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ORIGINAL PAPER

Bacteria were unable to tolerate the radionuclides, while the halophilic fungi tolerated and efficiently remediated them

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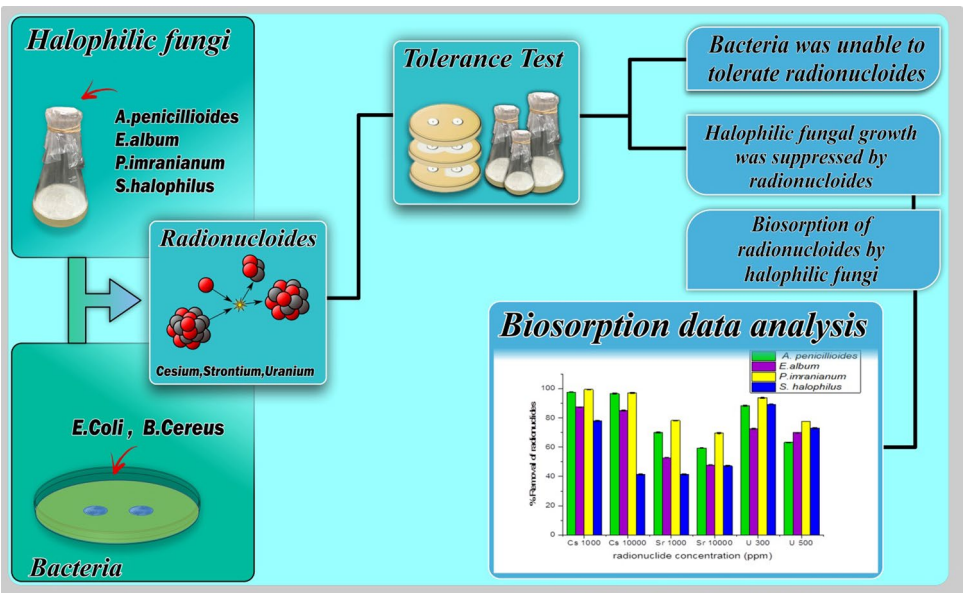
Abstract

Radionuclides are essential for chemical and biological innovations, but their presence as toxic pollutant particles poses a significant threat to human health. To state this issue, bioremediation methodologies utilizing microorganisms have been implemented cost-effectively for removing elevated levels of heavy metals and radionuclides from the environment. The study's goal was to look into how bacteria (*Bacillus cereus* and *Escherichia coli*) and halophilic fungi (*Aspergillus penicillioides, Engyodontium album, Penicillium imranianum,* and *Sterigmatomyces halophilus*) tolerate radionuclides (Cesium, Strontium, and Uranium). The radionuclides inhibited bacteria and suppressed fungal growth. Interestingly, combinations of radionuclides with fungi were found to be more lethal against bacteria. Fungi demonstrated varying tolerance to radionuclides and exhibited efficient biosorption of radionuclides. Among the halophilic fungi, *P. imranianum* has shown the best performance in terms of tolerance against both bacteria and radionuclides. At the same time, *S. halophilus* exhibited the least ability to handle the stress conditions imposed by radionuclides. This study highlights the considerable potential for biosorption by halophilic fungi under extreme stress conditions, delivering a rate effective ecological solution for the elimination of toxic radionuclides.

Graphical Abstract



Keywords Biosorption · Extreme environments · Extremophilic fungi · Heavy metals

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Extended author information available on the last page of the article

Introduction

Heavy metals and radionuclides pose significant environmental risks. Radionuclides like cesium (Cs), strontium (Sr), and uranium (U) are harmful due to their high radiotoxicity, can be extremely lethal to humans, even at very low concentrations, and pose a significant environmental risk, since nuclear fission occurs around the globe (Abou-Lilah et al. 2022). The nuclear power industry's increasing global power consumption could potentially reduce global warming, but accidental releases of radionuclides can cause environmental contamination (Adeola et al. 2022). Till now, several physicochemical techniques have been used to eliminate radionuclides and heavy metals (Singh et al. 2022). Biochemical precipitation and ion exchange are widely used methods, while reverse osmosis, filtration, oxidation/reduction, membrane technology, electrochemical treatment, and evaporation recovery are also often utilized (Razzak et al. 2022). Conventional technologies are utilized for treating radionuclides containing effluents, but these remediation methods are costly and have potential environmental impacts (Thakare et al. 2021). These methods are effective when concentration is high, but wasteful when it is low (Das et al. 2022).

Remediation technology for contaminated environments with low-radioactive nuclides is becoming popular due to its lowest investment, maintenance cost, convenience, safety, and environmental development (Max et al. 2019). Biosorption, involving microorganisms, offers a cheap and efficient bioremediation tool for heavy metal and radionuclide detoxification (Bhatt et al. 2023). The efficiency of remediation depends on selecting different microorganisms for different radionuclides or metals, their uptake facility, and their accumulation ability (Thakare et al. 2021). Studies have focused on selecting favorable microorganisms (bacteria and fungi) to tolerate pollutants and facilitate efficient remediation (Bala et al. 2022). Microbes are fast-growing species and potential candidates for removing radionuclides from contaminated environments (Ali et al. 2023). Bacteria detoxify the environment by immobilizing radionuclides, while fungi utilize mycelial networks to scavenge for essential nutrients (Fomina and Skorochod 2020).

There are reports available of the use of bacteria and fungi for the removal of radionuclides. Wang et al. (2015) found seaweeds, fungi, and bacteria as effective adsorbents for radionuclide removal in aqueous solutions. Hameed et al. (2015) tested fungi for heavy metal and radionuclide biosorption on solid and liquid mediums. Robles et al. (2022) have discussed the contribution of bacteria and fungi to the remediation of radionuclides and heavy metals. Fungi and bacteria collaborate in vital processes like nutrient cycling, decomposition, and biosorption, navigating environmental challenges (Mfon et al. 2024). Halophilic fungi, being extremophiles, are gaining attention for their applications in biotechnology and environmental sciences (Ali et al. 2019). Bano et al. (2018) have shown efficient remediation of heavy metals by using halophilic fungi.

The study was designed and conducted in the first half of 2023 at Southwest University of Science and Technology, with the aim of understanding the tolerance of bacteria and fungi (halophilic fungi) in the presence of radionuclides. All possible available combinations were checked. The halophilic fungi were later introduced at higher concentrations of radionuclides to observe their potential biosorption. To the best of our knowledge, this is the very first study of this kind in many aspects and outcomes.

Materials and methods

Radionuclides and microorganisms used

To investigate the radionuclides Cs, Sr, and U, they were utilized as metal salts of cesium chloride hexahydrate ($CsCl.6H_2O$), strontium chloride hexahydrate ($SrCl_2.6H_2O$), and uranium nitrate [U6 $(No_3)_2$]. The microorganisms were obtained from the Thailand Institute of Scientific and Technology Research (TISTR). The bacteria were *Bacillus cereus* (TISTR 688) and *Escherichia coli* (TISTR 780) as gram-positive and gram-negative, respectively. Nutrient agar (NA) and nutrient broth (NB) were used as bacterial growth media. The halophilic fungi obtained were *Aspergillus penicillioides* (TISTR 3639), *Engyodontium album* (TISTR 3645), *Penicillium imranianum* (TISTR 3655), and *Sterigmatomyces halophilus* (TISTR 5926). The fungi were grown in potato dextrose broth (PDB) and potato dextrose agar (PDA). All the fungal media in this study were supplemented with 5% sodium chloride (NaCl) (Khan et al. 2022).

Bacterial tolerance to radionuclides

The assessment of the bacterial tolerance was primarily checked by supplementing the radionuclides in the nutrient broth. The U was supplemented at 300 ppm, while the Cs and Sr were inoculated at 1000 ppm in the broth. The difference in growth was calculated at time intervals of 6 h (h) compared to the control at an optical density (OD) of 600 nm.

The spread plate technique was applied for the bacterial tolerance test on the NA medium. The bacterial strains were cultured on the plates. A radionuclide tolerance test was performed on the agar plates aseptically, and a hole of 1 cm was punched with the help of a cork borer. The

radionuclides were dissolved in distilled water to attain the above-mentioned concentrations (Cs and Sr 1000 ppm and U 300 ppm). An aliquot of 100 µL was added to the 1 cm holes with distilled water for control. The plates were assessed at 6 h intervals (Ali et al. 2018a).

Bacterial tolerance to halophilic fungi

The tolerance test was performed on the agar plates aseptically, and a hole of 1 cm was punched with the help of a cork borer. The halophilic fungal (*A. penicillioides, E. album, P. imranianum, and S. halophilus*) filtrate aliquots of 100 µL were poured into holes of 1 cm on agar plates. The distilled water was used as a control. The plates were monitored at 30 °C after every 6 h intervals (Ali et al. 2018a).

Halophilic fungal tolerance to radionuclides

Spores were collected from the fungal culture using a sterile loop. The fungal mats were transferred to petri dishes containing PDA. The spore suspension was then transferred into 100 mL of PDB in a 250 mL flask, and the media was supplemented with concentrations (Cs and Sr 1000 ppm and U 300 ppm) and incubated at 30 °C for 14 days.

After incubation, samples were filtered through Whatman filter paper, and fungal mats were collected. The fungal mats were removed from the petri dishes and washed thoroughly with distilled water to remove any loosely bound radionuclide ions. The fungal biomass was dried in an oven at 80 °C for 24 h to obtain a constant dry weight and stored at 4 °C (Das et al. 2019).

Bacterial tolerance to halophilic fungi and radionuclides

The two bacterial strains, *B. cereus* and *E. coli*, were tested. Spores were collected from the fungal culture and then transferred into 100 mL of PDB in a 250 mL flask and incubated at 30 °C for 14 days. The bacterial tolerance to halophilic fungi and radionuclides was aseptically performed on the agar plates, and holes of about 1 cm were punched with the help of a cork borer. A 1 cm hole was filled with 100 µL of a mixture having 50 µL of the fungal filtrate and 50 µL of the radionuclide solution. The plates were incubated at 4 °C for 1 h, and later at 30 °C for 24 h to test the tolerance. The distilled water was used as a control (Das et al. 2019).

Biosorption of radionuclides

The fungal isolates were collected and cultured on PDA for seven days at 30 °C to obtain a pure culture for radionuclide biosorption. Spores were collected from the fungal culture using a sterile loop and suspended in a media solution. The spore suspension was then transferred into 100 mL of PDB in a 250 mL flask, supplemented with radionuclides (Cs and Sr 1000 ppm and U 300 ppm), and incubated at 30 °C for 14 days. The fungal mats were then collected by filtration using sterile filter paper, and the crude filtrate was collected and dried in an oven at 80 °C and stored at 4 °C until further use (Bano et al. 2018).

The protocol for the acid digestion method presented by Gulizia et al. (2022) was followed. The tubes were heated from 150 to 180 °C for 3 h. After cooling, added 3 mL of 30% hydrogen peroxide (H_2O_2) to each sample. The temperature was raised to 180 °C until the mixture turned colorless in Teflon tubes. After cooling, filtrated the solutions through filter paper. The washing step was repeated to eliminate insoluble elements. The filtered solution was obtained to a volume of 25 mL with deionized water (Jing et al. 2020).

Analysis of radionuclide biosorption

The elimination of radionuclides from the halophilic fungal medium was assessed using atomic absorption spectroscopy (AAS) (PerkinElmer 800, USA) from the Lab of Experiment Center of Life Science and Engineering, Southwest University of Science and Technology. Following the methodology explained by Das et al. (2019), data was calculated using the methodology explained by Bano et al. (2018).

Results and discussion

Bacterial tolerance to radionuclides

The bacterial tolerance to radionuclides was observed, with no growth via viable count (Supp. Figure 1). Consequently, the tolerance of bacteria to the radionuclides was tested by the plate screening method. Overall, *E. coli* tolerated the radionuclides better than *B. cereus* (Fig. 1). As in the Sr case, the diameter of inhibition was 12 mm larger in *B. cereus* than in *E. coli.* Almost equal inhibition of *B. cereus* and *E. coli* was observed in the U tolerance.

Bacterial tolerance to halophilic fungi

All used halophilic fungi were found to inhibit gram-negative bacteria (*E. coli*) more as compared to gram-positive bacteria (*B. cereus),* as shown in Fig. 2. The most inhibition has been shown by *P. imranianum* against *E. coli* (16 mm), while the least activity has been shown by *S. halophilus* against *B. cereus* (8 mm).

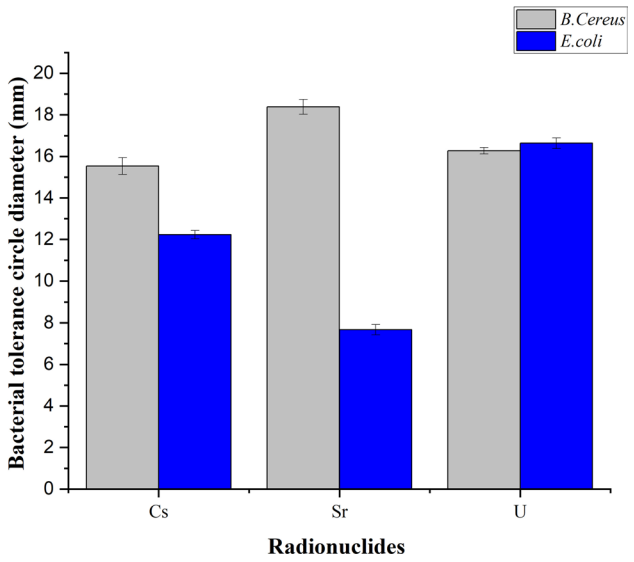

Fig. 1 Comparisons were made between gram-positive and gram-negative bacteria (*B. cereus* and *E. coli*) and three radionuclides (Cs, Sr, and U; the concentrations of Cs and Sr were 1000 ppm, respectively, while the concentration of U was 300 ppm). The bacterial tolerance was measured as inhibition of growth through the clear zone observed in mm

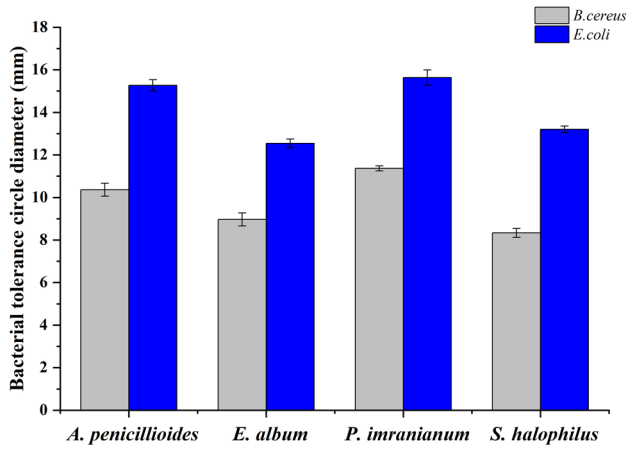

Fig. 2 Comparisons were made between gram-positive and gram-negative bacteria (*B. cereus and E. coli*) and halophilic fungi (*A. penicillioides, E. album, P. imranianum,* and *S. halophilus*). The bacterial tolerance was measured as inhibition of growth through the clear zone observed in mm

Halophilic fungal tolerance to radionuclides

The growth of all halophilic fungi tested was found to be diminished as compared to the control, which had no radionuclides (Fig. 3). The U was most tolerated by all halophilic fungi. *P. imranianum* was overall found to be the most tolerant one against all the radionuclides tested, such as having 0.6 mg of growth in Sr and 1.4 mg of growth in U in terms of dry weight. *S. halophilus* was found least tolerant to

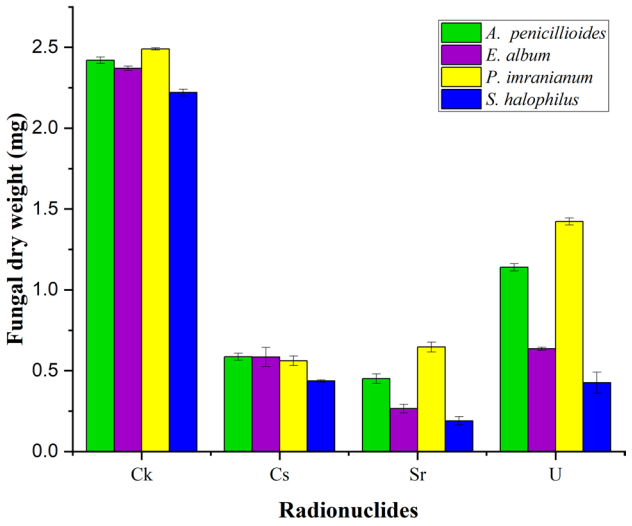

Fig. 3 The graph compares the dry weight and tolerance of four halophilic fungi (*A. penicillioides, E. album, P. imranianum,* and *S. halophilus*) against radionuclides (Cs, Sr 1000 ppm, and U 300 ppm). CK is the control of halophilic fungal dry weight without the addition of any radionuclide

radionuclides such as heaving 0.19 mg of dry weight growth in Sr.

Bacterial tolerance to halophilic fungi and radionuclides

Mostly, the combination of the radionuclides and *P. imranianum* has performed better than others, such as when mixed with Cs, the *P. imranianum* created 19 mm of clear zone against *E. coli,* while making a clear zone of 26 mm against *B. cereus* when mixed with U. Most of the inhibition activity has been exhibited against bacteria in combination with U. Moderate activity has been found against bacteria in combination with halophilic fungal interaction with the Cs and Sr, whereas *S. halophilus* in combination with the Cs has outperformed against *B. cereus* by making a clear zone of 20 mm (Fig. 4a, b).

Results of the biosorption of radionuclides

The halophilic fungi in this study have shown a high removal percentage of Cs. Specifically, *A. penicillioides* and *P. imranianum* have removed nearly 100% of the Cs, both in lower (1000 ppm) and higher (10,000 ppm) concentrations. The *E. album* has shown moderate performance in removing Cs at 1000 ppm and 10,000 ppm, estimating over 87% and 85% of the removal percentage, respectively. Sr can be biosorbed by halophilic fungi like *A. penicillioides* and *P. imranianum*, which have a removal percentage of about 70–80% at 1000 ppm. *E. album* showed a minor difference

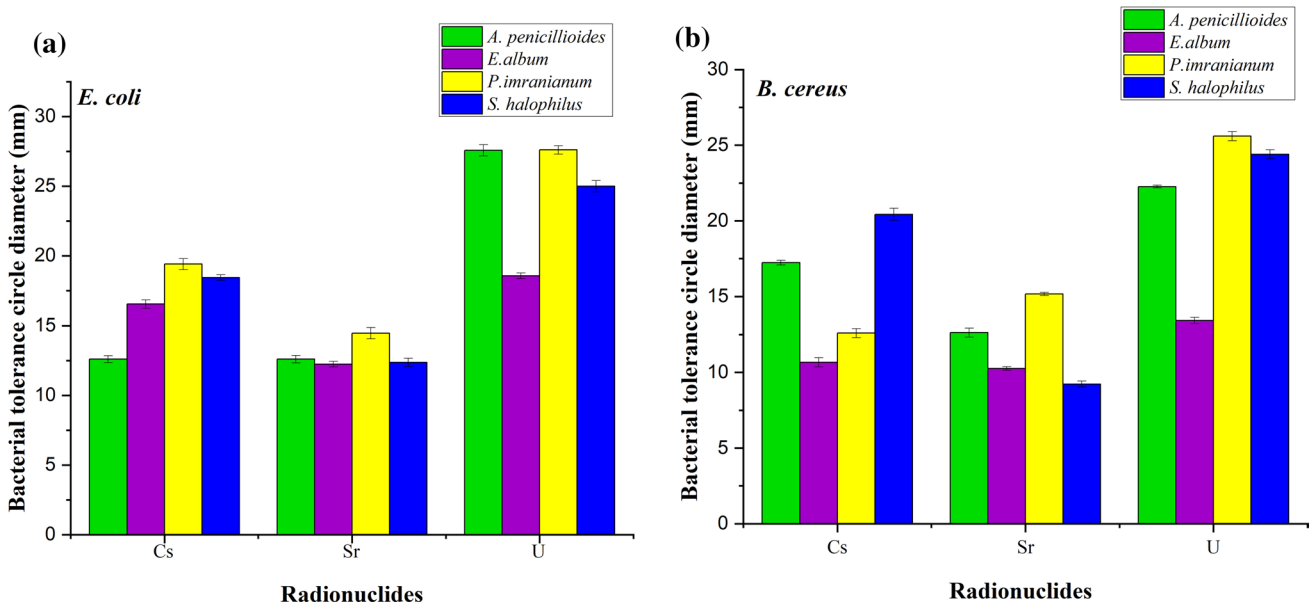

Fig. 4 **a** The graph shows the combination of 100 µL halophilic fungal filtrates (*A. penicillioides, E. album, P. imranianum,* and *S. halophilus*) and radionuclides (Cs, Sr, 1000 ppm, and U 300 ppm) against the gram-negative bacteria (*E. coli*). Tolerance was measured as inhibition of growth through the clear zone in mm. **b** The graph shows the combination of 100 µL of halophilic fungal filtrates (*A. penicillioides, E. album, P. imranianum,* and *S. halophilus*) and radionuclides (Cs, Sr, 1000 ppm, and U 300 ppm) against the gram-positive bacteria (*B. cereus*). Tolerance was measured as inhibition of growth through the clear zone in mm

in both lower and higher concentrations. *S. halophilus,* in the case of Sr, interestingly displayed 5% more performance at higher concentrations than at lower concentrations. Halophilic fungi in this study have shown a high removal percentage of U. Notably, *A. penicillioides* and *S. halophilus* have removed approximately 90% of the U at lower concentrations (300 ppm), and *A. penicillioides* was found to be least efficient at higher concentrations (500 ppm) of the U. *S. halophilus* showed almost 73% at 500 ppm which similar to performance of *E. album* 73% at 500 ppm. Meanwhile, *P. imranianum* overall performed best in both higher and lower concentrations of radionuclides (Fig. 5), and (Supp. Figure 2 and Supp. Figure 3).

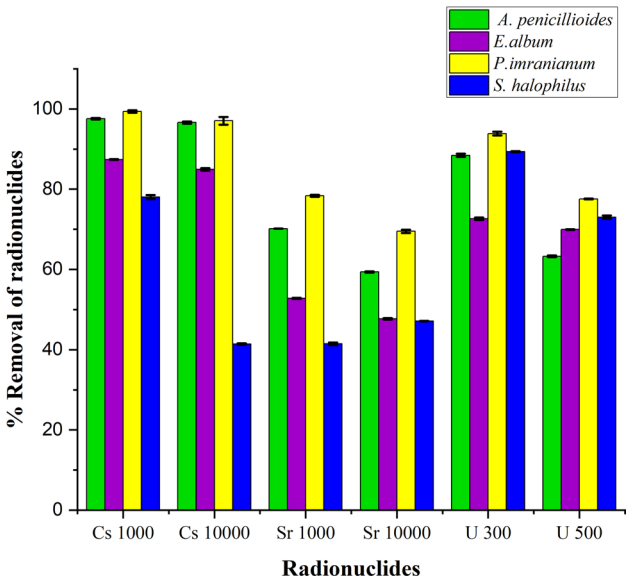

Fig. 5 The removal of radionuclides by halophilic fungi (*A. penicillioides, E. album, P. imranianum,* and *S. halophilus*) is shown in percentages. The concentrations of Cs and Sr were 1000 and 10,000 ppm, respectively, and the concentrations of U were 300 and 500 ppm

Discussion

The study delves into the effective and sustainable application of biosorption for heavy metals and radioactive pollution (Jing et al. 2020; Qi et al. 2022). A comprehensive exploration was undertaken to compare the potential of halophilic fungi against bacterial strains in the biosorption of radionuclides (Lopez-Fernandez et al. 2021). The study was established to understand microbial interactions with radionuclides, their tolerance, and the biosorption capabilities of halophilic fungi. It focused on understanding the natural habitats of microorganisms and their tolerance to radionuclides and determining the ability of tested halophilic fungi to remove radionuclides.

Biosorption is an effective and sustainable method to remove heavy metals and radioactive pollution (Jing et al.

2020; Qi et al. 2022). The potential of halophilic fungi was compared to that of bacterial strains, and the biosorption of radionuclides was explored (Lopez-Fernandez et al. 2021). This study was developed to understand the natural habitats of microorganisms interacting with radionuclides. It was aimed primarily at finding the tolerance of bacteria and fungi against radionuclides. The secondary aim of the research was to determine the ability of tested halophilic fungi to remove the radionuclides.

The gram-negative bacteria are traditionally found to be more resilient than gram-positive bacteria due to factors such as cell wall structure, lipopolysaccharides, efflux pumps, genetic adoptability, and prion protein. Primarily, the cell wall structure with an outer membrane provides an extra barrier against antimicrobial agents and protects them from external threats (Breijyeh et al. 2020). In this study, the tested fungi were found to inhibit more of gram-negative *E. coli* as compared to gram-positive *B. cereus, such as P. imranianum, A. penicillioides,* and *S. halophilus* which were found to be more active (inhibiting 4 mm, 5 mm, and 5 mm, respectively) against gram-negative bacteria than gram-positive bacteria. This finding is similar to the previous published reports (Ali et al. 2014, 2018b). This means that halophilic fungi have more potential to be applied in the pharmaceutical industry for the production of antibiotics against gram-negative bacteria (Ali et al. 2019). The combination of fungi with radionuclides was found to be more lethal against bacteria (Frei et al. 2023). For example*, P. imranianum* alone inhibited *E. coli* with 15.2 mm of inhibition zone, and U alone inhibited 16.6 mm of inhibition zone, while in combination, the inhibition zone of both of them increased to 27.6 mm. The bacteria are increasingly developing resistance to traditional antibiotics (Liu et al. 2022). In situations where antibiotics are ineffective, radionuclides may be utilized to treat resistant bacteria (Frei et al. 2023). However, there must be a need to biosorb the radionuclides from the tested systems (Kunze et al. 2022). Where halophilic fungi can be useful in terms of efficient removal of radionuclides, as proven in this study (Lopez-Fernandez et al. 2021).

Halophilic fungi showed a high removal percentage of Cs, *A. penicillioides,* and *P. imranianum*, removed nearly 100% (98% and 99%, respectively). In the biosorption of Sr, the halophilic fungi demonstrated a moderate level of removal percentages. In the removal of U, the halophilic fungi showed a high removal percentage, with *A. penicillioide*s and *S. halophilus* removing approximately 90% (88% and 89%, respectively) at lower concentrations. These findings are similar to those of Bano et al. (2018). However, at higher concentrations, the removal percentage of radionuclides decreased for all strains. These findings suggest that halophilic fungi have potential for use in the biosorption of contaminated extreme environments (González-Abradelo et al. 2019).

The present study results align with studies using the wood-decay fungus *F. fomentarius* for Cs biosorption by Dulanska et al. (2018) with a concentration of 60 to 70 ppm and a removal rate of approximately 99%. In this study, the concentration of Cs was over 16 to 142 folds higher than Dulanska et al. (2018), but *P. imranianum* has shown the same removal rate of 99%. Researchers (Dai et al. 2020; Ilyas et al. 2020; Soleymani et al. 2023) have recently found a high removal rate of Sr of 40 to 97% by *B. pumilus, B. cereus,* and *Sargassum sp.* The concentration they have used ranges from 130 to 700 ppm. The halophilic fungi in this study, were incubated with 8–14 folds of a high concentration of Sr. The best biosorption results have been found to be 78% (at 1000 ppm) by *P. imranianum* and the lowest (42%) by *S. halophilus* at 1000 ppm, which shows that even at a high concentration, the halophilic fungi were capable of removing most of the Sr. This present study complies with Liu et al. (2019), who discovered that *B. amyloliquefaciens* biosorbed U at a concentration of 200 ppm with a 90% removal capacity. However, *P. imranianum* showed better removal of U (93%), and the least removal of U (73%) was exhibited by *E. album* at 300 ppm. The higher removal rates of U exhibited by halophilic fungi (Fig. 5) in comparison to Cs and Sr can be due to the lower concentrations of U. These results indicate that halophilic fungi can be excellent candidates for the removal of radionuclides in nuclear related disasters.

The halophilic fungi in this study have again shown the behavior of being polyextremophilic in nature (Ali et al. 2019, 2016b). They and their metabolites not only survive in high salt concentrations, but can also withstand other extremes such as temperature and alkalinity (Ali et al. 2013, 2016a). In this study, they are proven to tolerate and grow at extremes of radionuclide concentration, proving them to be metallophilic as well as radiophilic (Bano et al. 2018).

Conclusion

The bacteria in this study were unable to tolerate the radionuclides. While, the halophilic fungi not only tolerated but efficiently removed them. The outcomes of this study highlight the potential of using the halophilic fungi against drug-resistant or superbug bacteria alone or in combination with radionuclides. Similarly, halophilic fungi also emerged as excellent choices for the remediation of radionuclides in the environment, especially in the case of environmental disaster management of soil or water. This study (being a pioneer) has highlighted the biosorption potential of halophilic fungi for the removal of radionuclides at higher concentrations; further research could investigate the mechanisms behind

this tolerance and explore the potential use of halophilic fungi in other biotechnological applications.

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Author contributions TA and IA conducted experiments; CX supervised the research. II helped with calculations.

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Declarations

Conflict of interest All authors declare that there is no competing interest, and they approve the manuscript submission.

References

Abd El Hameed AH, Eweda WE, Abou-Taleb KA, Mira H (2015) Biosorption of uranium and heavy metals using some local fungi isolated from phosphatic fertilizers. Ann Agric Sci 60(2):345–351

Abou-Lilah RA, Rizk HE, Elshorbagy MA, Gamal AM, Ali AM, Badawy NAJIJoEAC, (2022) Efficiency of bentonite in removing cesium, strontium, cobalt and uranium ions from aqueous solution: encapsulation with alginate for column application. Int J Environ Anal Chem 102(12):2913–2936

Adeola AO, Iwuozor KO, Akpomie KG, Adegoke KA, Oyedotun KO, Ighalo JO, Amaku JF, Olisah C, Conradie JJEG, Health (2022) Advances in the management of radioactive wastes and radionuclide contamination in environmental compartments: a review. J Environ Chem 1–27

Ali FS, Akbar A, Prasongsuk S, Permpornsakul P, Yanwisetpakdee B, Lotrakul P, Punnapayak H, Asrar M, Ali I (2018a) Penicillium imranianum, a new species from the man-made solar saltern of Phetchaburi province, Thailand. Pak J Bot 50(5):2055–2058

Ali I, Akbar A, Aslam M, Ullah S, Anwar M, Punnapayak H, Lotrakul P, Prasongsuk S, Yanwisetpakdee B, Permpornsakul P (2016a) Comparative study of physical factors and microbial diversity of four man-made extreme ecosystems. Proc Natl Acad Sci India Sect B Biol Sci 86:767–778

Ali I, Kanhayuwa L, Rachdawong S, Rakshit SK (2013) Identification, phylogenetic analysis and characterization of obligate halophilic fungi isolated from a man-made solar saltern in Phetchaburi province, Thailand. Ann Microbio 63:887–895

Ali I, Khaliq S, Sajid S, Akbar A (2019) Biotechnological applications of halophilic fungi: past, present, and future. Fungi in extreme environments: ecological role and biotechnological significance: Springer Sci 291–306

Ali I, Prasongsuk S, Akbar A, Aslam M, Lotrakul P, Punnapayak H, Rakshit SK (2016b) Hypersaline habitats and halophilic microorganisms. Maejo Int J Sci Technol 10(3):330–345

Ali I, Siwarungson N, Punnapayak H, Lotrakul P, Prasongsuk S, Bankeeree W, Rakshit SK (2014) Screening of potential biotechnological applications from obligate halophilic fungi, isolated from a man-made solar saltern located in Phetchaburi province, Thailand. Pak J Bot 46(3):983–988

Ali J, Sohail A, Wang L, Rizwan Haider M, Mulk S, Pan G (2018b) Electro-microbiology as a promising approach towards renewable energy and environmental sustainability. Energies 11(7):1822

Ali S, Baloch SB, Bernas J, Konvalina P, Onyebuchi EF, Naveed M, Ali H, Jamali ZH, Nezhad MTK, Mustafa AJER (2023) Phytotoxicity of radionuclides: a review of sources, impacts and remediation strategies. Environ Res J 117479

Bala S, Garg D, Thirumalesh BV, Sharma M, Sridhar K, Inbaraj BS, Tripathi MJT (2022) Recent strategies for bioremediation of emerging pollutants: a review for a green and sustainable environment. J Toxics 10(8):484

Bano A, Hussain J, Akbar A, Mehmood K, Anwar M, Hasni MS, Ullah S, Sajid S, Ali I (2018) Biosorption of heavy metals by obligate halophilic fungi. Chemosphere 199:218–222

Bhatt J, Desai S, Wagh NS, Lakkakula J (2023) New bioremediation technologies to remove heavy metals and radionuclides. In: Industrial wastewater reuse: applications, prospects and challenges. Springer, pp 267–316

Breijyeh Z, Jubeh B, Karaman R (2020) Resistance of gram-negative bacteria to current antibacterial agents and approaches to resolve it. Molecules 25(6):1340

Dai Q, Zhang T, Zhao Y, Li Q, Dong F, Jiang C (2020) Potentiality of living Bacillus pumilus SWU7-1 in biosorption of strontium radionuclide. Chemosphere 260:127559

Das P, Dutta T, Manna S, Loganathan S, Basak PJER (2022) Facile green synthesis of non-genotoxic, non-hemolytic organometallic silver nanoparticles using extract of crushed, wasted, and spent Humulus lupulus (hops): characterization, anti-bacterial, and anti-cancer studies. Environ Res J 204:111962

Das S, Singh VK, Dwivedy AK, Chaudhari AK, Upadhyay N, Singh P, Sharma S, Dubey NK (2019) Encapsulation in chitosan-based nanomatrix as an efficient green technology to boost the antimicrobial, antioxidant and in situ efficacy of Coriandrum sativum essential oil. Int J Biol Macromol 133:294–305

Dulanská S, Zvachová S, Silliková V, Mátel Ľ, Šauša O, Maťko I (2018) Modified biosorbent wood-decay fungus Fomes fomentarius for pre-concentration of 137 Cs in water samples. Radioanal Nucl Chem 318:2493–2500

Fomina M, Skorochod IJM (2020) Microbial interaction with clay minerals and its environmental and biotechnological implications. J Minerals 10(10):861

Frei A, Verderosa AD, Elliott AG, Zuegg J, Blaskovich MA (2023) Metals to combat antimicrobial resistance. Nat Rev Chem 7(3):202–224

González-Abradelo D, Pérez-Llano Y, Peidro-Guzmán H, del Rayo S-C, Folch-Mallol JL, Aranda E, Vaidyanathan VK, Cabana H, Gunde-Cimerman N, Batista-García RA (2019) First demonstration that ascomycetous halophilic fungi (Aspergillus sydowii and Aspergillus destruens) are useful in xenobiotic mycoremediation under high salinity conditions. Bioresour Technol 279:287–296

Gulizia AM, Brodie E, Daumuller R et al (2022) Evaluating the effect of chemical digestion treatments on polystyrene microplastics: recommended updates to chemical digestion protocols. Macromol Chem Phys 223:2100485

Ilyas S, Srivastava RR, Ilyas N (2020) Biosorption of strontium from aqueous solutions. Strontium Contamination in the Environment:65–83

Jing L, Zhang X, Ali I, Chen X, Wang L, Chen H, Han M, Shang R, Wu Y (2020) Usage of microbial combination degradation technology for the remediation of uranium contaminated ryegrass. Environ Int 144:106051

Khan SA, Akbar A, Aslam M, Shafee M, Samad A, Rehman FU, Mehmood K, Ali I (2022) Biotechnologically potent halophilic fungal biodiversity from mangrove ecosystem of lasbela, balochistan. Pak J Bot 54(3):1103–1112

Kunze C, Preugschat B, Arndt R, Kandzia F, Wiens B, Altfelder S (2022) Development of a UAV-based gamma spectrometry system for natural radionuclides and field tests at central asian uranium legacy sites. Remote Sens 14(9):2147

Liu L, Liu J, Liu X, Dai C, Zhang Z, Song W (2019) Kinetic and equilibrium of U (VI) biosorption onto the resistant bacterium Bacillus amyloliquefaciens. J Environ Radioact 203:117–124

Liu W, Tang J-W, Lyu J-W, Wang J-J, Pan Y-C, Shi X-Y, Liu Q-H, Zhang X, Gu B, Wang L (2022) Discrimination between carbapenem-resistant and carbapenem-sensitive Klebsiella pneumoniae strains through computational analysis of surface-enhanced raman spectra: a pilot study. Microbiol Spectr 10(1):e02409-02421

Lopez-Fernandez M, Jroundi F, Ruiz-Fresneda MA, Merroun ML (2021) Microbial interaction with and tolerance of radionuclides: underlying mechanisms and biotechnological applications. Microb Biotechno 14(3):810–828

Max MD, Johnson AH, Max MD, Johnson AHJE, Commercialization PoONGHCFf (2019) Energy Overview: Energy Options and Prospects for Natural Gas. J Exploration Production of Oceanic Natural Gas Hydrate 1–55

Mfon EIJIJoD, Sustainability, 4 EM (2024) Microbial Biotechnology: Application of Bacteria in Various Industrial Processes and Environment Remediation. J Environ Sustain Dev 25–33

Qi X, Xiao S, Chen X, Ali I, Gou J, Wang D, Zhu B, Zhu W, Shang R, Han M (2022) Biochar-based microbial agent reduces U and Cd accumulation in vegetables and improves rhizosphere microecology. J Hazard Mater 436:129147

Razzak SA, Faruque MO, Alsheikh Z, Alsheikhmohamad L, Alkuroud D, Alfayez A, Hossain SZ, Hossain MMJEA (2022) A comprehensive review on conventional and biological-driven heavy metals removal from industrial wastewater. J Environ Adv 7:100168

Robles-Fernández A, Areias C, Daffonchio D, Vahrenkamp VC, Sánchez-Román MJM (2022) The Role of microorganisms in the nucleation of carbonates, environmental implications and applications. J Min 12(12):1562

Singh BM, Singh D (2022) Enhanced phytoremediation strategy for sustainable management of heavy metals and radionuclides. Environ Eng 5:100176

Soleymani F, Khani M, Pahlevanzadeh H, Amini Y (2023) Intensification of strontium (II) ion biosorption on Sargassum sp via response surface methodology. Sci Rep 13(1):5403

Thakare M, Sarma H, Datar S, Roy A, Pawar P, Gupta K, Pandit S (2021) Understanding the holistic approach to plant-microbe remediation technologies for removing heavy metals and radionuclides from soil. CRBIOT 3:84–98

Wang F, Tan L, Liu Q, Li R, Li Z, Zhang H, Hu S, Liu L, Wang JJJoER, (2015) Biosorption characteristics of Uranium (VI) from aqueous solution by pollen pini. J Environ Radioact 150:93–98

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