Transfer factor of Radiocesium from soil to spinach plant (Amaranthus sp)

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Abstract. Transfer factor of radiocesium from soil to spinach plant (Amaranthus sp). Transfer of Cs radionuclide from andosol soil to spinach plant (Amaranthus sp), which highly consumed by Indonesian people had been studied to obtain the transfer factor value for human internal dose assessment according to soil–crop–human pathway. Spinach plants are planted on andosol type soil media containing 134Cs. The research was carried out by growing spinach plants on andosol type soil media containing 134Cs until the plants could be harvested. The number of absorbed and accumulated 134Cs by plant parts, namely, the roots, stems, leaves, and flowers, are observed every five days. The amount of 134Cs uptake accumulated by plants and 134C concentrations remaining in the soil was measured using a gamma spectrometer. Transfer factor values were determined by comparing the concentration of 134Cs accumulated by plants to their concentrations in soil media. The results of this study obtained that the transfer factor value at harvest age for consumption, i.e., 52 days was 0.527, and the highest was 6.56 when the plant was 76 days. The transfer factor value of higher than one indicates that the spinach plant is a radiocaesium accumulator. Keywords: accumulation, radiocaesium, transfer factor, spinach, soil.

1. Introduction

Typically, nuclear reactor operation does not have negative impacts on the public and the environment. Even though the environmental safety on site and offsite, furthermore the worker and public safety have to be concerned. In the case of a reactor accident, several radionuclides may be released to the environment. The worst accident can cause the fission product release to the environment, and expose externally and internally the public and the environment. For nuclear safety assessment, i.e., for public internal dose assessment through the soil-crop-human pathway, it is necessary to obtain transfer factor values of radionuclides from soil to crops. 137Cs radionuclide is regarded as important radionuclide in radioecology, because of their relatively high fission yields and affinities to the human body. Soil contamination with radiocaesium has a long-term radiological impact due to its long physical half-life (30 years for 137Cs and two years for 134Cs) and its high biological availability. Consumption of agricultural produce contaminated with radiocaesium represents the principal route of human exposure to this radionuclide [1,2].

Unfortunately, data of transfer factor values of radionuclides from soil to tropical crops are minimal. On the IAEA publications about radionuclides transfer in the environment, some transfer factor values of radionuclides from soil to variety of crops are listed [3]. However, the crops listed are the temperate zone crops, that off course is different from the crops planted and consumed in the tropical area, which...
have very different climates and environments. Therefore, it is impossible to apply those transfer factor values for radiological risk assessment in Indonesia with the tropical climate [4].

In this research, the transfer factor value of Cs radionuclide from Andosol soil to spinach plant was determined. The Andosol is soil type around the TRIGA 2000 research reactor, Bandung. In contrast, the spinach plant is one of the common vegetables planted and consumed by Indonesian people. According to the Statistic Central Bureau of Indonesia, the annual spinach production reaches 155.6 tons, and the consumption is nearly 1 kg/year/capita [5].

The transfer factor value obtained from this research is expected can be used in internal dose assessment for the public around through the soil-crop-human pathway. Furthermore, the transfer factor value of Cs radionuclide from soil to spinach plant can complete or fulfill the transfer factor value for the tropical region.

2. Method
The method used in this study refers to the IAEA General Protocol for Transfer Measurement with several modifications to be fit in laboratory conditions [6]. The Andosol soil was taken from the TRIGA 2000 Research Reactor site, Bandung. The soil was analyzed for chemical parameters at The Vegetables Plants Research Institute of Department of Agriculture [4]. For enhancing soil fertility, the organic fertilizers were added with the proportion of 10 kg fertilizer for 180 kg soil. The soil was then filled to the container of 1 x 1 x 0.5 m³. The 134Cs radionuclide was added to the soil, so the 134Cs concentration becomes 48.75 Bq/kg soil. To control the plant growth, a container with the same size was prepared. The control container was filled with the soil without the addition of 134Cs.

The small spinach plants with the uniform size (10 cm tall with four leaves) were planted on both soil with a density of 25 plants/m² and plant distance of about 20 cm. The plants were grown for about three months and periodically observed for the 134Cs uptake and growth rate. The observations were conducted every five days by taking the plants and soil samples. The plant samples were separated into the root, stem, and leaves, then weighed and measured the stem length. The soil samples were also weighed. All the plants and soil samples were then dried using the oven at 100 °C for about 4 hours until the constant weight had been obtained. The dried samples were measured for 134Cs activity using a gamma spectrometer with an HPGe detector for 600 seconds [6].

Transfer factor value was determined by comparing the concentration of 134Cs on the edible part of the plant to that of the 134Cs concentration on soil according to the soil-plant compartment model [7], as shown in Fig 1.

\[
\frac{dC_2}{dt} = k_{12}C_1 - \lambda C_2
\]

Figure 1. Soil to plant compartment model.

where:

- \(C_1\) = radionuclide concentration on soil (Bq/g)
- \(C_2\) = radionuclide concentration on plant (Bq/g)
- \(\lambda\) = decay constant (1/days)
- \(k_{12}\) = transfer rate coefficient of radionuclide from soil to plant (1/days)
In this model, no radionuclide transfer from plant to soil is assumed, so the $k_{21}$ (transfer rate coefficient from plant to soil) is equal to zero.

The plant can accumulate certain kinds of chemical elements that lead to the element concentration on plant much higher than that on the medium where they are grown. The ability of the plant to accumulate chemical elements is expressed as a transfer factor that defined as a ratio of element concentration on biota to that of concentration on medium. The transfer factor is formulated as [8] :

$$T_f = \frac{C_2}{C_1}$$  \hspace{1cm} (2)

where :

$T_f$ = Transfer factor
$C_2$ = element concentration on plant tissue (Bq/g)
$C_1$ = element concentration on soil (Bq/g)

The transfer of radionuclides in the environment, especially the soil path to plants is a complex phenomenon and is influenced by various factors [1], so the $T_f$ value has a large variation based on the type of soil where the plants grow, and the type of radionuclides [9,10]. The transfer of radionuclides from soil to plants has been widely studied, especially for fission radionuclides, which have the potential danger of internal radiation in humans because of their relatively high energy and long half-life, such as Cs and Sr [11]. The International Atomic Energy Agency (IAEA) has recorded radionuclide transfer values in ecosystems and published in the "Handbook of Parameter Values for the Prediction of Radionuclides Transfer in The Ecosystem" [8]. However, the value of the transfer factor available is for plants that grow in temperate climates, while the data for the tropics and subtropics is minimal [3]. The application of transfer factor values to temperate climates to tropical ecosystems is highly unlikely, given the very different types of plants, soil types, and climates [12].

3. Results and Discussions

3.1. Plant growth

To test the difference of plant growth between the plant growing up on contaminated soil compared to the plant growing up on control, the statistic t-test was applied to the data of plant weight and stem length. According to the test using a confidence level of 95%, it was obtained that there are no significant differences between the plant growing up on contaminated soil to that of on control soil. It is the existence of $^{134}$Cs on soil that does not affect plant growth.

3.2. The concentration of $^{134}$Cs on soil

The concentration of $^{134}$Cs in soil was decreased according to the time as caused by physically decaying of $^{134}$Cs beside of uptake by the plant (Figure 2). However, the concentration decreased contributed by the physical decay was small compared to the decrease caused by plant uptake.
Figure 2. The decrease of $^{134}$Cs concentration on the soil.

3.3. The distribution of $^{134}$Cs concentration on plant

The distribution of $^{134}$Cs concentration on the plant is shown in Figure 3. The $^{134}$Cs were detected on the plant on 25$^{th}$ days after a small plant was planted on contaminated soil. The highest concentration of $^{134}$Cs was found on leaves and followed by flowers, stem, and roots. The concentration of $^{134}$Cs in the stem was unstable. It is understood that stem is part of the plant that has transportation function, that carries the elements from roots to the leaves for photosynthesis process and then transports the photosynthesis products to the cells of the plants.

From the results of BALITSA (Balai Penelitian Tanaman Sayur/Vegetable Research Institute, Lembang, Jawa Barat) laboratory tests, it was found that the amount of K that can be exchanged (K available for plants) is 1.38 me/100 gr. According to the criteria issued by BALITSA, the K content of 1.38 me/100 gr is included in the very high category (>1 me/100 gr). As stated in the research of G. Zhu and E. Smolders, the mechanism of entry of Cs at high K concentrations is not yet known clearly [13]. The entry of the solution into the root is through the osmosis phenomenon. It moves from the root to the other parts of the plant because of the difference in the osmosis value between the solution and the cell wall.

Figure 3. The distribution of $^{134}$Cs concentration on the plants.
The activity of $^{134}\text{Cs}$ in roots is smaller compared to the accumulation in stems and leaves. This is because the content of $^{134}\text{Cs}$ found in the roots will be distributed to the other parts of the plant. Besides, the larger size of the stem and leaves will cause the accumulated power potential of the two parts to be higher than the root accumulation power.

In the stem, $^{134}\text{Cs}$ will be distributed through the xylem to the leaves. Water and other solutions are distributed through media called apoplast. On the leaves, enough elements or unneeded elements will be returned to the stem via the phloem. Cesium will metabolize the plants the same as potassium. Therefore if no more $^{134}\text{Cs}$ are needed, $^{134}\text{Cs}$ will be returned to the stem. This can be a cause of higher stem accumulation than root accumulation [14].

The process of transpiration in the leaves causes the minerals absorbed into the roots to move to the top of the plant. Leaves that are exposed to irradiate light will lose water through the stomata, cuticles, or through cell lines, which will soon be replaced by water molecules underneath. The process of increasing this water molecule also carries a variety of dissolved minerals, including $^{134}\text{Cs}$. The highest accumulation of power is found in leaves that also have a significant dry weight. In general, leaves have higher nitrogen, phosphorus, and potassium content than other parts [14]. Based on the statement, $^{134}\text{Cs}$ will tend to accumulate in the leaves rather than other plant parts as well as potassium. In potassium, leaves play a role in the process of opening and closing stomata. They are activators of many enzymes that are important in the process of photosynthesis and respiration[14].

In spinach plants, flowers emerge from the armpit of the leaves on the stem. Cesium, which is distributed by the stem to the leaves, can also be distributed to the flower. Therefore, at the flower, there is also an accumulation of $^{134}\text{Cs}$ activity even though the activity in flowers are smaller than other plant parts.

In Figure 3, it can be seen that the concentration of $^{134}\text{Cs}$ has a different distribution pattern with the activity of $^{134}\text{Cs}$. The sequential concentration of the largest is leaves > flowers > roots > stems. The concentration of $^{134}\text{Cs}$ in the stems and leaves tends to be unstable, which initially rises then falls and then rises again while the concentration on roots and flowers continues to increase.

The increase in concentration due to plants in their growth requires nutrients absorbed in the form of solutions from the soil, which also contain $^{134}\text{Cs}$ ions so that cesium ions can accumulate in plant tissues. However, in its development, the accumulation of $^{134}\text{Cs}$ was not comparable with plant growth, so that its concentration decreased.

The highest distribution of concentration is initially found in the leaves, after the spinach plants flower, the concentration in flower continues to rise and finally equals the concentration in the leaves. Concentration on leaves is high because leaves tend to store more potassium content than other parts. Potassium has many roles in the processes that occur in leaves.

As with potassium, $^{134}\text{Cs}$ will also experience the same metabolic process. Therefore the accumulation of the activity on the leaves tends to be proportional to its growth. Interest activity is smaller than the activity in other parts of the plant. However, because the flowers have the smallest dry weight, the concentration becomes higher and matches the concentration in the leaves. The concentration of $^{134}\text{Cs}$ in roots continues to increase. This condition indicates that the accumulation of $^{134}\text{Cs}$ at the root is proportional to its growth. The smallest concentration is found in the stem. In terms of activity, the stem has the second-highest activity after the leaves. However, the stem also experiences considerable growth so that the rate of accumulation of $^{134}\text{Cs}$ is not proportional to the rate of growth. In spinach plants, these stem parts have the highest weight when compared with other plant parts.

### 3.4. Transfer Factor (Tf)

The transfer factor is obtained by comparing the content of $^{134}\text{Cs}$ in plants after harvesting with $^{134}\text{Cs}$ in the soil. The amount of transfer factor from spinach plants at each sampling can be seen in Figure 4.

From Figure 4, it can be seen that the plant transfer factor has exceeded the number one in the $7^{th}$ sampling when the plant has reached the age of 57 days. The value of the transfer factor exceeding one indicates that the amount of cesium is concentrated in plants larger than cesium, which is concentrated in the soil. It can also be said that spinach plants at 57 days are accumulators of $^{134}\text{Cs}$. Distribution of
transfer factors in each part of the plant can be seen in Figure 4, that the most effective transfer factor or accumulator of $^{134}$Cs is the leaves and flowers. This condition is in line with the high concentration of $^{134}$Cs in both parts.

![Figure 4. Transfer factor in spinach plants.](image)

By definition, transfer factors are calculated after achieving saturation of concentration in plant tissues. Spinach plants have saturation concentration at the 11th sampling when the plant's age reaches 76 days. Transfer factors are calculated based on the sum of the transfer factors in each part of the plant at the 11th sampling. From Figure 4, it can be seen that the value of the transfer factor for spinach plants is 6.555.

Value of transfer factor $^{134}$Cs from soil to spinach plants for parts of roots stems and leaves when spinach plants can be harvested for consumption (54 days plant age) of 0.158; 0.074; and 0.295. These three values can be calculated as the value of the total transfer factor from the soil to spinach plants at harvest, which is equal to 0.527.

G. Zhu and E. Smolders suggested that transfer factors for vegetable crops grown on clay/clay generally ranged from 0.001-1, while in sandy soils or organic soils, transfer factors in vegetable crops could reach 28,1 [13]. From this statement, it can be seen that the transfer factor of spinach plants is classified as high (>1), even though TRIGA 2000 research reactor site soil is clayey clay and contains K, which can be exchanged in high amounts. Theoretically, judging from the soil characteristics, spinach plants that grow on the soil of the TRIGA 2000 research reactor of andosol type have a low transfer factor. However, obtained from this study, the transfer factor values exceed 1 (high).

The amount of transfer factors in plants is not only influenced by soil chemical characteristics, but also by plant physiological factors. Plants have genetic differences in their nutritional and mineral needs. Genetic variation in radiocesium absorption causes variations in the magnitude of transfer factors in various plant species[13,15].

Willey, N. J. et al., in their research report regarding the differences in absorption of $^{134}$Cs/ $^{137}$Cs between plant taxa, it was suggested that the highest cesium accumulation was found in spinach (genus Amaranthus) and compatriot mustard (genus Brassica) [16]. So indeed, the spinach plants used in this study have the potential as $^{134}$Cs accumulators.

4. Conclusion
Spinach plants can absorb and accumulate $^{134}$Cs from the ground. Radionuclide $^{134}$Cs are distributed and accumulated in all parts of the plant with the highest accumulation of leaves, roots, and stems.
The highest transfer factor is reached when the plant is 76 days old, with a total value of 6.56. Transfer factors for plant parts are as follows: 1.53; 0.89; 2.07; 2.05 each for roots, stems, leaves and flowers. While the transfer factor when spinach plants can be harvested is 0.527, with details of 0.16; 0.07; 0.29 for roots, stems, and leaves, respectively.

References
[1] Badan Pusat Statistik (BPS), Neraca Bahan Makanan Kota Bandung 2013. Penerbit BPS, Bandung. 2013.
[2] Butkus D., Luksiene B., and Konstadinova M., “Evaluation of $^{137}$Cs soil-to-plant transfer: Natural and model experiments”. Journal of Radioanalytical and Nuclear Chemistry, 279 (2): 411-6. 2009.
[3] Choi Y.H., Lim K.M., Jun I., Park D.W., Keum D.K., and Lee C.W. "Root uptake of radionuclides following their acute soil deposition during the growth of selected food crops." Journal of Environmental Radioactivity; xxx 1 – 6. 2009.
[4] Fujimura S, Yoshioka K, Saito T, Sato M, Sato M, Sakuma Y, Muramatsu Y., “Effects of applying potassium, zeolite, and vermiculite on the radionuclide uptake by rice plants are grown in paddy field soils collected from Fukushima Prefecture." Plant Prod. Sci. 16: 166-170, 2013.
[5] Fujimura S, Yoshioka K, Ota T, Ishikawa T, Sato M, Satou M., “The inhibitory effects of potassium chloride versus potassium silicate application on $^{137}$Cs uptake by rice”. J. Environ. Radioact. 153: 188-194, 2016.
[6] Greger M., “Uptake of nuclides by plants." Technical report. Stockholm: Swedish Nuclear Fuel and Waste Management Co, p. 13 -52. 2004.
[7] Gyrucza V, de Boul ois HD, Declerck S. “Effect of potassium and phosphorus on the transport of radiocesium by arbuscular mycorrhizal fungi”. J. Environ. Radioact. 101: 482-487., 2010
[8] International Atomic Energy Agency (IAEA), “Handbook of parameter values for the prediction of radionuclides transfer in temperate environments”. Technical Report Series No. 364. Vienna : IAEA, p.1- 34. 1994.
[9] Kang DJ, Ishii Y, Tazoe H, Isobe K, Higo M, Hosoda M, Yamada M, Tokonami S., “Remediation of radiocesium-137 affected soil using napiergrass under different planting density and cutting frequency regimes”. Water Air Soil Pollut. 228: 268, 2017.
[10] Kang DJ, Tazoe H, Yamada M, Ishii Y. “Differences in remediation effect of $^{137}$Cs in napiergrass (Pennisetum purpureum Schum.) under different land-use soil and cutting frequency conditions". Water Air Soil Pollut. 225: 2022, 2014.
[11] MALTZ J., “Compartmental Modelling”. Available form URL:http://www.berkeley.edu, [cited 2014 June].
[12] Sasmaz M., Sasmaz A. “The accumulation of stronism by native plants grown on Gumuskoy mining soils”. Journal of Geochemical Exploration 181, p. 236-242, 2017.
[13] Tjahaja, P.I., Sukmabuana, P. and Roosmini, D., “The EDTA Amendment in Phytoextraction of $^{134}$Cs From Soil by Indian Mustard (Brassica juncea).” Journal of Phytoremediation, Volume 17, Issue 10, Francis and Taylor. 2015.
[14] Wang D., Wen F., Xu C., Tang Y., Luo X. “The uptake of Cs and Sr from soil to radish (Raphanus stivus L.) – potential for phytoextraction and remediation of contaminated soils”. Journal of Environmental Radioactivity 110, p. 78-83, 2012.
[15] Willey, N. J., Tang, S., and Watt, N. R., “Predicting inter-taxa differences in plant uptake of cesium-134/137”, J. Environ. Qual. Vol. 34, 2002, 1478 - 1489. 2012.
[16] Zhu, Y. G. And E. Smolders. 2000. Plant Uptake of Radiocesium: A Review of Mechanisms, Regulation, and Application. Journal of Experimental Botany. Australia. 2000.