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Challenges and complexities in remediation of uranium contaminated soils: A review

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ABSTRACT

Uranium contamination of soil has been a major concern with respect to its toxicity, accumulation in the food chain and persistence in the environment. Owing to these problems, remediation of uranium-contaminated soils has been investigated by various techniques. This review focuses on the challenges and complexities associated with the remediation of uranium-contaminated soil at field level. Therefore, laboratory studies have been excluded from this review. Challenges faced during remediation of uranium-contaminated soil using various techniques such as microbial/phyto/chemical/material based strategies have been discussed with suitable examples. Various factors that have a major influence on uranium decontamination process in soil such as soil type, uranium speciation, the presence of coexisting ions and organics, etc., have been highlighted. This review brings out the significance of the integrated role of various factors which determine the efficiency of the uranium decontamination process.

1. Introduction

Most of the nuclear energy plants use uranium and mixed oxide (MOX) fuels as a source for power generation. Uranium is a naturally occurring radioactive element in the earth's crust and present in the various form of isotopes and minerals such as uranite, pitchblende, coffinite, brannerite, davidite, thucholite and thucholite along with various other secondary uranium minerals (Cornelis and Hurlbut, 1985). The nuclear fuel contains more than one oxide is commonly referred to as MOX fuel. It is a fissile material consisting of uranium (it may be natural or depleted or reprocessed) blended with plutonium. MOX is considered to be an alternative to low-enriched uranium (LEU) used for nuclear power generation which exists either in single phase solid solution or in two phase solution. MOX fuel can be also used in thermal reactors as efficient energy source whereas efficient fission of plutonium can be achieved only in fast reactors (Burakov et al., 2010). Due to the increase in nuclear power plants and increasing need for nuclear power, the production of uranium is expected to increase with year. Countries like Kazakhstan, Australia and Canada account for approximately 63.5% of world's uranium production (Zammit et al., 2014). The annual production of uranium in these countries has been increasing ever since 2005 (Fig. 1).

The characteristics of uranium including its concentrations in the environment have been well reviewed by Gavrilescu et al. (2009). Recently, International Atomic Energy Agency (IAEA) has classified soil uranium deposits into 15 major categories based on its geology and abundance (Table 1). The same classification was adopted in Redbook in 2014 and updated 2016 version of Nuclear Energy Agency (NEA) document (Uranium, 2016: Resources, Production And Demand, NEA document No. 7301). Depleted uranium (DU) resulting from fuel fabrication has been used to make ammunitions (Bleise et al., 2003). Anthropogenic activities like mining and processing of uranium ores, nuclear weapon test sites (Child and Hotchkis, 2013) and natural leaching process such as weathering of rocks and soil bed into aquifers have become pressing issues throughout the world. Uranium contaminated soil and aquifers turn into an ecological threat and make the environment unfit for natural microbes, flora, and fauna living in the contaminated zone. The natural radioactive form of uranium like ^{235}U and ^{238}U, have a half-life of 7×10^8 and 4.4×10^9 years, respectively which makes them persistent in the environment and ultimately accumulates in the ecosystem in one or the other form. Similar to the isotopes, the uranyl ions in the various state can also accumulate in multiple ecosystems. Uranium mostly occurs in +4 or +6 valence states in the natural environment. The +4 is more dominant under reducing environment and is less soluble; however, the +6 state is present mostly in the oxidizing environment and is highly soluble

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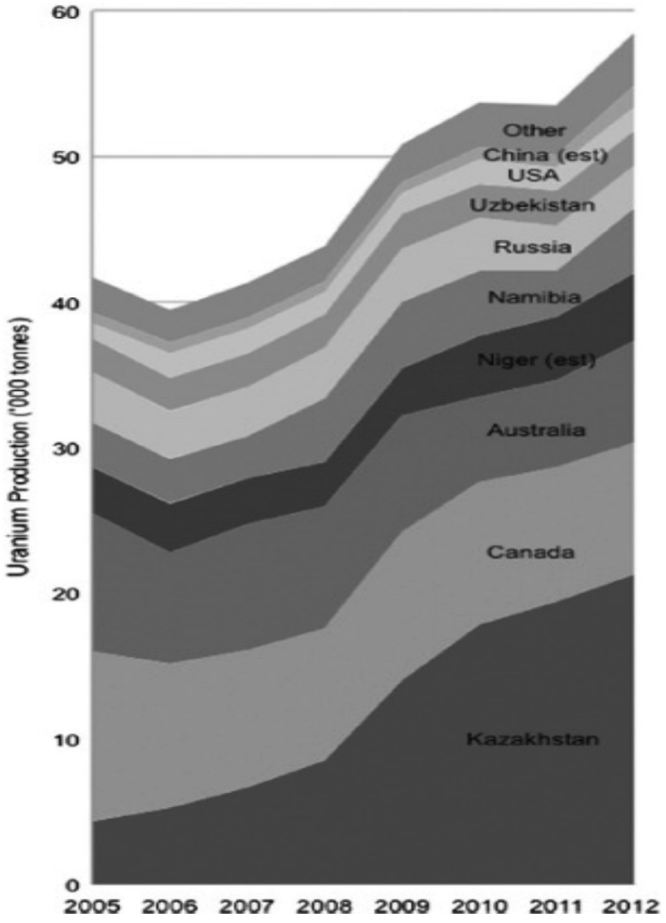

Fig. 1. World Uranium production data (Source: Zammit et al., 2014) (Reproduced with permission).

Table 2
Permissible uranium levels in drinking water.

Regulatory body	Maximum Contaminant Level (MCL)
US-EPA[a], 2009	30 µg/L
WHO[b], 2012	30 µg/L
ADWG[c], 2011	17 µg/L
Dept of Heath, Vermont, USA	20 µg/L
Canadian Drinking Water Quality, 2014	20 µg/L
German Drinking Water Ordinance, 2011	10 µg/L
NIPHW[d], Netherland (proposed in 2014)	30 µg/L

[a] United States- Environment Protection Agency.
[b] World Health Organisation.
[c] Australian Drinking Water Guidelines.
[d] Nation Institute for Public Health and Environment.

(Langmuir, 1978; Scott et al., 2005). Uranium in ionic and isotopic forms can accumulate in plant and animals leading to various toxic health effects and ecological imbalance by affecting the food chain. In animals and human beings, uranium gets adsorbed through the gastrointestinal tract via drinking water or food and damages the tubular cells in the kidney (Konietzka, 2015). Due to these health effects, various countries have kept very stringent permissible limits for uranium in drinking water (Table 2). In case of plants, uranium accumulation starts with the root system and gets deposited into various parts (Dushenkov et al., 1997). In microbes, the ability to oxidize or reduce uranium compounds as part of their metabolism plays a major role in deciding the fate of uranium in the environment and ecosystem (Zammit et al., 2014). To remediate such contaminated soil ecosystems, various strategies have been adopted. Attempts have been made to remediate such uranium contaminated environment using physical, chemical, and biological methods (Li and Zhang, 2012; Prakash et al., 2013). The physical approaches mostly involve coagulation, precipitation, evaporation, extraction and membrane separation technologies. The chemical approaches use co-precipitation or photochemical, electrochemical and chemical leaching methods. The biological approaches employ micro-organisms (bacteria and fungi) and plants for

Table 1
Geology of uranium deposits.
Source: Bruneton et al., 2014; http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Uranium-Resources/Geology-of-Uranium-Deposits.

Type	Types	Rocks/minerals associated	Country available
Intrusive deposits	–	alaskite, granite, pegmatite, and monzonites	Canada, Greenland, South Africa, Namibia and South Australia
Granite-related deposits	Endogranitic and Perigranitic	meta-sedimentary rocks and granites	Australia, Canada, Czech Republic and Europe
Polymetallic iron-oxide breccia complex	–	sedimentary rocks	Australia
Volcanic-related deposits	associated with molybdenum and fluorite	volcanic rocks	Australia, China, Kazakhstan, Mexico, Mongolia, Peru and Russia
Metasomatite	–	structurally deformed rocks affected by sodium and/or potassium metasomatism	Russia, Brazil, Ukraine, Australia, Canada and China
Metamorphite	Calcium and phosphate rich	metasediments and/or metavolcanics and not related to granite	Australia, Austria, Brazil, Congo, Czech Republic, India, Kazakhstan and Canada
Proterozoic unconformity		metasedimentary rocks and sandstones	Australia, Canada and India
Collapse breccia pipe		coarse fragments and a fine matrix of the penetrated sediments	USA
Sandstone deposits	Basal channel deposits, Tabular deposits, Roll-front deposits, Tectonic/lithologic deposits, Mafic dykes or sills	Sandstone, interbedded basic volcanic ash, ferro-magnesian minerals	Australia, Canada, Czech Republic, France, Gabon, Kazakhstan, Niger, Russia, USA and Uzbekistan
Palaeo-quartz-pebble conglomerate	Detrital uranium, Quartz-pebble conglomerate	granitic and metamorphic	Canada and South Africa
Surficial	–	calcite, gypsum, dolomite, ferric oxide, and halite, Clay Sediments, Granite and Sandstones	Australia and Namibia,
Lignite-coal	–	silt, clay, Sandstone beds	Australia, USA, South Africa, Kazakhstan, Germany
Carbonate deposits	–	limestone or dolomite	China, India and Kazakhstan
Phosphate deposits	–	fine-grained apatite	Central African Republic, Jordan, Morocco and USA
Black shale deposits	–	Organic minerals and clays	China, Germany and USA