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Radiation, radionuclides and bacteria: An in-perspective review

Arpit Shukla, Paritosh Parmar, Meenu Saraf*

Department of Microbiology, University School of Sciences, Gujarat University, Ahmedabad 380009, Gujarat, India

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A B S T R A C T

There has been a significant surge in consumption of radionuclides for various academic and commercial purposes. Correspondingly, there has been a considerable amount of generation of radioactive waste. Bacteria and archaea, being earliest inhabitants on earth serve as model microorganisms on earth. These microbes have consistently proven their mettle by surviving extreme environments, even extreme ionizing radiations. Their ability to accept and undergo stable genetic mutations have led to development of recombinant mutants that are been exploited for remediation of various pollutants such as; heavy metals, hydrocarbons and even radioactive waste (radwaste). Thus, microbes have repeatedly presented themselves to be prime candidates suitable for remediation of radwaste. It is interesting to study the behind-the-scenes interactions these microbes possess when observed in presence of radionuclides. The emphasis is on the indigenous bacteria isolated from radionuclide containing environments as well as the five fundamental interaction mechanisms that have been studied extensively, namely; bioaccumulation, biotransformation, biosorption, biosolubilisation and bioprecipitation. Application of microbes exhibiting such mechanisms in remediation of radioactive waste depends largely on the individual capability of the species. Challenges pertaining to its potential bioremediation activity is also been briefly discussed. This review provides an insight into the various mechanisms bacteria uses to tolerate, survive and carry out processes that could potentially lead the eco-friendly approach for removal of radionuclides.

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* Corresponding author.
E-mail addresses: drarpitshukla@gmail.com (A. Shukla), sarafmeenu@gmail.com (M. Saraf).

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1. Introduction

Microorganisms, being the witness and survivor of various extreme conditions on Earth over the time, are today been exploited in remediation of radioactive waste. They possess the advantage of being environment friendly, easy to grow, adaptability, specificity, ability to carry out desirable reactions and processes-with generation of no or minimal polluting byproducts. They possess the characteristic self-sustaining capability (Gazsó, 2001). This review provides an insight into the occurrence of microbes in environments containing radionuclides, the mechanisms involved for its survival and tolerance to radiation with special emphasis on the interactions between the bacterial cell and radionuclides which show immense potential for bioremediation. The use of bacteria in bioremediation of radionuclides is also briefly discussed later in this review.

2. Radiation and microorganisms: exposure and survival

2.1. Effect of ionizing radiations

It is important to acknowledge the lethal implications of radioactive substances. Gamma rays and other ionizing radiations, in general, have been known to inhibit reproduction of microbes by engaging in alteration of DNA (IAEA, 2017). The detrimental effects of ionizing radiations occur on the core nuclear material of any cell-the DNA. Exposure to such stress could lead to formation of lesions leading degradation of DNA by direct and indirect mechanisms. Directly, an electron is ejected out of the DNA whereas indirect pathway involved the process of radiolysis (Ravanat and Douki, 2016).

2.2. Mechanism of resistance and/or tolerance to ioning radiations

The most radioresistant bacteria, *Deinococcus radiodurans* has been studied extensively. Lethal dose (LD_{10}) for *D. radiodurans* R1 has been calculated to be 10×10^3 Sv (Hitoshi et al., 1983). Few species of *Deinococcus* and *Rubrobacter* have been identified to survive gamma radiation doses of greater than 25×10^3 Sv. Some species of *Chroococcidiopsis* have been reported to survive up to 15×10^3 Sv and with members of genus *Micrococcus* exhibiting a more humble radiation resistance (Brim et al., 2000; Krabbenhoft et al., 1965). Radionuclide ^{241}Am imparted a chronic effect on the growth of *Photobacterium phosphoreum*, a bioluminescent bacterium, with a decrease in its growth while increasing the intensity and duration of its luminescence at low temperatures. Alexandrova et al. (2011) attributed it to the formation of peroxides in the medium solution resulting from radiolysis of water. The same study also noted the accumulation of ^{241}Am in DNA of the bacterium. In addition to radiation, the bacteria have also exhibited resistance to desiccation, ultraviolet radiation and oxidative agents. While investigating the cause of such immense resistance, the presence of multiple pathways for amino acid synthesis have been identified (Venkateswaran et al., 2000). It was found that accumulation of Mn (II) in the bacterium promoted resistance (Daly et al., 2004). The genetic basis for radiation resistance in the bacterium was found to be an exonuclease repair pathway, as investigated by Misra et al. (2006). *Deinococcus radiodurans* was been found to survive ionizing radiation levels up to 10×10^3 Sv (Cox and Battista, 2005). U, Ni, Co, Cu and Cd resistant bacteria belonging to the genus *Bacillus*, *Serratia* and *Arthrobacter, Pseudomonas, Rhodococcus, Bacillus* were been discovered. Upon subjected to further studies, resistance was revealed to be due to instrinsic characteristics of the bacteria. Intracellular sequestration of U was found to contribute to resistance while processes such bioprecipitation and biomineralization were found to limit the toxic effects of U. (Choudhary et al., 2012; Merroun and Selenska-Pobell, 2008; Choudhary and Sar, 2011; Suzuki and Banfield, 2004). Bioadsorption and 'localized biomineralization' have shown to be responsible for providing uranium resistance to *Pseudomonas aeruginosa* J007 and *Arthrobacter nicotianae* (Suzuki and Banfield, 2004). It was recently discovered a unique interaction between bacteria, isolated from spent nuclear fuel pond, and Co^{2+}. It showed that the tolerance to cobalt was due to an efficient efflux pump mechanism similar to that of Ni^{2+} and Zn^{2+} -since cobalt tolerance is usually associated with them (Dekker et al., 2014). Members of genera *Serratia* are known to be resistant to Cs^{137}, Sr^{90} and Co^{60} (Paterson-Beedle et al., 2006). Resistance to nickel and cobalt in *E. coli* has been acknowledged to the presence of a novel YohM protein *rcnA*, a first that does not rely on the traditional NiCoT (Nickel Cobal Transporter) family (Rodrigue et al., 2005). S-layer proteins have also been identified to provide resistance against gamma-radiation (Gerbino et al., 2015).

The studies following the devastating accident in Chernobyl revealed that radiation from nuclear power plant had a positive effect on in spore germination in areas, affected by radiation. The phenomena was later termed as '*radiostimulation*' (Dadachova and Casadevall, 2008). In the same study, Chernobyl-associated fungi exhibited radiotropism and exhibited their ability to utilize radiation as source of energy.

3. Soil and microorganisms

3.1. Soil as habitat

Soil serves as one of the most important habitats. Teeming with variety of nutrients, organic matter and even metals soil serves as one of the most economical ecosystems for the growth and proliferation of microbes. From species *(taxonomic)* to functional and from proteomic to genomic, soil continues to swell the already exhausting list of microbes. As previously mentioned, microbes have even been isolated from soils containing radionuclides.

3.2. Radionuclides in soil

Radionuclides are usually been dispersed in nature, in minute concentrations. Natural radioactivity results primarily due to ^{4} K and from the members of ^{238}U decay chain. Incidence of U, Rn, Th in agricultural lands of Bulgaria and Cu, Cd and Pb from acid drainage waters have instigated the development of various bioremediation techniques for radionuclide pollutants (Groudev et al., 2001). Following the applications of *Rhodococcus*, *Nocardia and Deinococcus radiodurans* in remediation of radwaste with concentrations greater than 10 μCi of $^{137}Csg^{-1}$ and for concentrations greater than 20 μCi $^{137}Csg^{-1}$ respectively, model microbes *Deinococcus radiodurans*, *Pseudomonas putida*, *Shewanella putrefaciens* CN32 have been reported to be used as pure culture in remediation (Lloyd and Renshaw, 2005). Commercial acid-leaching of radionuclides from mine has been one of the prime causes of terrestrial presence of radionuclides (U, Th, Pu) and some heavy metals (Cu, Cd, Pb) in agricultural lands in Bulgaria (Groudev et al., 2001). A recent study devised an expedient method for identification and estimation of concentration of naturally occurring radioactive material (NORM) in soil horizons (Michalik, 2017). It has been duly emphasized upon that, chronic radiation in an oligotrophic environment leads to excersion of selective pressure to enhance certain microbes which significantly alters the richness, diversity and abundance of bacteria in that environment (Tišáková et al., 2013). In India, naturally occurring radionuclides are; ^{238}U, ^{232}Th, ^{4} K, ^{226}Ra, Ca. Levels of radiation in South Konkan village soil are 68.08×10^{-9} Svh^{-1}.