

EFFECTS OF POTASSIUM FERTILIZATION ON RADIOCAESIUM TRANSFER FROM SANDY SOIL TO BARLEY (*HORDEUM VULGARE* L.)

SM SOLIMAN, AHMED A MOURSY* AND HS EISSAB¹

*Soils and Water Research Department, Nuclear Research Center,
Atomic Energy Authority, P.O. 13759, Egypt*

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Abstract

Uptake and translocation of radiocesium artificially added to sand soil cultivated with barley as affected by different rates of potassium were traced in outdoor pot experiment. Experimental soil was contaminated with 0.01 and 0.1 mM ¹³⁷Cs equal to (200 and 400 Bq/kg) in the form of CsCl and incubated for 14 days prior to 150 days plant growth period. The transfer factor (TF) average values from soil-to-total biomass were found to range from 0.40 up to 0.53 as affected by interaction between tested treatments. Increasing K rates from 125 to 250 kg/ha markedly reduced the mean averages of TFs of ¹³⁷Cs from soil-to-roots by about 24 to 68%, respectively and from soil-to-total biomass by about 36 and 74%, respectively lower than corresponding control. In all cases, the discrimination factor was below unity, indicating that Cs is less efficiently absorbed from soil than its nutrient analogue K.

Introduction

Soil contamination with radiocesium has a long term radiological impact due to its long physical half-life (30 years of ¹³⁷Cs and 2 years of ¹³⁴Cs) and its high biological availability. Due to its chemical properties, ¹³⁷Cs is readily soluble in water, and, in solution, and more easily absorbed by plants than native stable ¹³³Cs in the soil because a part of the ¹³³Cs is in a soil structure where it is hard to replace with ¹³⁷Cs. Due to the chemical similarities with potassium, it enters the food chain pathway and may cause a health hazard to humans (Chino *et al.* 2011). Plant consumption, either as direct foodstuff or indirectly as animal foodstuff, is a major pathway for radiocesium incorporation. In fact, its content in foodstuff has been controlled since the Chernobyl accident happened, with temporary permissive limits for different foodstuff after an emergency (Hamada 2012). In the environment, radiocesium is mainly present in soil solution as a free hydrated cation (¹³⁷Cs⁺) with little or no tendency to form soluble complexes. Barley plant after maize and wheat contamination of the edible parts. The chemical-physical characteristics of the soil, root interception, ion uptake by roots, ion transport, ion translocation, remobilization of mineral nutrients, and root exudation are some of the factors affecting the transfer of radionuclides from soil to plants. The soil-to-plant transfer factor is regarded as one of the most important parameters in environmental safety assessment needed for nuclear facilities. This parameter is necessary for environmental transfer models which are useful in prediction of the radionuclide concentrations in agriculture crops for estimating dose intake by humans (IAEA 1994).

Transfer factor (TF) is defined as the ratio of radionuclide concentrations transfer vegetation and soil. The soil-to-plant transfer factor is an important parameter widely used to evaluate food chain transfer. However, for a number of long-lived radionuclides it varies by up to three orders of magnitude. This can be explained by chemical, biological, hydrological, physical peculiarities of the soil, or by variety of plant physiological processes (Ehlken and Kirchner 2002). Radionuclide

*Author for correspondence: <ahmad1a2m3@yahoo.com>. ¹Protection Department, Nuclear Research Center, Atomic Energy Authority, P.O. 13759, Egypt.

transfer depends on landscape and vegetation, and soil as well as on the amount of a radionuclide, its chemical properties and meteorological conditions during the fallout (Yoshida *et al.* 2004). It is well established that TFs vary widely among crops and soils, i.e., the values are region-specific, and soil-plant TFs decrease with time after contamination. Compilation of TFs of ^{137}Cs illustrates that they vary by 3 orders of magnitude for the same plant (IAEA 2009) even in controlled comparative studies that, for example, assessed the effect of soil properties only (Smolders 1997). Cesium uptake is inhibited when the potassium concentration in soil solution increases (Waegeneers *et al.* 2009). Thus, potassium fertilizers are effective counter measure, especially on nutrient poor soils with low K status (Smolders 1997) and low degree of base saturation (Rosén *et al.* 2011). Thus, the application of fertilizers containing potassium at elevated rates is one of the most effective countermeasures for reducing radiocesium uptake (Perepelyatnikov *et al.* 2007). The purpose of this work was to examine the concentration levels of ^{137}Cs and K application on the radiocaesium soil-to-barley plant transfer and uptake under sandy soil condition.

Materials and Methods

The experiment was carried out with outdoor potted plants in Soils and Water Research Department farm, Nuclear Research Center, Inshas, Egypt. Sand soil samples were collected from Inshas area at a depth of 0 - 30 cm. It was air-dried, ground and screened to pass through a 2.0 mm sieve. Chemical and physical properties of the experimental soil were determined according to Page *et al.* (1982) and the results are presented below. Some physical and chemical properties of the soil used.

A - Course sand 64.1%; Fine sand 26.4%; Silt 2.7%; Clay 6.8%; Textural class (Sand).

Cations				Anions			
Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	CO ₃ ²⁻	HCO ₃ ³⁻	Cl ⁻	SO ₄ ²⁻
1.25	1.00	0.32	0.09	----	0.88	1.25	0.53

B - Chemical properties of the investigated soil.

C – pH (1 : 2.5 soil suspension), EC (paste extract), organic matter (OM), total N (TN) ratio and CaCO₃ content.

pH (1:2.5) 2.5)	EC (dSm ⁻¹)	OC gkg ⁻¹	OM gkg ⁻¹	TN gkg ⁻¹	CaCO ₃ gkg ⁻¹
7.97	0.27	0.17	0.3	0.007	10.0

Liquid solution of 0.01 and 0.1 mM equal to about 200 and 400 Bq of carrier-free ^{137}Cs was added as $^{137}\text{CsCl}$, respectively and thoroughly mixed with 10 kg sand soil pot. The recommended field rate (100 kg / ha) equal to 41.67 mg/ pot of single superphosphate (15.5% P₂O₅) was added to the soils for each pot before sowing of barley seeds; while, (NH₄)₂SO₄ as a source of N was applied at rate of (523.2 kg /ha) equal to 218 mg/pot at two stages, one at early vegetative stage and the rest before flowering. K₂SO₄ (48%) was applied at rates of 125 and 250 kg/ha (equal to 52.08 and 104.17 mg/ pot soil were watered so as to reach about the water holding capacity. The treatments were replicated three times and the experiment was arranged in a completely randomized block design. At maturity, (day-150), plants were harvested and separated into roots; straw and grains. Soils from each pot were collected. Plant and soil samples were dried at 70 and 105°C, respectively, then ground, sieved and prepared for analysis. The dry weight of each part was recorded Cs⁺ and K⁺ concentrations in both crop and soil samples were measured using ICP

mass spectrometry. Measurement of γ -ray activities were made with a Nucleus-Tennlec apparatus with a 70.3 cm³ active volume of high purity Germanium detector, coupled to a nuclear data (ND) multichannel analyzer with Tc-243 amplifiers and ND, Analog-to-Digital Converter (ADC). In addition, a correction factor for random summing effects was calculated and applied following the procedure after Kratochvil *et al.* (1986).

The soil-to-plant (TF) is the index of the ability of a plant to take up or accumulate activity from soil. It can be obtained dividing the activity concentration in plants by the activity concentration in soil according to the following equation (IUR 1994).

$$TF = \frac{\text{(Activity of radiocesium in plant dry weight Bq/kg)}}{\text{(Activity of radiocesium in dry weight soil Bq/kg)}}$$

In order to examine the relationship between Cs⁺ and K⁺ ions in plants the discrimination factor was used, according to the following equation (Ciuffo *et al.* 2003). The Cs/K discrimination factor was defined as follows:

$$\text{Cs/K discrimination factor} = \frac{[\text{Cs}]/[\text{K}] \text{ in plants}}{[\text{Cs}]/[\text{K}] \text{ in soils}}$$

where [Cs] is Cs concentration (mg/kg) in plants and soils, and [K] is K concentration (mg/kg) in plants and soils.

Results and Discussion

Increasing activity concentration of CsCl traced with ¹³⁷Cs from 0.01 to 0.1 mM (200 to 400 Bq/kg) resulted in increase of ¹³⁷Cs content in different plant parts (Table 1). On the other hand, it tends to decrease with increasing K levels. Also, it is obvious that roots of barley plants accumulated more ¹³⁷Cs activity concentration than straw or grain. The concentration of radio cesium in barley plants was correlated with those in the soil. In this concern, the average values were 60.05, 27.81 and 10.19 Bq/kg for roots, straw and grains, respectively. ¹³⁷Cs content in the above-ground parts was increased with increasing ¹³⁷Cs concentration in the soil. The average activity concentration of ¹³⁷Cs reduced from 98.09 to 31.68 Bq/kg for total biomass, while, it reached from 192.91 up to 268.14 Bq/kg remained in soil with increasing K fertilization up to 250 kg/ha. The highest ¹³⁷Cs content of total biomass plant and those remained in soil were 139.09 and 260.91 Bq/kg, when ¹³⁷Cs was added at rate of 0.1 mM. In accordance, many previous physiological experiments have indicated that high K⁺ concentration in the rhizosphere could reduce Cs⁺ absorption by the roots in several plant species (Robison *et al.* 2009). This reduction was thought to be due to similarity of chemical properties of K⁺ and Cs⁺. Because they are both alkali metals, Cs⁺ is assumed to enter the root cells through the K transport apparatus, which is where the competition between these elements is thought to occur. Increasing K⁺ applied to soil from 125 up to 250 kg/ha caused markedly reduced ¹³⁷Cs content in different parts of barley plants in the presence of two levels of ¹³⁷CsCl. In this respect, the relative decrements of ¹³⁷Cs content were approximately accounted for 13 and 58.4% in roots; 37.5 and 78% in straw; 48.2 and 89.2% in grains less than control at rates of 125 and 250 kg K/ha, respectively. This may be attributed to the lower activity concentration for cereal grain than straw, since cesium behaves similar to potassium. Waegeneers *et al.* (2009) found that cesium uptake was inhibited with increasing potassium concentration in soil solution. Thus, the application of fertilizers containing potassium at elevated rates is one of the most effective counter measures for reducing radiocesium uptake (Perelyatnikov *et al.* 2007, Kobayashi *et al.* 2016). Marschner, and Marschner (2012) provided evidence for the presence of two distinct pathways for root K⁺ uptake. One system of low selectivity for Cs⁺, Rb⁺ and K⁺, a carrier mediated transporter, which operates at low external concentration of K⁺, probably driven by cation symport with H⁺. A second system highly selective

for K^+ , channel mediated, which operates at high external K^+ concentration. Also, lower ^{137}Cs grain: straw activity ratios in barley and wheat plants were reported earlier (Wu *et al.* 2009). The results suggested that ^{137}Cs plant uptake is better described when ratio of $^{137}Cs/K$ in soil is considered, because an increment of K concentration in soil inhibits ^{137}Cs uptake by the plant. This observation suggests an inhibitory effect of potassium on radiocesium uptake by plant roots. In addition, the concentration of radiocesium remained in soil contaminated with $^{137}CsCl$ was found to range between 142.91 and 354.57 Bq/kg soil, showing an approximately 40% variation between the upper and lower limits of the range. While, the average values of radiocesium concentration remained in soil was 192.9, 226.2 and 267.99 Bq/kg soil for 125 and 250 kg/ K kg, respectively.

Table 1. ^{137}Cs concentration (Bq/ kg DW) in barley plant parts, total biomass and soil as affected by $^{137}CsCl$ concentration (mM) and potassium levels (kg /ha).

$^{137}CsCl$ concentration (mM)	K rate (kg/ha)				
	0		125		250
	Roots				
0.01		37.90		25.19	15.20
0.10		82.20		79.10	34.82
Mean		60.05		52.15	25.01
	Straw				
0.01		15.12		6.73	2.70
0.10		40.59		28.00	8.81
Mean		27.81		17.37	5.76
	Grains				
0.01		4.07		1.60	0.40
0.10		16.30		8.90	1.80
Mean		10.19		5.25	1.10
	Total biomass				
0.01		57.09		32.52	18.30
0.10		39.09		116.00	45.43
Mean		98.09		74.26	31.82
	Soil				
0.01		142.91		166.48	181.70
0.10		260.91		284.00	354.57
Mean		192.91		225.24	267.99
LSD _{0.05}	Roots	Straw	Grains	Total biomass	Soil
K	5.85	8.33	7.57	8.83	3.83
Cs	20.22	8.17	11.56	12.25	15.95
K*C _s	0.907	11.02	2.24	4.60	4.70

^{137}Cs transferred to roots from soil has a TF average value of 0.29, and a range between 0.26 and 0.31 with increasing $^{137}CsCl$ concentration from 0.01 to 0.1 mM, respectively (Table 2). TF average value transferred from soil-to-total biomass was 0.47, with a range of 0.40 - 0.53, for the same sequence. While, transport or translocate of ^{137}Cs as an average values from root to straw, straw to grain and root to grain were 0.45, 0.33 and 0.16, respectively at 0 kg /K ha.

It was observed that radiocesium translocate values from root to straw was higher than from root to grains. It means that more than 55 and 67% of ^{137}Cs accumulated in the roots is due to its less translocation to straw and grains, respectively. In the same time, 33% of ^{137}Cs content in straw was transported to grains. In this regard, Sachdev *et al.* (2006) indicated that the highest level of fertilizer reduced TFs to cereals by up to 33% and to cabbage by about 50%. Similarly, Schuller *et al.* (2006) found that K fertilization reduced Cs TFs to Swiss chard, sweet corn and cabbage by 30 - 75% in one (the Umbric Andosol is a silty loam soil) and 60 - 75% in another (Dystric Fluvisol is a loam soil). So, transfer of ^{137}Cs from roots to straw or grains further depends on the biological properties of plant species, and not merely on the rate of the above-ground biomass growth. Higher plants possess the ability for accumulation of ^{137}Cs in roots or shoots, where the TFs of ^{137}Cs in plants are often less than 1 (Godyn *et al.* 2016). Increasing K rates from 125 to 250 kg/ha markedly reduced the TFs of ^{137}Cs from soil-to-roots by about 25 and 68% and from

Table 2. Transfer factor values for ^{137}Cs as affected by K (kg/ha) fertilization and ^{137}Cs (mM) levels added to sand soil cultivated by barley plants.

$^{137}\text{CsCl}$ conc. (mM)	Rate of K applied kg/ha				
	0	125	250		
Soil to root					
0.01	0.26	0.15	0.084		
0.10	0.31	0.28	0.098		
Mean	0.29	0.22	0.091		
Root to straw					
0.01	0.40	0.27	0.18		
0.10	0.49	0.35	0.25		
Mean	0.45	0.31	0.22		
Root to grains					
0.01	0.11	0.06	0.03		
0.10	0.20	0.11	0.05		
Mean	0.16	0.09	0.04		
Straw to grains					
0.01	0.27	0.24	0.14		
0.10	0.40	0.32	0.20		
Mean	0.33	0.28	0.17		
Soil to biomass					
0.01	0.40	0.19	0.10		
0.10	0.53	0.40	0.13		
Mean	0.47	0.30	0.12		
LSD _{0.05}	Soil-root	Root-straw	Root-grains	Straw- grains	Soil- biomass
K	0.066	0.16	0.082	0.13	0.15
Cs	0.34	0.051	0.075	0.03	0.11
K*Cs	0.011	0.11	0.044	0.04	0.12

soil-to-total biomass by about 36 and 74% less than the corresponding control for 125 and 250 kg K/ha, respectively (Table 2). The present results are consistent with previous findings revealed that the transfer factor of ^{137}Cs tended to decrease with increasing concentrations of potassium in

soils (Kratochvil *et al.* 1986). Also, Rosén *et al.* (2011) reported that K fertilizers can reduce the radio cesium transfer by about 40 - 60%, being more successful in the lower K^+ available in soil. The reduction effects are lasting and observable during long periods, after fertilization (Rosén *et al.* 2011). The inhibitory effects of K fertilizer on ^{137}Cs transfer from soil to barley grain are in agreement with the results obtained by Bogdevitch *et al.* (2008).

Application of $0.01 \text{ mM}^{137}\text{CsCl}$, in combination with 250 kg K/ha markedly decreased the translocation of ^{137}Cs to grains from straw and roots by about 51.52 and 48%, respectively. While, it was about 48.89% in ^{137}Cs transport from root-to-straw. But, at $0.1 \text{ mM}^{137}\text{Cs}$, the reduction in ^{137}Cs transport from straw and roots to grains was 75 and 59%, respectively. On the other hand, for the previous treatment, the decreasing in ^{137}Cs transfer from soil either to straw or total biomass plants recorded about 67 and 75%, respectively. It means that about 33 and 25% from the total concentration of ^{137}Cs in sand soil transfer to roots and total biomass, respectively. Whereas, at the low level of K (125 kg K/ha) with $0.01 \text{ mM}^{137}\text{Cs}$, the reduction in radiocesium transfer from soil to roots and to total biomass was 42 and 52% less than corresponding control, respectively. While, with increasing the concentration of ^{137}Cs ($0.1 \text{ mM}^{137}\text{Cs}$) added to soil at the same rate of K, the reduction in ^{137}Cs was 9 and 24% lower than control for the previous sequence. Fertilizing the soil with K^+ ions reduce cesium transfer into plants by as much as 60% (Lembrechts 1993). Despite its smaller diameter (K 0.33 and Cs 0.31 nm in radius), Cs^+ is taken up at a much lower rate than K^+ . Obviously, factors other than ionic diameter are involved in the uptake regulation; one of them being the affinity for membrane bound carriers, or channels (Marschner and Marschner 2012), also reported that high K concentration in soil acts as inhibitor and prevents Cs uptake. It is well accepted that K^+ uptake by plant roots is a consequence of two different, but parallel, mechanisms present on plasma membranes: (a) high-affinity energized transporter system and, b) low-affinity mechanism, usually associated with ion-channels.

Table 3. Cs/K discrimination factor values, in barley grown on sand soil.

^{137}Cs Cl conc.(mM)	Rate of K applied kg/ha		
	0	125	250
	Cs/K		
0.01	0.098	0.075	0.050
0.10	0.142	0.095	0.081
Mean	0.120	0.088	0.026

Due to the competitive interactions that occurred between Cs and K ions, the discrimination factor (DF), which is often used to evaluate a plant's efficiency to absorb nutrients from soil, was additionally estimated (Table 3). The obtained Cs/K (DF) values were found to range from 0.05 to 0.141 and varied among the treatments. $^{137}\text{CsCl}$ increased from 0.095 to 0.142 with increasing the applied $^{137}\text{CsCl}$ concentrations from 0.01 to 0.1 mM. While, it was found to reduce from 0.120 to 0.088 and 0.026 with rates of 0, 125 and 250 kg K/ha, respectively. Combined treatments of $^{137}\text{CsCl}$ and K fertilization, resulted in reduction % in Cs/K discrimination factor by 21 and 47% at $0.01 \text{ mM}^{137}\text{CsCl}$ concentration; while it was 33 and 43% at $0.1 \text{ mM}^{137}\text{CsCl}$ concentration less than corresponding control treatment when barley plants fertilized with K_2SO_4 at the rates 125 and 250 kg K/ha, respectively. The discrimination factor was in all cases below unity, indicating that K was better assimilated by barley plants than radiocesium. The present results are consistent with the results obtained by Niesiobedzka and Krajewska (2009). Also, Smolders *et al.* (1996) reported that the DF values ranged from 0.04 and 0.26 in spring wheat plants grown at different soil K

concentrations. Thus, it is possible that plants reject Cs^+ ions and absorb K ions, which are necessary for their growth. Moreover, the DF values indicated that K appears to be one of the main factors influencing plant mobility of Cs and behaves not only as a competitor to Cs ions, but also as an effective inhibitor of Cs uptake by plants (Table 3).

Results showed that root ^{137}Cs uptake from soil solution markedly decreased with increasing soil K application. At high dose, K (250 kg/ha) exhibits counteracting effects on Cs availability because it can mobilize exchange or water soluble reactions, while it also blocked ^{137}Cs through cation ^{137}Cs ion uptake by the roots. It is retarded by potassium application added to soil. In the root, cesium occurs mainly in the form of Cs^+ , as it is being supplied with the addition of $^{137}\text{CsCl}$ to soil. Barley plants grown on ^{137}Cs - artificially contaminated soil for 150 days showed a low soil-to-plant transfer factor (TF). Potassium application to sand soil was effective at the 125 and 250 kg K/ha level. Application of 250 kg K/ha resulted in (51%) reduction in ^{137}Cs transfer straw and up to (75%) to grain. The reduction in ^{137}Cs transfer to plant was markedly related to the amount of K content in organs. The TFs and Cs/K discrimination factor (DFs) were below unity, show inhibitory influence of K on translocation of ^{137}Cs process from soil to plant. It could be recommended that repeated annual potassium fertilization was an effective and practicable counter measure for reducing contamination of agricultural products by radiocesium. The major differences in the ^{137}Cs root uptake and further translocation into above-ground biomass are closely related to the level of soil radioactive pollution and K fertilization that should be considered in land use policy. The results showed that ^{137}Cs from roots and straw to grains in the presence of potassium fertilization is safe in environmental, also safe on animal and human.

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