^{-1}$ to $3.2 \times 10^{-1}$ for $^{228}$Ra, and $3.5 \times 10^{-2}$ to $8.5 \times 10^{-2}$ for $^{210}$Po, depending on the type of soil used for planting.
In a general manner, results obtained in this study indicated that radionuclide mobility in both soils was low. Main factors that could have influenced were: short experiment interval and low water flow to which the soil was submitted. However, such conditions were necessary due to plant characteristics; lettuce has a short cycle of approximately forty days.

Finally, as radiological protection is concerned, it is worth mentioning that all data obtained demonstrated the viability of phosphogypsum use in the Cerrado region. Additional studies have been carried out in order to comprehend Transfer Mechanisms in the soil/plant system for heavy metals, natural radionuclides, and some nutrients, in other cultures cultivated in that region.

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