STATE-OF-THE-ART REVIEW ON STRONTIUM TOXICOKINETICS, MECHANISTIC RESPONSE, ALTERATIONS AND REGULATIONS

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ABSTRACT: Strontium is mostly present in oil, coal, soil and rocks in the form of isotopes of four types ^{84}Sr, ^{86}Sr, ^{87}Sr and ^{88}Sr. It resembles the chemical form of calcium and even replaces the position in bones and other places where calcium finds its importance in the human or animal body. Strontium, if exchanged with calcium in greater quantity, can cause serious effects like cancer in bone and its neighbouring tissues and necrotic lesions. However, the effect is negligible when the exchange is lesser. If present in the geo-environment, strontium compounds in both forms stable or radioactive percolates in the groundwater, but a majority of this compound present in soil remains undisturbed for a considerable amount of time. The permissible amount of strontium which can be acceptable in water according to the US Environmental Protection Agency (USEPA) is 4 mg L^{-1}. Further presence of strontium up to 240 mg kg^{-1} in soil is considered as less toxic to grownups not suffering from malnutrition. Anthropogenic and natural activities leading to the release of strontium in the atmosphere pose a chance of transportation and deposition by the wet deposition method. The natural treatment of strontium by biodegradation or hydrolysis does not decay atoms of strontium due to its form. This paper deals with the chemical and physical properties and toxico-kinetics of strontium. Moreover, few points pertaining to health of flora and fauna when it is in direct contact with strontium and the safety concerns with relevant regulations are discussed.

Keywords: Adsorption; Calcium; Desorption; Kinetics; Radioactivity; Strontium; Solubility; Toxicity

1. INTRODUCTION

Atomic explosions produce a lot of contaminants which affect the biosphere and one such is strontium-90 (^{90}Sr). ^{90}Sr enters the biosphere initially through nuclear weapons of heavy (megaton) intensities which deposits ^{90}Sr in the stratosphere [01]. After staying in the stratosphere for a span of 10 years, it further moves to the troposphere. On contrary, the emitted ^{90}Sr by the use of smaller (kiloton) weapons directly gets deposited onto the troposphere (Refer fig. 1). It is observed that the kiloton deposits are found in the vicinity of its origin whereas the debris of "megaton" is found in many parts of the world. The soil and foliage are receivers of ^{90}Sr and the grazing animals take in ^{90}Sr through the following routes (i) from the surface of the foliage (ii) through tissues of plants which is absorbed through foliar absorption and further gets mixed with plant calcium in variable levels, and (iii) through root absorption of plants which reach to the plant tissue analogous to the labile calcium in the soil as shown in the Fig. 1. Route (i) has the least amount of ^{90}Sr which is diluted in calcium while the maximum occurrence is in route (iii). The above mentioned three routes are time-dependent and significance of the route (i) and (ii) becomes less when the reduction of fallout takes place due to no recent radioactive contamination in comparison with route (iii). There are two major issues which grab attention in the study: (i) How much human population is inclined to ^{90}Sr in the present and future? (ii) what is the optimum quantity which may cause damage to human beings [02,03].

It becomes a matter of concern when traces of ^{90}Sr alters its analogue element i.e. calcium in the food chain. Since it is absorbed by the flora and fauna like any other essential ingredient; eventually it gets deposited in the bones; and finds its way to the mother's milk and even to the developing foetus. Diseases like leukaemia and tumours in the bone are suspected to be an outcome of ^{90}Sr [04].

A classic case study of Sr mobility was done starting from Bengal basin to the Bay of Bengal it showed that the Himalayan ranges, which are the primary source of Sr, reaches the Bay of Bengal through its numerous rivers in the North Indian plains. Measurements of water samples collected from different points of the Bay of Bengal suggest that the submarine groundwater discharge flux (SGD flux) of Sr was 13.5–40.5×10^5 mol yr^{-1}.

Further, comparing with the other oceans such as Atlantic, Pacific and Indian oceans, it was found that surface seawaters show similar concentrations of Sr which were lower than the deeper portions of the seas and the shores had relatively lower concentrations of Sr. In this view, Chakrabarti [05] have concluded the SGD flux plays a major role in Sr mobility in the oceans.

1.1 Strontium Exposure - Plants and Animals

Strontium compounds are also found in the air, which might be due to the combustion of fossil fuels like coal and/or, oil. For example, on an average 20 ng cm^{-3} of Sr are found in different parts of the United States. Although, most of the Sr in air, soil and water are found to be stable however the strontium present in air gets settled down and eventually finds itself in the bottom of lakes, rivers or ponds [06-07]. This is the final destination, where strontium finds itself will be a host to both stable form and radioactive form which eventually gets dissolved in water. Often, the colloidal form of Sr has been determined in the water bodies, whereas less than 1 mg L^{-1} or 0.1 pCi L^{-1} (0.004 Bq L^{-1}) has been determined in the United States. Further, the runoff/percolation of Sr-containing water into streams through the rocks and soils, acts as the major hosts for strontium via absorption/complexation of metal ions [38-39].

In addition, dumping of coal ash, incinerator ash, and industrial wastes pave the way for increase in the quantity of Sr in the soil, in spite of this the amount of Sr is very small and is only a fraction of the total concentration of strontium in soil. But at hazardous waste disposal sites, radioactive waste sites, and Department of Energy facilities located around the United States it has been reported to have higher concentration of Sr. Further, it was reported that the ground water is also very prone to be acquainted with Sr through movement of the surface water to the deeper levels of the ground that join the ground water. However, the compounds of Sr may be undisturbed in the soil for years without moving to the ground water the reason for this can be the effect of the environment which can be a chemical reaction that converts Sr into insoluble forms such as precipitates, also the reverse of this has also been observed due to various changes occurring in the environment [38].

Sr can be omnipresent in minute quantities and any individual can be exposed to low levels of the same through breathing or through consumption of food or water or by soil coming in contact with the digestive system. The largest sources of Sr exposure are found to be food and water. The fishes, livestock, vegetables, grains and even dairy products host strontium to a considerable extent and this gets conveyed into the life cycle of human beings. The fresh vegetables grown in the US may have less than 9 pCi or 0.3 Bq in 1 kg of oven dried vegetables [8]. Cabbage grown in US is an example in which the quantity of strontium is less than 64 mg kg^{-1} [8]. Usually the intake of strontium is moderate and it can be consumed by people through the vegetable grown in the waste site laced with radioactive strontium [9].

2. DETERMINATION OF STRONTIUM TOXICITY

In the evaluation of ^{90}Sr levels in the biosphere, there is considerable advantage in dealing with ^{90}Sr to calcium ratios rather than with the absolute amounts of ^{90}Sr entering or leaving an organism [03]. Since the main intake of ^{90}Sr into the life cycle of humans is through the food intake laced with ^{90}Sr, because of the affinity of Ca towards ^{90}Sr makes it easy to replace Ca by ^{90}Sr in our body [10]. In order to monitor the presence of Sr, the ratio of dietary intake of the calcium and strontium paves the way to the proportions of strontium-to-calcium ratios in the animal tissues and bones, when the calcium concentration in the tissue is known then ^{90}Sr to calcium ratio helps to calculate the level of contamination. Hence the question arises to identify the level of ^{90}Sr to calcium ratio in the human population as compared to the presence of the same in dietary intake. Further, it was noticed that these two parameters affected the ^{90}Sr to calcium ratio of the vegetation and in turn the overall effect of the same due to the quantity of ^{90}Sr hosted by the ground surface. The series of physical and physiological processes govern the differential behaviour between the ^{90}Sr to calcium ratio in the body and that deposited on the soil under steady state conditions [04,11].

The sources of the reservoirs of calcium are the animal bones, milk, vegetation and upper layers of the water and soil. The level of dilution in various stages of food chain is also a governing factor for the amount of differential behaviour of calcium and strontium. The vulnerability to the ^{90}Sr to calcium ratio for new born babies is as high as 25 (Sr/Ca ratio) and that for adults is 6 which can be ascertained by the differential behaviour discussed earlier and the effects also depend on the food habits [03].

2.1 Prevention and Protection from Strontium Exposure

Generally, physician may approach the state health department to investigate that people are being exposed to strontium at serious levels. Exposure of children to lot of dirt may make them vulnerable to the ill effects of ^{90}Sr, hence avoiding direct contact with the soil, washing hands

frequently and before consuming food helps in reduction in intake of ^{90}Sr.

Discouraging children from putting their hands in mouth helps in reduction of intake of ^{90}Sr especially near a hazardous waste site. Balanced diet with sufficient vitamin D (12 -29 ng mL^{-1}),

calcium (8.5 – 10.2 mg dL^{-1}) and protein (1 g kg^{-1} body weight day^{-1}) will be protective by reducing the amount of ingested strontium that is absorbed [02,12].

Table 1 Speciation of Cu, Cr and Sr at different pH values

Type of ions	pH	Reaction	End product
Cation	0 – 5.5	$Cu^{2+}+OH^- \rightarrow [CuOH]^+$	Coppermono hydroxide
Cation	>7.7	$[CuOH]^++OH^- \rightarrow Cu(OH)_2$ or $Cu^{2+}+2OH^- \rightarrow Cu(OH)_2$	Cupric hydroxide precipitate
Cation	0-2	$Cr^{6+}+3e^- \rightarrow Cr^{3+}$	Trivalent chromium ion
Cation	2-6	$Cr^{3+} + OH^- \rightarrow [CrOH]^{2+}$	Chromium mono hydroxide
Cation	6-8	$[CrOH]^{2+} \rightarrow [Cr(OH)_2]^+$	Chromium di hydroxide
Neutral charge	8 - 10	$[Cr(OH)_2]^+ +OH^- \rightarrow Cr(OH)_3^0$	Chromium tri hydroxide
Anion	10 - 14	$Cr(OH)_3+OH^- \rightarrow [Cr(OH)_4]^-$	Chromium tetra hydroxide
Cation	13.5	$Sr^{2+}+OH^- \rightarrow (SrOH)^+$	Strontium hydroxide

3. MECHANISTIC RESPONSE FOR STRONTIUM REMOVAL IN SOILS

Strontium removal in water and waste waters, its response to various sorbents along with mechanisms involved in Sr treatment have been highlighted in this section. A number of sorbents (based on carbon and non-carbon) have been evaluated for removal of Sr in soils [13]. The efficiency of sorption or a material which can remove or retain the highest amount of Sr is determined through some common parameters either experimentally or projected analytically using a number of empirical, semi empirical and mechanistic models that predict the best sorbent material [14, 38, 39]. Predominantly, Langmuir and Freundlich isotherms for monolayer and heterogeneous sorption are tested.

Further, evaluating the material, based on thermodynamic equations and extending it to lagergren pseudo orders, such as first order and second order equations which to a certain extent ascertain physic sorption for pseudo first order and physico and chemical sorption through pseudo second order. The long-term reliability of sorption is validated through Elovich equation which shows trends in terms of chemisorption [14, 40]. Since, diffusion is also an integral part of sorption process whereas intraparticle diffusion model predicts whether sorption takes place through pure sorption

or diffusion. It quantifies the predominance between sorption and diffusion. Even after having a refined literature on sorption there remains a major challenge to understand sorption onto heterogeneous materials such as soils, which are the major component on the earth's crust [15,16].

In the sorption processes pH of the media plays an important role in evaluating the efficiency of sorption, but in case of Sr being very stable it has been found that at a pH range of 0–13.5 it remains as Sr^{2+} ions. Only after crossing 13.5 it forms a precipitate of strontium hydroxide (SrOH$^+$). Hence it can be deduced that Sr is very stable in the environment. Table 1 gives a comparison of three elements namely copper, chromium and strontium, it can be seen that hexavalent chromium being very unstable and change its forms at different pH followed by copper, whereas strontium remains stable [17].

A number of studies relying on computational techniques such as Visual minteq and PHREEQC softwares have been used by many researchers. Where, it codes on sorption models i.e., diffuse double layer model, constant capacitance model etc. that predict sorptive behavior at different input parameters such as pH temperature, ionic strength. One can obtain results in terms of distribution of various chemical species without actually conducting sorption experiments, which not only saves time but also gives an indication for use on radioactive elements where experimental norms limit repeatability of tests. A lot of work is based on

regular and safe contaminants are studied because of regulatory and safety practices but not much work is available due to difficulty in getting radioactive elements [18,19,20,21].

3.1 Strontium Alteration Strategy

Expansion of the nuclear industry also brings a serious concern for disposal of generated radioactive waste. Accidents, spillage of radioactive low level liquid wastes (LLRW) are common in the routine operations of nuclear power plants. The LLRW is discharged by the techniques like evaporation, ion exchange, precipitation, inorganic sorption and membrane filtration which is developed to adhere to the standards so that the amount of radioactive waste should reduce. Hence in order to curtail the mobility of Sr in the environment alteration strategies in the form of soil amendments, innovative sorbents can be made use of, the following section gives details of some of the adopted alteration techniques. Among the methods mentioned earlier the effectiveness of inorganic sorption in reducing the adverse effect of the final waste material is testified because the inorganic sorption technique is compatible with inorganic adsorbent; stabilize the radiation, highly selective and economical.

Details of different sorbents and their sorption efficiency for strontium removal are given in Table 2. Studies conducted in the recent past have shown that the fission nuclides (^{134}Cs, ^{137}Cs, ^{90}Sr, etc.) and activated corrosion products (^{60}Co, ^{63}Ni, ^{59}Fe, etc.) are greatly prone to enhance the effort by modified, natural, synthesized adsorbents. Materials like the titanosilicates (CST), zeolites and hexacyanoferrates are commercially available and are used for the removal of ^{137}Cs and ^{90}Sr. The value of pH restricts the effects of the materials. The abundance of non-radioactive ions such as K^+, Ca^{2+} and Na^+ present in the radioactive nuclides in LLRWs demand the use of sorbents with high selectivity in radioactive-nuclides.

The use of pyrochlore antimony pentoxide in ion exchange is found to be effective due to its inclination towards the strontium in acidic solutions. When Mn(IV), Ce(IV), Zr (IV), Ti(IV), Si(IV), are doped, the display of Sr^{2+} ion exchange properties is found to take place by the composite oxides due to their affinity towards Cs^+ and Co^{2+} ions. Oxides of Si/Sb are particularly effective in adsorption of Cs^+ and Sr^{2+}. With 35,500 mLg^{-1} distribution coefficient value (K_d, mL g^{-1}) for 0.1 M HNO_3 solution and 3700 mLg^{-1} distribution coefficient value (K_d, mLg^{-1}) for 0.5 M HNO_3 solution, whereas a high uptake of Sr^{2+} is observed when the concentration of calcium is found to be 0.01 M along 3200 mLg^{-1} of K_d values for Ti/Sb with different antimoniates. The variation in the chemical composition, structure and versatility in

ion exchange process has made Sn/Sb oxides (Sn/Sb) given more consideration. Crystalized pyrochlore with Sn/Sb exchangers are synthesized with a lower ratio of Sn:Sb and are found to be selective for the ions of Sr^{2+}.

On contrary, a rutile crystalline and amorphous structure having a higher Sn:Sb ratio has high affinity to Co^{2+} ions, maintaining a high K_d value in the range of 223,000–602,000 mLg^{-1} with 0.1 M HNO_3 solutions as media. ^{90}Sr and ^{60}Co are considered to be very hazardous radionuclides in LLRWs, an agent to remove the radionuclides together in the form of LLRWs finds a lot of applications in nuclear industry [7,17,22,23,24,25].

4. REGULATIONS

In order to provide a brief view on the various regulations for strontium exposure it has been found in literature that the USEPA (United States Environment Protection Agency) recommends standards which are widely acceptable over vast geographical locations. To quickly summarize, EPA has recommended that drinking water levels of stable strontium should not be more than 4 mgl^{-1}. The Department of energy (DOE) has identified the derived air concentrations (DAC) for creating awareness regarding the exposure to radiation in workplace at DOE facilities.

The DAC shows 2×10^{-9} μci ml^{-1} (70 μbq ml^{-1}) radioactive particles in air remains in the lung for 100 days whereas 8×10^{-9} μci ml^{-1} (300 μbq ml^{-1}) of radioactive particles remains in the lung for less than 10 days. The US national council on radiation protection and measurements (USNRC) established an annual intake limit of 20 μci (7 mbq) for onsite exposure of ^{90}Sr in air. EPA sets standards for the concentration of ^{90}Sr in community water supplies.

The average annual concentration of ^{90}Sr in water supplies should not exceed from 8 pci l^{-1} (0.3 bq l^{-1}). EPA also established maximum contaminant levels (MCLS) in drinking water for radionuclide activities to protect against harmful effects of ^{90}Sr. For beta particles like strontium, the mcl is 4 m rem $year^{-1}$ (4×10^{-5} sv $year^{-1}$). The USNRC has set a permissible limit of ^{90}Sr as 31 μci (1.1 mbq) for workplace.

4.1. Stable Strontium

The USEPA derived a chronic reference dose (RFD) of 0.6 mg kg^{-1} day^{-1} for strontium [26]. The USEPA has not developed the classified stable strontium for human carcinogenicity [26]. The American conference of governmental industrial hygienists (ACGIH) has classified the strontium chromate in A2 category, suspected human carcinogen, and has established time-weighted-average (TWA) of 0.0005 mg m^{-3} for a duration of

8-hour especially for occupational exposure [8]. The international agency for research on cancer (IARC) has put strontium chromate and others in group 1 based on the human carcinogen sources. However, IARC has not listed any other stable strontium compound other than ^{90}Sr.

4.2. Radioactive Strontium

MRLS were not derived for inhalation or oral exposures to radioactive strontium. The USEPA was not successful in deriving reference concentrations (RFCS) or RFDS for strontium which are radioactive [26], nor does the integrated risk information system (IRIS) database provide cancer assessments for radioisotopes of strontium. Henceforth, all radionuclides, including radioisotopes of strontium, are classified as known human (group A) carcinogens. The international commission on radiological protection (ICRP) has framed guidelines regarding the basic principles pertaining to the biological impacts observed due to the exposure to the ionizing radiations and has also set the allowable degree of exposure on the basis of these analyses.

The National Council on Radiation Protection and measurements (NCRP) was chartered by the U.S. congress for the sake of (1) recommending the safe limit of exposure to radiations and for spreading the awareness to the public regarding the same in the interest of the public, (2) develop cooperation and mutual understanding among the organizations working on the radiation safety, (3) conceptualise the basic requirements regarding the radiation safety, (4) developing cooperation with ICPR and with the international commission on radiation units and its measurements.

In spite of NCPR being a non-government firm, it has come up with suggestions which lay the guidelines for the establishment of policies of federal relations, requirement of agencies, and laws governing the statutory bodies. The recommendations framed by the NCPR are majorly adopted by the government firms that have paved the way towards the awareness regarding the use of radioactive materials and safe handling management of radiations.

The food and drug administration (FDA) has standards for radioactive material concentrations developed for food [28] and in medical devices used in radiation therapy [27]. FDA [28] has given recommendation levels for accidental radioactive contamination of foods (both domestic and imported) as a reference document. These derived intervention levels (DILS) are the predicted levels of food that may pave the way for exposure to the radiations which are on par with the guidelines prescribed by the FDA protection action guide (PAG) which is either of the 0.5 rem (5 MSV) or the

prescribed limit, the dose for the same being the 5 rem (5 msv) equivalent to the human tissue or any organ.

Derived intervention levels, which are based on food intake rates, are calculated for different age groups and the DIL for the most vulnerable group is then adopted to provide a conservative margin of safety for the entire population. For ^{90}Sr, with a half-life of 28.8 years, the DIL is based on the dose to the bone surface in 15-year-old individuals, who have the highest rate of bone growth. For ^{89}Sr, with a half-life of 50.5 days, 3-month-old infants represent the most sensitive group because of the higher doses to the lower intestine from milk consumption.

The Department of Transportation (DOT) in collaboration with USNRC has been identified as the regulating authority for the transportation of radioactive materials. On the other hand, federal emergency management administration (FEMA) is responsible for coordinating emergency responses from government side to accidents pertaining to radioactive materials.

The national regulations have been framed in order to govern the occupational exposure to ionizing radiation with the following bodies such as 10 CFR 20 as per US national council on radiation protection and measurements (USNRC), 29 CFR 1910.1096 as per Occupational Safety and Health Administration (OSHA) and 10 cfr 835 as per department of energy (DOE). Even fly ashes and bottom ashes contain trace concentrations of Sr which remains non-volatilized during coal incineration phase [41]. US EPA is responsible for setting radiation policy and safety standards in such a way with the main aim of preventing over exposure to radiation and provides an appropriate balance for protection of public health maintaining desirable dose limits [8].

5. CONCLUSIONS

In this paper an attempt has been made to document the toxicity mechanistic response, alterations and regulations pertaining to strontium element. A number of studies have been conducted in order to understand its behavior in various media and the mechanisms it undergoes during its course of mobility. Physico-chemical sorption along with complexation and encapsulation are the probable mechanisms of sorption whereas several researchers have given primary emphasis on sorption and ion exchange as the potential methods to treat Sr. Its chemical speciation at various pH values remains in stable 'Sr' elemental state, and precipitates as strontium hydroxide only at pH of 13.5. Various remediation techniques are available to treat Sr contaminated soils and water. Some of the

sorbents with efficient treatment of Sr, discussed in this paper include, macro porous zeolite, tin antimonite, birnessite, Fe-hexacyanoferrate, activated carbon, monosodium titanate, alkyl phenylphosphonic, naturalclinoptilolite, fly ash mixed with clays, polyvalent metal silicates and bauxite wastes of alumina.

As per ASTDR, 4 mg L^{-1} is the safe dosage of Sr in drinking water. To conclude some basic steps would help us in avoiding Sr exposure such as avoiding direct contact with the soil, maintaining basic hygiene before consuming food helps in reduction in intake of ^{90}Sr especially near a hazardous waste site. Balanced diet with sufficient vitamin D, calcium, and protein will reduce the amount of ingested strontium that is absorbed.

Table 2 Efficacy of different sorbents for Sr Removal

Sl. No.	Sorbent	Sorbate	Parameters Studied	Remarks	Reference
1.	Red mud	Sr, Cs	Adsorption isotherms, pH, Distribution coefficients, temperature and ionic strength dependence.	The distribution coefficients. equilibrium activity in solution showed a maximum with Cs, and a gradual decrease trend with Sr. The solution activity with adsorption data were fitted to B.E.T. (essentially types IV-V) isotherms for Cs and B. E. T. Langmuir isotherms for Sr. A rise in pH favours the ion exchange sorption of Sr, while for Cs, it is negatively affected. Competitive adsorption of an inert electrolyte, i.e., NaCI, severely hinders Cs sorption, while Sr sorption on water-washed red mud is not significantly affected. Desorption, temperature, pH, and ionic strength-dependence tests revealed that the primary mode of sorption for both cations is specific adsorption while the secondary mode is ion exchange.	Apak et al. [29]
2.	Fly ash	Sr, Cs	Adsorption isotherms, pH, Distribution coefficients, temperature and ionic strength dependence.	Mechanisms of radionuclide retention by fly ash are specific adsorption of Csf^a and irreversible ion-exchange uptake of SrZ^{+b}. Described well by Langmuir adsorption isotherm. Cesium retention sharply drops with ionic strength while strontium adsorption increases sharply and steadily at low and moderate concentrations of the inert electrolyte, respectively.	Apak et al. [30]
3.	30 synthetic adsorbents including layered and framework polyvalent metal silicates and phosphates, sodium phlogopite, layered sodium titanium silicate framework niobium, zirconium and titanium	Sr, Co	For these 30 sorbents, materials cesium and strontium ion exchange capacities as a function of pH were determined.	Despite the fact that sodium mica has a layered structure and sodium titanium silicateNa$_2$Ti$_2$SiO$_2$H$_2$O is a framework compound, both of them have ambient adsorption sites for the Cesium ion size.	Bortun et al. [31]
4.	Mixture of desert soils and fly ash	Sr	Brittle bush plant and its bio remediation capacity for Sr when planted on	Brittlebush isotopically equilibrates with desert soils whose fly ash components are as low as 0.25% by weight. Fly ash Sr	Capo and Chadwick [32]

			desert soil fly ash mixture.	is apparently more available to the plant than Sr derived from the soils.	
5.	Natural zeolite± clinoptilolite, modified natural clinoptilolite, synthetic zeolites	Sr, Co	Sr distribution coefficient (K_d) and calcium concentration.	K_d decreased significantly with increased calcium concentration. Synthetic zeolites (IE-96[c], TIE-96[d]) had moderate values of both parameters distribution coefficient and selectivity.	Marinin and Brown [33]
6.	Novel extractants, alkyl phenylphosphonic acids, for Sr removal by supported liquid membranes (SLMs) with strip dispersion.	Sr	Batch sorption tests performed	The SLMs removed radioactive ^{90}Sr to the target of 8 pCi L^{-1} or lower from feed solutions of 300-1000 pCi L^{-1}. Overall mass transfer coefficient data indicate that the mass transfer resistance for the membrane phase is negligible. An analysis of mass transfer resistances shows that the interfacial resistances due to extraction and stripping reactions are dominant.	Ho and Wang [34]
7.	Monosodium titanate	Sr, U(VI)	Batch sorption tests performed	Sorbed Sr exhibited specific adsorption as partially-hydrated species whereas sorbed U exhibited specific adsorption as monomeric and dimeric U(VI)-carbonate complexes. Sorption proved site specific.	Duff et al. [35]
8.	Activated carbon	Sr	The adsorption of strontium(II) on activated carbon follows pseudo-first order kinetics and the energy of activation E_a calculated using the Arrehenius equation was found to be 3.042 kJ mol^{-1}.The adsorption isotherms could be fitted by the Langmuir model with the maximum adsorption capacity Q_o being 5.07×10^{-4} mol g^{-1} at 293.15 K.	The values of the mass transfer coefficient βL (cm s^{-1}) at different temperatures indicated that the velocity of mass transfer of Sr(II) ions onto activated carbon was slow. The intraparticle diffusion mechanism is of great importance in determining the overall rate of removal and the negative entropy of activation ΔS value 145.13 J mol^{-1} K, reflects that no significant change occurred in the internal structure of activated carbon during adsorption of strontium(II). The Gibbs free energy ΔG° values range from –36.61 kJ mol^{-1} to –41.75 kJ mol^{-1} at 293.15–333.15 K, which show the physical adsorption properties of activated carbon and indicate the feasibility of the process.	Chegrouche et al. [36]
9.	Fe-hexacyanoferrate was fixed into Mg/Fe hydrotalcite	Sr	It was found that the sorbent has good stability in different solutions. Removal reaction is chemisorptions via exchange between Fe-hexacyano ferrate (Fe^{2+}) and Sr ions and the reaction kinetics is controlled by diffusive transport through solid-liquid boundary and sorbent particles.	The results show that the material has fairly constant buffer ability with limited contribution of temperature changes. Its buffer effect and higher decontamination factor (D$_f$) values, suggest its utilization in pre-treatment step to neutralize and reduce contamination levels in waste solutions.	Gasser et al. [15]
10.	Birnessite (water molecules and potassium ions are interlaced between MnO layers)	Sr, Co	The reaction is spontaneous, endothermic and of increased disorder. The value of enthalpy change indicates that CoCl$^+$ is bonded to Birnessite via chemical reaction, whereas Sr^{2+} is bonded	The removal process is achieved by exchanging hydrogen ions in the interlayer hydroxyl group and CoCl$^+$ or Sr^{2+} species. Transient removal investigations were carried out and cobalt removal was found faster than strontium.	Ghaly et al. [37]

|			via hydrogen bond in a double step reaction. Generalized Langmuir model and the sorbent have higher affinity to stabilize strontium.		
11.	Tin antimonate	Sr, Co	Freundlich multicomponent isotherm and Sheindorf–Rebuhn–Sheintuch equation, pseudo-second order equation	Good affinity to both Sr(II) ions and Co(II) ions across a wide pH range of 2–12 even in the presence of various non-radioactive ions	Alexander et al. [11]
12.	Macroporous zeolite A monolith[e] (named LTA-monolith)	Sr, Co	Continuous flow through process	LTA-monolith in-flow process discloses a decontamination capacity four times higher in comparison to batch processes. Furthermore LTA-monolith can be directly used as storage radioactive matter without solidification to perform.	[12]
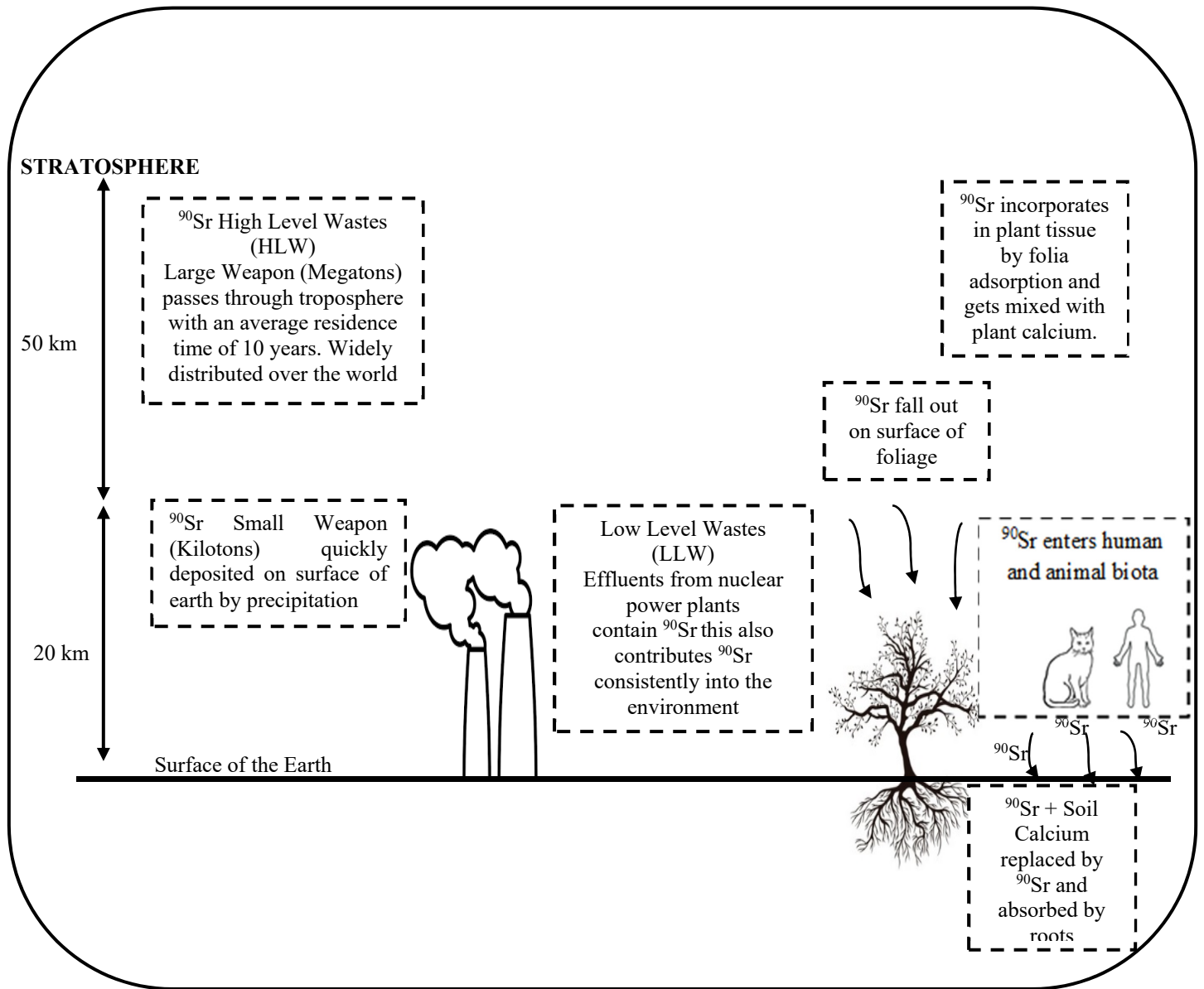
Fig.1 Distribution /uptake of strontium in the environment

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