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Uranium Sources, Uptake, Translocation in the soil-plant System and Its Toxicity in Plants and Humans: A Critical Review

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ABSTRACT

Uranium(U) is one of the highly toxic heavy metals and radionuclides that has become a major threat to soil health. There are two types of sources of Uranium in the soil system, natural and anthropogenic. Natural sources of uranium include rock systems and volcanic eruptions while anthropogenic sources include mining activities, disposal of radioactive waste, application of phosphate fertilizers, etc. Uranium accumulation impacts germination, early seedling growth, photosynthesis, metabolic and physiological processes of the plants. Through its accumulation in the aerial parts of the plants, Uranium finds its way to the human body, where it has deleterious health impacts. Different studies have identified the various sources of Uranium, explored, and explained the geochemistry of Uranium in soil, assessed the Uranium uptake and toxicity to the plants, and further studied the impact on human health. Most studies focused on two stages, either soil-plant or plant-human system. However, few studies have critically reviewed and summarized the U in the soil-plant-human system. Thus, the review has been designed to focus on the sources, geochemical behaviour, uptake, and translocation, plant toxicity, food chain entry, and finally, impact on human health. The relationship between the bioavailability of Uranium in the soil-plant system with soil properties like pH, Organic matter, and microorganisms have also been included. The study is further intensified by analyzing the accumulation of Uranium in various parts of the plants.

Keywords: Soil, Plant, Uranium, Translocation, Bioavailability, Health Impact.

INTRODUCTION

Uranium, a naturally radioactive element having an atomic number of 92 and an atomic weight of 238.03, was initially found as a part of pitchblende discovered by German Chemist Martin Heinrich Klaproth in 1789[1]. In its crystalline state, its valence varies from +3 to +6. Only the hexavalent uranyl compounds (UO_2^{2+}) are thermodynamically and kinetically stable in an aqueous solution for biological activities. Uranium forms various oxides, such as UO_2, U_3O_8, and UO_3. Uranates are made by fusing uranium with carbonates available on earth. Uranium, a very lethal environmental contaminant, has gained considerable attention in the field of research due to its chemical and radiotoxicity.

It has been discovered as a highly detrimental environmental contaminant for all living beings, including humans, and its chemical reactions and radiotoxicity make it a reason for toxicity to plants, animals, and humans[2,3].

Uranium is carcinogenic and a radioactive element[4,5] once its concentration increases above 0.05 mg/kg body mass[6]. When Organisms ingest U, it has a long-term chemical toxicity effect[7]. The entry of U into an organism via the food chain is hazardous[8]. The most common way for U to enter the body is via drinking water. The suggested permissible limit of uranium for drinking water is 30 μg/L, exceeding which could have long-term health consequences for humans[9]. Both anthropogenic and geogenic activities influence the sources of elements in groundwater[10-13]. Ingestion of groundwater containing high levels of U for a long time may affect bone and kidneys[14]. The bioavailability of Uranium is inversely proportional to its chemical state[15]. The presence of radiations in foods and plants is an concern as this leads to contamination of meals[16-18]. Humans are exposed to uranium mainly through the soil-crop system because it easily becomes a part of the food chain. So, this review is compiled to focus on biogeochemical behavior of U in soil-plant system and various impacts of this heavy metal.

Sources of Uranium

Natural U comprises three isotopes: U^{238}, U^{235}, and U^{234} [19]. It contains about 99.283% of U^{238} by weight and rest U^{235} and U^{234} [20]. U^{238} has a half-life of 4.5×10^9 years and is an exceptionally long-lived isotope. Uranium is a radioactive element found in all types of soils, rocks, and water sources[21]. Uranium comes from both natural and anthropogenic sources (Fig. 1). Weathering of the rocks and volcanic eruption is considered the primary sources of natural U in soil[22,23]. Other sources of Uranium includes mining, extracting and purifying ore, coal ash generation, phosphate fertilizer production, and waste from nuclear power plants[24]. Wang *et al.,* 2019 concluded that mining is the primary anthropogenic source of U contamination in soil and water[25]. With ever exploding global population increase, this anthropogenic content of U will increase in the future due to higher demand for minerals, electricity, and food[8,26-28].

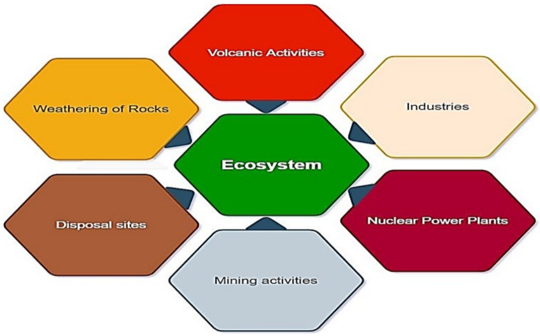

Fig. 1. Uranium sources in the ecosystem

Distribution and sources of Uranium in soil

Uranium concentration and radiation strength in the soil of different countries varies highly, as shown in Table 1[29-31]. Highest concentration and radiation of Uranium in the soil was found in Portugal (25.10 mg/kg and 311.24 Bq/kg respectively). The average amount of uranium in the earth's crust is about 2.82 mg kg^{-1} [32,33]. U can also leach or accumulate in specific soil profile horizons during the weathering process. Acid leaching is considered a significant factor in the distribution and mobility of Uranium in the soil profile[34]. Sequestration and reduction are considered the primary factors for the high level of Uranium in soil rich in organic matter[35,36]. U is retained in tropical environments in red soils due to its affinity for iron minerals[34,37]. The source of contamination of Uranium varies greatly. A certain amount of Uranium is found in the coals[38-45], mining, extraction, and disposal of U-containing products or their by-products are considered the anthropogenic sources of U contamination of soils[46,47]. Phosphorous fertilizers made from natural rocks in agriculture are another potential source of U enrichment in soils[48]. The average value of U in such fertilizers is 100 times higher than in soils[49,50]. The pollutant's source and the intended use of the contaminated soil determine the concentration levels that are considered harmful. mobilization and transportation of water in vertical directions and at the surface depend on contaminated soil[51]. Irrigation with U-contaminated water has also increased natural uranium in agricultural soil[52,53].

Factors affecting Uptake of Uranium by plants

The migration, uptake, and accumulation of minerals from the soil to the plant is a complex process involving runoff, capillary rise, leaching, sorption, and root uptake. The availability and uptake of essential macro and micronutrients like nitrogen, potassium, and zinc by plants influence the uptake of non-essential components. The term "bio-availability" refers to a chemical element's tendency to adhere to or move across an organism's cell surface[54]; hence it determines how much concentration of essential and non-essential elements will be taken up by plants. Uranium uptake by plants is generally confined to the dissolved fraction in the soil, suggesting there might be lesser availability of uranium to plants. The uranyl ions are the only plant soluble and available fraction of U. Plants receive all macro and micronutrients from the soil through the movements of ions from the soil solution to the roots, including the uranyl ion. The translocation of U and other radionuclides is influenced by soil factors such as soil characteristics, climatic conditions, plant type, plant part concerned, the physicochemical form of the elements, and the presence of other elements influences the transfer factor values as well[55,56].

Concentration of Uranium in Soil

For uptake and accumulation of Uranium by the plant, it must be available in the soluble fraction of the soil; hence, the concentration of all elements, including the radionuclides and the intake of heavy metals inside the plant, is directly proportional to the concentration in the soil solution[57]. The potential risk for uranium uptake and intake from different sources is higher for individuals who consume food grown in areas having soil with high concentrations of uranium because of its greater availability and absorption by plants[58].

Soil pH

The availability and solubility of minerals and metals, including radionuclides in soils, depends on the soil's pH. Different studies have concluded that the mobility and bioavailability during interaction with different soils are affected by pH[59]. Heavy metal cations at neutral pH are strongly bounded to the soil minerals and hence are not bio-available. Since Uranium forms strong insoluble compounds, therefore it has low biological mobility at high pH, however, at low pH increases in heavy metal adsorption and hence increase in the concentration in plant parts are observed[61-63]. Therefore, due to high metal bioavailability in highly acidic soil, metal toxicities are often observed in plants growing in such soil[64]. Soil pH of less than 5.5 is required to convert U to its most plant available form in soil[61], as some ions in soils get adsorbed on oxides at low soil pH. So, the solubility of these cations and anions can be decreased by dissolving the Fe-, Mn-, and Al-oxides, which releases bound or adsorbed metals into the soil solution[62,64].

Organic matter in the Soil

The mobility of Uranium depends on organic components present in soil[65]. Abdel-Haleem *et al.,* (1997) found that organic wastes (biosolids) and municipal solid waste addition to soil increased the absorption of U in corn and sesame[66].

Uranium speciation

The mobilization and the solubility of uranium in both biotic and abiotic systems are a very complex process influenced by the uranium species present[67]. The soil properties, especially pH and soil type, greatly influence U speciation[61,68,69] and are considered the key factors altering U uptake by plants. U(VI) is the most mobile and soluble form of U in soil[70]. U(VI) is present in solution mainly as UO_2^{2+} and soluble carbonate complexes[71,72]. U(VI) exists primarily in hydrolyzed forms at a pH range of 4-7.5[73].

Soil type

The uptake of Uranium in the soil-plant system is not only confined to the bio-availability, but the several soil characteristics also help and influence the uranium sorption, subsequent desorption of metals, and uptake in plants[74]. Ramaswami *et al.,* (2001) discovered that the efficiency of uranium extraction in hydroponics and two different soils (sandy-loam and organic-rich soil) reduced sharply from hydroponics to sandy and then organic soil, indicating that soil organic matter sequest uranium, making it largely unavailable for plant uptake[75].

Soil Chelates

The presence of Chelates increases the accumulation of Uranium[63]. The Chelates available in the soil bind metals and acidify the soil solution, increasing the bioavailability that aids in the translocation of metals from root to shoot[76]. Citric acid has a high rate of environmental degradation, making it the most eco-friendly chelate for phytoextraction[62].

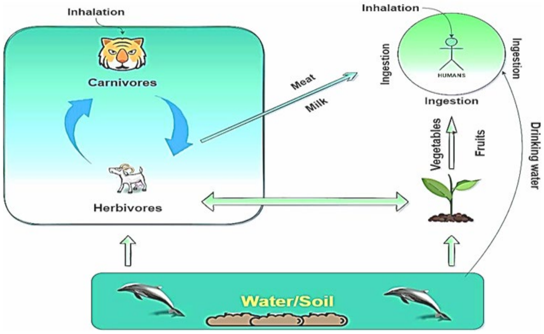

Fig. 2. Uranium cycle in water-soil-plants-humans

Table 1: Comparison of Uranium concentration and radiation in soils of different countries

Sr. No	Country	U^{238} mg/kg	U^{238} Bq/kg	References
1	India	11	54	[77]
2	England	2.6	32.24	[77]
3	Malaysia	9.43	117	[78]
4	Greece	2.25	28	[79]
5	Turkey	1.11	13.8	[80]
6	Pakistan	3.62	45	[81]
7	Germany	1.90	23.56	[82]
8	Portugal	25.10	311.24	[83]
9	Spain	13.5	167.4	[84]
10	Japan	1.74	21.57	[85]
11	USA	3.50	43.4	[86]
12	Chile	0.79	9.79	[87]
13	Canada	1.20	14.88	[77]
14	China	3.13	38.81	[88]
15	Europe	2.46	30.50	[89]
16	World	2.82	35	[33]

Traslocation of Uranium in Plants

U(VI) salts as UO_2^{2+} and carbonate complexes are the most mobile form of Uranium[71,90] while Other forms are less bioavailable and hence remain confined to soil particles. The Mycorrhiza fungi (Glomus genus), because of their high binding capacity for heavy metals, including Uranium, enhance their immobilization and significantly increase their plant uptake[55,91,92,93]. Fungal mycelium via fungal tissues helps transport uranyl cations to roots[91,94]. This has been proven by an experimental study done on *Medicago trunctula* cv. Jemalong plants in comparing treatments with and without the presence of the mycorrhizal fungus Glomus intraradices[55]. It was also concluded that experimental plants infected with the fungus have higher U uptake by roots. In the inoculated plants, the concentrations of uranium in stems were higher, indicating that mycorrhizal root colonization increased U uptake. Organic acids also stimulate the phytoextraction of U[62]. U uptake is also likely related to plant iron content[95]. Gunther *et al.,* (2003) showed that Uranium is most likely bound to phosphoryl groups as uranyl (VI) phosphate[96]. Various growth anomalies and the highest concentration of Uranium in the stems of Capsicum annum Cucumis in experiments conducted on Capsicum annuum and Cucumis sativus plants treated with uranium nitrate salts[97]. Plants can absorb these elements in water-soluble forms, which are distributed from roots to aerial parts. While U contents greater than 3 mg/kg in tissues dry mass has been observed in some plants like Uncinia leptostachya and Coprosma Arborea (Mamangi)[98,99].

Root to shoot Parts translocation

Accumulating uranium in root parts via soil or water takes place through penetration into the shoots and leaves (Table 2 and Table 3). In various plant species, such as sunflowers[100], *Pisum sativum* L.[101], *Nicotiana tabacum* L. [102], maize, wheat and pea[72], carlina corymbosa[103], sweet potato[104], mustard[105] U in roots and stem parts has been observed. Its translocation in the upper parts of the plants, including *Sesbania rostrata*[106], Water lily[107], *Bidens pilosa* L[108] depends on the potential of U in soil and gene expression in plants[109-111]. Generally, the translocation of U from roots to the upper part of plants depends on three mechanisms, i.e., sequestration into root cells, symplastic transport among the central part of the plants, and its release through xylem[112-114]. Uranium is transported after the formation of U chelates, i.e., UO_2-citrate- and UO_2-lactate in xylem tissues[111]. In the symplastic process, U ions from roots transfer to xylem vessels, probably due to transpiration[115,116]. The selective permeability of the cell plasma membrane also regulates the Uranium transport through Membrane transport proteins[116,117].

Uranium toxicity

Uranium toxicity to plants

Uranium is toxic to plants, and factors like organic acids (citrate, tartrate, and oxalate), phosphate content, and polyamines affect its bioavailability[118-120]. The cultivation substrate and its nature also influence the amount, distribution, movement, and toxicity level of Uranium in tobacco plants[102]. At various pH levels, U has a considerable impact on Arabidopsis thaliana's photosynthesis pathway[118]. Since uranium is a toxic element for plants, it hinders the various physiological and biochemical processes like seed germination and photosynthesis. In addition, it causes damage to the structure of DNA and blocks the process of mitosis. Plant toxicity is mainly due to their environmental conditions, uranium concentration, and types of species[72,108,121].

Table 2: Uranium uptake by different plant species during pot experiment

Plants	Roots (mg/kg)	Shoot (mg/kg)	Uranium Treatment (mg/kg)	References
Sesbania rostrata	20.61	23.74	80	[106]
Juncus bufonius	39.9	2.5	135	[103]
Maize	32.01	3.50	50	[72]
Sunflower	136	4.08	82	[100]
Italian Ryegrass	800	290	150	[122]
Wild ramie	721.46	35.88	7.98	[123]
Zebrina	20.91	1.23	15	[124]
Juncus squarrosus	227	1.1	250	[103]
Mustard	7145	380	47.74	[105]
Carlina corymbosa	134	0.9	149	[103]
Macleaya cordata	36.8	12.5	18	[125]

Effect on Germination

Germination under U stresses vary from plant to plant as each plant tends to tolerate some level of U concentration. The results obtained from the germination of cleome amblyocarpa Barr. & murb seeds showed increase in the germination upto 200ppm, and after that decrease at higher concentrations was noticed (250ppm and 300ppm)[126]. In case of three vegetables (tomato, spinach, and cabbage) germination was inhibited at 320ppm, whereas in cucumber, it was inhibited at 1280ppm[127]. Similar types of results were observed in cynodon dactylon (Bermuda)[6] and aristida purpura (purple Threeawn)[128]. U concentration lower than 100ppm did not affect the germination of maize seeds but at higher concentrations a reduction to 80% and 63% in germination percentage has been observed at 500ppm and 1000ppm, respectively. This might be because at a lower concentration of Uranium, some enzymes promote seedling growth, or the net photosynthetic rate increases and thus enhances seed germination[126]. When the U concentration reaches the maximum limit of tolerance power of the seed, its metabolic activities get disturbed and damage the DNA structure of plant cells, thus decreasing the rate of seed germination[7,127,132].

Table 3: Uptake of Uranium under hydroponics conditions by different plant species

Plant species	Roots (mg/kg)	Shoot parts (mg/kg)	Hydroponics (umol/L)	References
Sweet potato	2216	6.67	25	[104]
Purple sweet potato	5712	3.48	25	[104]
Water lily	1538	3446	55	[107]
Nicotiana tabacum L.	82000	357	500	[102]
Wheat	12000	28	100	[129]
Pea	44000	21	100	[129]
Maize	29737	6	100	[129]
Indian mustard	36541	122	100	[129]
Arabidopsis halleri	3500	170	-	[130]
Arabidopsis thaliana	50352	15	50	[131]
Bidens pilosa L.	728	809	1000	[108]

Uranium treatment on the seeds has an adverse effect on mitotic cell division. Furthermore, it leads to chromosomal cell defects[133]. According to a study conducted on the *Vicia faba* a decrease in the mitotic index has been observed on the root tip cell[134]. It was found that uranium adversely affected the germination rate and seedling growth, and the level of toxicity depends upon the physiological state and selective permeation of different metal ions through tissues surrounding the embryo and hence determines the toxicity. Seedling growth is severely inhibited at a much lower concentration of heavy metal. The early visible symptoms of toxicity are disturbances of germination and change in leaf color, and germination percentage is negatively correlated with uranium concentration[135].

Effect on Photosynthesis

Heavy metal stress is already known to affect photosynthesis, resulting in decreased plant growth, delayed plant development, and sometimes plant death[136,116]. Reducing chlorophyll content is one of the harmful effects of exposing plants to various metals[137]. Reductions in the chlorophyll a and chlorophyll b content due to the toxic effect of uranium has also been observed in different plant species such as *Bidens pilosa* L.[108], *Arabidopsis thaliana* or Thale cress[131], *Pisum sativum* L. is also called garden pea[143], *Triticum aestivum* L.[139], *Leptochloa fusca* L.[140], *Nymphaea tetragona* Georgi[107], *Pisum sativum* L.[101] and Green broad bean[38].

According to Shtangeeva and Ayrault, U treatment increased light's coefficient of reflection (CR) at spectral channel 0.38-0.63m, indicating a low chlorophyll content in the plant[141]. This decrease in chlorophyll biosynthesis is because of the replacement of Mg^{2+} ions by $(UO_2)^{2+}$ [142]. Uranium toxicity may disrupt the first step in glycolysis by replacing magnesium with uranyl in the enzyme[143]. Jagetiya and Purohit (2006) have also observed a gradual and contrasting reduction in the chlorophyll a, b and total chlorophyll content with increasing uranium concentration[144].

Effect on Plant Physiology

Since uranium accumulates in plant roots, shoots adversely affect plant physiological parameters. The root and shoot length decreased significantly in Arabidopsis thaliana at 50uM U[145], duckweed at 50 uM solution of uranium[146], and broad bean at 25uM U[147]. A decrease in root shoot fresh weight of Phaseolus vulgaris at 1000 uM U has been observed[143] and in the weight of fresh leaves at 100uM U in Thale cress[148]. In Ryegrass, maize, radish, and cabbage, the length of root and dry mass and stem height decreased significantly at 150mg/kg, 500mg/kg, and 2560 mg/kg Uranium, respectively[72,127,122].

Uranium toxicity in human

The natural uranium isotopes 234U, 235U, 238U) decay to emit alpha, beta, and gamma rays, presenting both chemotoxicity and radiotoxicity effects in humans[149]. Uranium can enter the body in three routes: inhalation, ingestion, and absorption through intact or damaged skin[150]. Various anthropogenic activities like nuclear power plants, military practices led to the formation of suspended uranium in air. Thus it can easily inhaled by humans and its radiotoxicity directly affect at the cellular, subcellular and protein levels, similarly it also affects kidney[151]. Human beings also exposed through environmental uranium from ingesting water or food in natural uranium-contaminated areas[152].

Hence consumption of food, especially vegetables, fruits, cereals, and table salt, is the primary source of Uranium in the human body[153,154]. Cothern and Lappenbusch (1983) conducted study and found that food contributes 15 percent of the ingested U, while on other hand drinking water contributes 85% of Uranium[155]. The solubility of the uranium from consumed food affects the gastrointestinal absorption of uranium, with a variation in absorption rate from 0.1-31%[156-159].

Uranium entry through contaminated water finds its way directly into the human bloodstream and has a negative impact on human health. The daily Uranium intake is estimated to be 1-2 µg and 1.5 µg from food and water, respectively[160]. The human body contains an average of 56 µg Uranium, attributing 32 µg (56%) to the skeleton, 11 µg to muscle tissue, 9 µg in fat, 2 µg in blood, and less than 1 µg in the body organs like kidney, lungs, etc.[161]. Abnormalities in the gene, gulf war syndrome, infertility, and neurotoxic effects, occur due to Uranium in the human body[162]. Accumulating Uranium causes lung, bone, and thyroid cancer in humans. Sometimes higher intakes result in acute renal failure and even death[163-165]. Its concentration builds up in the human body's organs and tissues, posing various health risks[166,167]. It causes chronic problems with the liver, kidneys, and bones[168-170]. The absorption of uranium into blood as an uranyl anions which further complexed with proteins (such as transferrin, albumin, or bicarbonate anions, etc[171]. The two main target organs of U are kidney and bone. More than 80 percent of the Uranium is eliminated from the blood compartment via urethral excretion. The main target of Uranium in human cells is mitochondria which ultimately leads to apoptosis. The geological origin of soils, groundwater, and flora's living area has a significant impact on U transfer (Fig. 3) to the human food chain[172].

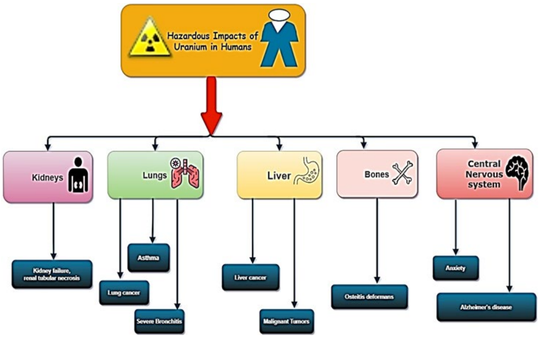

Fig. 3. Hazardous effect of Uranium on human health

CONCLUSION

Natural radioactive minerals uranium is found int in rocks, soils, and water. But with increased industrialization and population explosion, its environmental concentration is rising. Although Uranium is not necessary for plants, it is taken up by the plants along with specific essential metals like Zn, Ni, Ca, and Cu. At a lower concentration, it does not pose any harm to plants. However, if the concentration of Uranium reaches its threshold level, in that case, it causes direct toxicity causing damage to the plant by disturbing the cell structure (due to the production of reactive oxygen species causing oxidative stress), and it also inhibits several cytoplasmic enzymes. The uptake, retention, movement, and distribution profile of radionuclides in plants is strongly affected by the soil properties like pH, organic matter contents, soil characteristics, climatic conditions and, also by plant type, plant parts, the physicochemical form of the U and soil amendments such as fertilizer and chelate application. Transfer Factor (TF) estimates the quantity of Uranium taken up by plants from the substrate. The U taken up by plants is translocated to the others parts of the plant. However, the concentration of U in different parts of plants follows the trend of roots>shoots>leaves. It adversely affects the germination of seeds and early seedling growth in plants. Uranium treatments in plants negatively affected the mitotic division and caused chromosomal abnormalities in seeds. Plant yield, shoot growth, root growth, and dry matter of plants are significantly reduced due to Uranium uptake. So, it can be concluded that Uranium absorption by plants from contaminated soil directly impacts plant development and yield and finally leads to the food crisis. Consumption of contaminated plant parts is the primary source of Uranium entry into the human food chain, and it represents a high potential risk to human health due chemical toxicity of Uranium.

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Conflict of interest

The authors declare that there is no conflict of interest.

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