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Physiological and Molecular Diversity in Radiation-resistant Fungi

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ABSTRACT: The field of radio-resistant fungi is comparatively nascent, and there has been a lack of comprehensive information about the natural distribution of the ionising radiation-resistant fungi in natural environments. IRR fungi are predominantly isolated from regions that have been exposed to ionising radiation by anthropogenic activities. The radio-tolerant fungi have also been reported from several regions, as biofilms and as main contaminators. Additionally, the importance of melanin in IR resistance is emphasised by the greater abundance of melanised fungi in almost all types of habitats. Most of the radiation-resistant fungi are observed to accumulate melanin or some other pigments that are hypothesised to protect against radiation. It has also been proven and demonstrated that when the fungal spores are subjected to a collimated source of radiation, the germinated spores grow in the direction of the source of radiation, which is attributed to the presence of melanin. Radioprotection in melanised fungi is attributed to ionizing radiation-induced alteration in the redox potential of melanin. The identical resistance to ionising radiation in the case of WT as well as the pks1 mutant, deficient in the synthesis of melanin pigment.

Keywords: Extremophiles, radiation-resistant fungi, melanin, DNA-damage.

INTRODUCTION

Extremophiles are the organisms that thrive in ‘extreme’ environments, such as glaciers, deserts, or hypersaline environments (Gostinčar *et al.*, 2023; Gostinčar *et al.*, 2009). These extremophiles, mostly microbes, are so adapted to their environment that they perceive extreme and stressful conditions as optimal for their growth (Gostinčar *et al.*, 2023; Gostinčar *et al.*, 2009*;* Coleine *et al.*, 2022; Yarzábal Rodríguez *et al.*, 2024; Ameho & Christina 2021). Among rare exceptions are *Wallemia ichthyophaga*, a phylogenetically distinct basidiomycete that cannot grow without nearly 10% NaCl in the medium (Zajc *et al.*, 2014), or *Mrakia psychrophila*, a cold-loving basidiomycetous yeast that cannot grow at temperatures above 20°C (Su *et al.*, 2016), along with some other similar species. Some of the halotolerant fungi grow above 17% NaCl (w/v), and halophiles cannot grow in normal mycological media (Plemenitaš *et al.*, 2014). Some microbes thrive under extreme radiation due to defensive mechanisms provided and facilitated by primary and secondary metabolic products, called extremolytes (Gabani & Singh 2013; Bruckbauer & Cox 2021). Such as scytonemin, mycosporine-like amino acids, shinorine, etc, which absorb a wide spectrum of radiation and protect the organism’s DNA from being damaged (Gabani & Singh 2013). Versatile metabolism and good antagonistic activity, extremotolerant generalists often have a range of biotechnological applications (Tiquia-Arashiro & Grube 2019; Singh & Gabani 2011), a prime example being *Aureobasidium pullulans*, which is known for the production of the polysaccharide pullulan, antimycotic aureobasidin A, and different enzymes (Bozoudi & Tsaltas 2018). Extremophilic and extremotolerant fungi have evolved multiple times to survive in extreme environments, including hypersaline and acidic lakes, as well as cold deserts. These fungi can exhibit diverse morphologies and display substantial phenotypic plasticity. A combination of extreme-tolerant features and ecological and morphological plasticity makes fungi key organisms in the search for the limits of life on Earth and in the Universe.

Life on Earth is exposed to varied forms of radiation originating from different sources, which include cosmic rays, terrestrial radiation, and internal radiation. Maximum radiation exposure is incurred by cosmic rays from space, but their impact is negated by Earth's magnetic field and its atmosphere (Singh *et al.*, 2011). On the other spectrum is terrestrial radiation, which originates from different radioactive minerals such as Uranium, Thorium,which is present in the earth's crust, while internal radiation is a component of living beings represented by ^{40}K and ^{14}C (Jha *et al.*, 2024). Anthropogenic activities such as mining for uranium ores, nuclear power plants, disposal of nuclear waste, and nuclear warfare are additional sources of radiation exposure in nature (Ochiai, 2013). The electromagnetic radiation is a spectrum of radiation that includes gamma, X-rays, ultraviolet, visible light, infrared, radio waves, and microwaves (Vollmer, 2021). The shorter wavelength radiation, such as X-rays and gamma rays, is high-energyradiationthatis capable of ionizing the medium throughwhich itpasses and is termed "ionizing radiation". Although ultraviolet radiation is high-energy radiation, but is incapable of ionising the medium that it passes through; therefore termed "Non-ionising" radiation (Fig. 1).

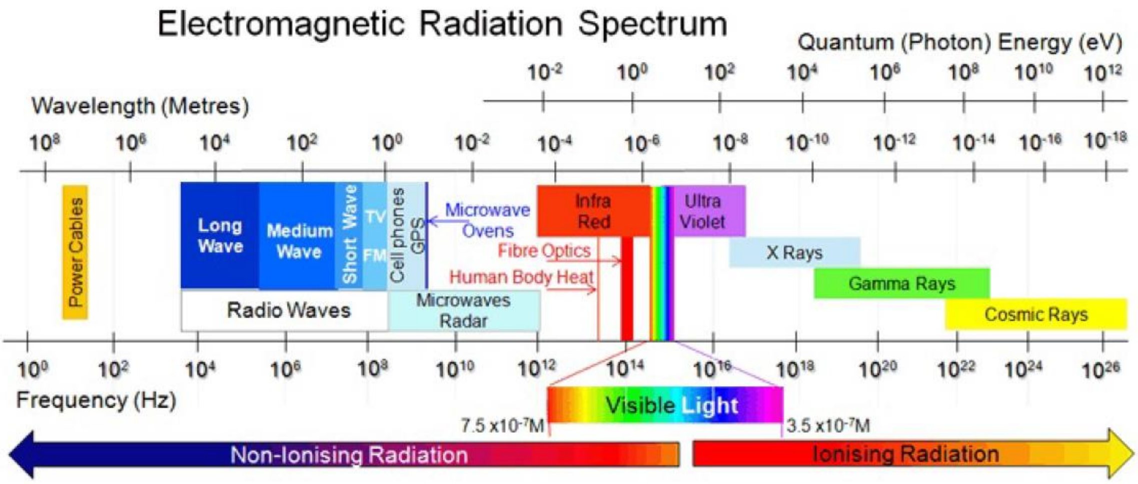

Fig. 1. The Electromagnetic radiation (Toghchi *et al.*, 2018).

The present review describes about the ecology and biology of radiation-resistant fungi.

Ecology and Diversity of Radiation-Resistant Fungi. Life on Earth emerged with comparatively higher background radiation as compared to the current levels of background radiation on Earth (Dadachova & Casadevall 2008). Radiation resistance in any life forms has been proposed to develop as a result of the by-product of exposure to several environmental conditions, such as desiccation, oxidising conditions, or anti-microbial compounds. Radiation-resistant organisms are characterised by their capacity to withstand ionising radiation without losing their capacity to replicate (Byrne *et al*., 2014; Bozoudi & Tsaltas 2018). The field of radio-resistant fungi is comparatively nascent, and there has been a lack of comprehensive information about the natural distribution of the ionising radiation-resistant (IRR) fungi in natural environments. Amongst the notable examples of natural distribution of IRR fungi from the environment are fungal species isolated from the "Evolution Canyon", Israel. Singaravelan *et al.* (2008) reported that the *Aspergillus* spp. isolated from the African/Southern slope were resistant to UV radiation as compared to their counterparts obtained from the European/Northern slope. In a similar observation, Volz *et al.* (1997) demonstrated that *Alternaria* spp., *Fusarium* spp., and *Stachybotrys* spp. *Humicola* spp. *Staphylotrichum* spp. *Aspergillus* spp., *Mucor* spp., *Sordaria* spp., *Ulocladium* spp. could tolerate upto 0.4kGy of ^{60}Co.

IRR fungi are predominantly isolated from regions that have been exposed to ionising radiation (IR) by anthropogenic activities, such as the accident site of the Chernobyl Power plant, notably the damaged reactor and the reactor cooling water (Zhdanova *et al.*, 2004), and from nuclear waste sites such as the Hanford waste sites, USA (Durrell and Shields 1960). The radio-tolerant fungi have also been reported from several regions, such as the abundance of the members of *Basidiomycota* surrounding the Fukishama nuclear power plant, Japan, that was damaged following a tsunami in 2011 (Ohnuki *et al.*, 2019). Interestingly, several strains of *Aspergillus* have been reported from the International Space Station (Cortesão *et al.*, 2020). Silva *et al.* (2018) by using massively parallel sequencing, studied the diversity of the biofilms found in the Spent fuel pool (SFP) and Fuel Transfer Channel (FTC) of Brazilian Nuclear Power Plant (Angra1) and established that Fungi (*Basidiomycota and Ascomycota*) as the main contaminators, while *Ustilaginomycetes* was the major class contributor (70%) in the SFP and FTC. Table 1 lists a few fungi found at the radioactive waste sites.

Table 1: Diversity of ionising radiation-resistant fungi.

Fungi	Isolated from	D10 values	References
Alternaria alternata	Chernobyl nuclear power plant accident site	> 1.5kGY	Mironenko *et al.* (2000)
Stemphylium botryosum	Chernobyl nuclear power plant accident site	> 5kGy	Dadachova and Casadevall (2008)
Cladosporium cladosporioides	Chernobyl nuclear power plant accident site	> 5kGy	Dadachova and Casadevall (2008)
Alternaria tenuis	Soil sample	>5 kGy	Dadachova and Casadevall (2008)
Histoplasma capsulatum	Soil sample	6.7kGy	Dadachova and Casadevall (2008)
Beauveria bassiana,	Chernobyl nuclear power plant accident site	ND	Zhdanova *et al.* (2004)
Penicillium citrinum,	Chernobyl nuclear power plant accident site	ND	Zhdanova *et al.* (2004)
Phialophora	Chernobyl nuclear power plant accident site	ND	Zhdanova *et al.* (2004)
Rhodotorula taiwanensis	Acid mine drainage	2.5kGy	Tkavc *et al.* (2018)
Cryptococcus neoformans	Chernobyl power plant, Human pathogen	4.3 KGy	Dadachova and Casadevall (2008)
Ustilago maydis	Plant pathogen causing corn smut	> 6 KGy	Holloman *et al.* (2007)
*Aspergillus niger**	International Space station	0.3 kGy	Cortesão *et al.* (2020)
Cryptococcus laurentii	Standard culture collection	6.5	Shuryak *et al.* (2019)

- Resistant to Ultraviolet radiation.

Effect of Ionising Radiation on Biological Systems. When high-energy photons such as γ, α, or β are incident on any surface, they are capable of knocking out electrons from the outer orbitals of molecules on which they are incident, causing ionisation and formation of free radicals (Riley, 1994). The central dogma of radiation biology is the hydrolysis of water that produces H_2O^+, e^- (aq) that, upon further reaction with surrounding water, produces more stable superoxide radical, O_2^-, and H_2O_2 (Riley, 1994). The superoxide radical and H_2O_2 so formed form a highly reactive hydroxyl radical, OH**,** that damages DNA by producing both single-strand breaks (SSBs) and double-stranded breaks (DSBs) by ionising bases in nucleic acids in particularly Guanine, and formation of peroxyl radicals ($ROO^{\cdot}$), (Siddiqi & Bothe 1987; Dizdaroglu & Jaruga 2012) (Fig. 1). The presence of cations such as Fe^{2+}, Cu^+ further aggravates the oxidative stress by producing hydroxyl radical through the Fenton-type chemistry (Fig. 1). Some of the unifying mechanisms to with stand radiation includes presence of a robust antioxidant and DNA repair system, compartmentalisation of damaged nucleic acid (Battista, 1997; Cox and Battista 2005) and more recently a common thread that has emerged in radiation biology is higher intracellular Mn/Fe (Daly *et al.*, 2004; Ghosal *et al.* 2005) that protects the proteins against oxidative damage (Daly *et al.*, 2007; Slade and Radman 2011). Additionally major carotenoid pigment of *Deinococcus radiodurans* R1, deinoxanthin, was shown to protect proteins from oxidative damage (Tian *et al.*, 2009).

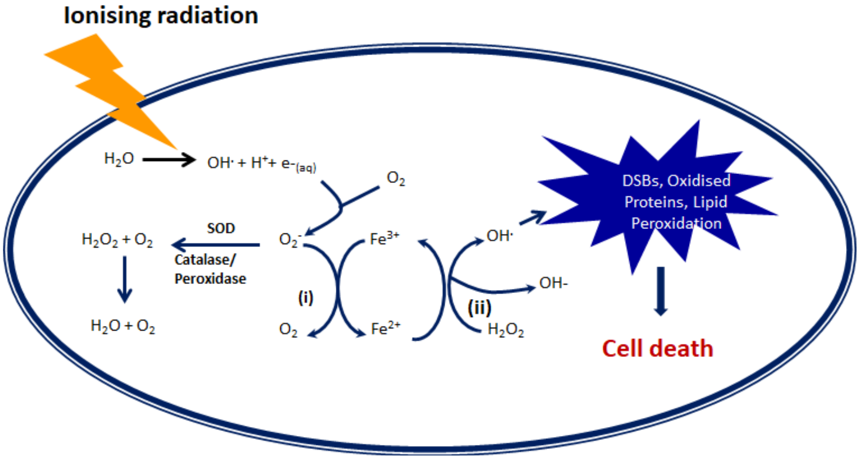

Fig. 2. Effect of ionising radiation in the biological system: DSBs: double-stranded breaks; (i) Haber Weiss reaction and (ii) Fenton's reaction.

Numerous studies have been conducted to assess the effect of ionising radiation on gene expression or proteomics in radiation-resistant fungi (Bruckbauer & Cox 2021; Jung *et al.,* 2016; Schultzhaus *et al.,* 2020); however, there are inconsistencies in the source of IR (^{60}Co or X-ray) or the length of exposure (chronic or acute). Despite the discrepancies in dose of radiation and source of radiation, there are some notable observations in all studies, which include genes involved in DNA damage repair, antioxidant genes, and the role of some novel genes that have been hypothesised to offer protection against damage caused by ionising radiation. Some of the unifying features observed in all radiation-resistant fungi are discussed below.

Melanin. There is a natural abundance of melanised fungi that can withstand higher levels of ionising radiation, such as those isolated form isolated from the walls of Chernobyl reactors and the reactor cooling water pool, as well as naturally resistant fungi, which include some pathogens as *Cryptococcus neoformans* and *Histoplasma capsulatum* (Dadachova and Casadevall 2008). Additionally, the importance of melanin in IR resistance is emphasised by greater abundance of melanised fungi on the southern slope of the “Evolution Canyon” that receives more natural radiation as opposed to the European face of the slope (Dadachova and Casadevall 2008). Most of the radiation-resistant fungi are observed to accumulate melanin or some other pigments that are hypothesised to protect against radiation.

Melanin is a ubiquitous pigment found ubiquitously distributed in all groups of organisms. Melanins in fungi are high molecular weight, negatively charged, hydrophobic pigments that are found associated with the cell wall or secreted. There are three main types of melanin, namely eumelanin (Black- and dark-colored polymers), pheomelanins (yellow and red polymers), and allomelaenins (Song *et al.*, 2023). All elomelanins, derived from the acetate malonate pathway and shikimate pathway, are polymers of dihydroxy naphthalene (DHN). Eumelanin and phenomelanin are derived from Dihydroxyphenylalanine (DOPA), a metabolic derivative of tyrosine.Melanin is dubbed as “fungal armour” as it proffers resistance against several stresses, such as oxidative, metal, and radiation stress (Gessler *et al.*, 2014). Melanin in IR-resistant fungi has been attributed to three phenomena: radiotropisim, radio adaptation, and radiostimulation (Casadevall *et al.*, 2017). Zhdanova *et al*. (2004) demonstrated that the fungal isolate obtained from radioactive contaminated and pristine zones was able to grow in the direction of radiation. This phenomenon was termed as *radiotropism*. The authors demonstrated that the fungal spores, when subjected to the collimated source of ϒ rays (^{109}Cd) and β rays (^{32}P), the germinated spores grew in the direction of the source of radiation. The magnitude of radiotropism was defined by the mean return angle. This study proposed that prior radiation exposure may predispose the fungal culture to radiotropism, as indicated by a greater proportion of fungal cultures obtained from radioactive zones as opposed to radioactive naïve fungal cultures. The authors also proposed this radiotropism to the higher concentration of melanin present in the cultures obtained from the contaminated zones. The radiotropism in fungal culture was attributed to the presence of melanin. The process of radiostimulation was first reported by Dadachova *et al*. (2007), and was proposed to be associated with the previous exposure to radiation and positive radiotropism. Tugay *et al*. (2006) assessed the ability of the fungal species isolated from irradiated zones and clean areas to germinate following exposure to ϒ rays (^{121}Sn) and a combination of β+ϒ rays (^{137}Cs). They could establish growth stimulation in 60% under ^{137}Cs irradiation and 40% under ^{121}Sn. An equal proportion, 48%, of the strains that exhibited growth stimulation also exhibited enhanced spore germination in the presence of either single irradiation or mixed radiation. Radioprotection in melanised fungi was attributed to ionizing radiation-induced alteration in the redox potential of melanin. Ionisation melanin causes sustained oxidation of melanin that was enhanced in the presence of a reductant, resulting in the production of an electric current (Turick *et al.*, 2011). Despite several studies that support the role of melanin in IR-resistant phenotype, a recent study in yeast *Exophiala dermatitidis* refuted the role of melanin in radioprotection and demonstrated that the presence of melanin did not protect from acute exposure to gamma radiation (Schultzhaus *et al.*, 2020). The authors demonstrated identical resistance to ionising radiation in the case of WT as well as the *pks1* mutant, deficient in the synthesis of melanin pigment. Additionally, they also established that melanin pigment-producing fungi, *E. lecarnii-cornii*, were more sensitive to *E.deramtitidis.* Other genomic-based studies also do not support the melanin-dependent protection against radiation (Robertson *et al.*, 2012).

Anti-oxidant defence mechanism. IR causes radiolysis of water, generating several free radical species that are detrimental to biomolecules and irreversibledamagethat can lead to death. Lee *et al.* (2001) demonstrated that cytosolic CuZn SOD, *Sod1,* and mitochondrial Mn SOD, *Sod2,* offered protection against radiation-induced Reactive Oxygen Species (ROS) in *S. cerevisiae;* however, they do not compensate for each other. In mutants lacking either of the two enzymes, other antioxidant enzymes such as G-6-Pdh are elevated in cells exposed to radiation. Along with superoxide dismutase, catalases, employed for detoxification of hydrogen peroxide, also form the frontline enzymes as the first line of defence against oxidative stress. Molin *et al.* (2007) experimentally established that irradiated *S. cerevisiae* strains experience peroxide stress. Nishimoto *et al*. (2015) demonstrated that no significant difference in survival was found in *S.cerevisiae* between the wild-type and ctaΔ, encoding peroxisomal catalase, in the late exponential phase culture; however, the survival of the cttΔ, encoding cytosolic catalase, was significantly lower than that of the other strains. The cttΔ mutant had lower catalase activity than the ctaΔ mutant, which explains the difference in the survival of the two mutants following irradiation. The authors also investigated the induction of catalases in response to exposure to ϒ rays, both in the WT strain as well as cells lacking either of the two catalases, cttΔ was upregulated at 0.5kGy, while no response was seen for ctaΔ. Induction of anti-oxidant defence system has also been observed in otherIR-resistant fungi such as *Wangiella dermatidis* (Robertson *et al.,* 2012) and *C. neoformans* (Jung *et al.,* 2016). *C. neoformans* encodes four catalases, *cat1, cat2, cat3, and cat4,* of which CAT1 and 3 are putative spore-specific catalases. CAT2 is peroxisomal catalase, while CAT4 is cytosolic catalase (Giles *et al.,* 2006). *C. neoformans* exhibited a significant change in expression of *cat*3 during recovery following an exposure of 3kGy while there was no change in expression of other catalases (Jung *et al.,* 2016). Unlike *S. cerevisiae,* none of the catalase provided any protection against irradiation in *C. neoformans* (Jung *et al*., 2016) indicating catalases were dispensable for the IR resistance phenotype of *C. neoformans.* Apart from SOD and catalases that form the major arsenal against the oxidative stress in organisms, peroxiredoxins, *TSA1* and *TSA3* thioredoxins, *TRX1* and *TRX2,* and sulfiredoxin *SRX1* aid in dissipation of the oxidative stress. Molin *et al.* (2007) used 2D- gel electrophoresis to demonstrate that the IR response of *S. cerevisiae* comprised induction of a group of antioxidant enzymes that included superoxide dismutases (Sod1 and Sod2), thiol-reducing enzymes (Trr1 and Trx2), and peroxidases (Ccp1, Ahp1, Tsa1, and Tsa2), in a Yap1- dependent manner. Yap-1 deficient strains however were not compromised in survival following IR exposure. These observations underscore the fact that anti-oxidant response is dispensable for IR resistance, despite induction of anti-oxidant response in all strains of fungi exposed to radiation. The expression of Sulfaredoxin, *Srx1,* was found to be up-regulated following irradiation in *C. neoformans.* SRX1 recycles sulfonic acid form of peroxiredoxin to its sulfenic acid form in an ATP-dependent reaction, and mutants of *srx*1 were compromised in radiation resistance underscoring the importance of ancillary anti-oxidative machinery system in radiation resistance (Jung *et al.,* 2016).

Protein quality control. Reactive oxygen species produced due to radiolysis produced by radiation causes irreversible damage to the proteins wherein the predominant damage is caused by carbonylation of protein (Reisz *et al.,* 2014; Radman, 2016). Carbonyl derivatives are formed by oxidative attack on the amino-acid side chains of proline, arginine, lysine, and threonine. The most important products of the carbonylation reaction are glutamic semialdehyde from arginine and proline, and aminoadipic semialdehyde from lysine. Compared to other oxidative modifications, carbonyls are relatively difficult to induce, and are an irreversible oxidative process (Nyström, 2005). Carobonylated proteins were found to be major source of radiation induced lethality in radiation resistant bacteria, *Deinococcus radiodurans* R1 (Makarova *et al*., 2001; Daly, 2009). Carbonylated proteins were found to be induced in a dose dependent manner in *S. cerevisiae* and its formation was further aggravated in absence of SOD (Lee *et al.,* 2001). Concurrent with the observation in *S.cerevisiae*, expression of HPREF 1120_8115, E3 ubiquitin ligase in *Exophiala dermatitidis* was found to be up-regulated and mutants of this gene were also compromised with respect to cell survival following radiation (Schultzhaus *et al.,* 2020). In response to gamma radiation in *C. neoformans,* component of the UPR pathway, Ire kinase, *ire1* and its downstream transcription factor, Hxl1, *KAR2,* an endoplasmic reticulum [ER]-resident molecular chaperone), *LHS1* a molecular chaperone of the HSP70] family, *PDI1*, a protein disulfide isomerase), and *SCJ1*, a homolog of *S. cerevisiae* DnaJ were found to be induced, however mutant analysis demonstrated that the response to radiation was dependent on the Ire Kinase but independent of the transcription factor, Hxl1 (Jung *et al.,* 2016). The effect of radiation on the ubiquitin-mediated endoplasmicreticulum-associated degradation (ERAD) pathway was analysed in *C. neoformans*, wherein the expression levels of *ubc6*, *ubc62*, and *ubc7* genes were transiently spiked following irradiation, while the expression of *ubc1* peaked after the irradiation (Jung *et al*., 2016). Taken together, the results in various radiation-resistant fungi indicate that the radiation inflicts damage to the cellular proteins that lead to the induction of both protein folding and protein degradation.Recycling of the damaged proteins plays an important role in recovery, followed by radiation, as indicated by the up-regulation of autophagy genes induced following irradiation in *C.neoformans* (Jung *et al*., 2016).

DNA damage control. One of the major damages induced by radiation is the lesions to DNA, which can be either direct or indirect through the formation of free radicals, impacting the genomic stability that may compromise the viability of the organisms (Rastogi *et al*., 2010; Liu *et al*., 2025). Response to DNA damage in yeast and other related fungi is mediated by DNA damage sensors (Rad17, Rad24, Ddc1, and Mec1), which relay the information to the central kinases that include Mec3, Rad53, and Dun-1 (Kondo *et al*., 1999; Cong *et al*., 2025). Activation of these kinases leads to differential effector proteins that include several cell cycle checkpoint kinases and DNA repair proteins (Watson *et al*., 2011; Xiao *et al*., 2006). Apart from ionising radiation, several other stresses are capable of inducing DNA damage. Concurrent with the idea, Watson *et al.* (2011) in their transcriptomic analysis of *Schizosacchromyces pombe* demonstrated that early gene induction in response to γirradiation was controlled by Sty1 MAP kinase that controls the Core Environmental Stress Response (CESR), while the late responses were positively regulated by Rad3. Rad 3 regulated genes included cell cycle control, signal transduction, transcriptional regulation, cell metabolism, and DNA repair proteins, *rhp51+* and *rhp54+, which* included the putative trans lesion DNA synthesis repair enzyme, *dinB,* and the meiotic recombination repair protein *rad50* (Watson *et al*., 2011). Cell cycle arrests following irradiation ensure DNA repair before resuming growth, as indicated in

Exophiala dermatitidis, wherein nutrient-starved cells arrested in G0/G1 phase cause radio resistance (Schultzhaus *et al*., 2020).

Double-strandedDNA breaks are repaired either via homologous recombination or non-homologous end joining (NHEJ). Schultzhaus *et al*. (2020) demonstrated that rad52, a conserved gene in HR, and Ku70/80, a complex essential in NHEJ, were strongly induced in *Exophiala dermatitidis* cells exposed to radiation. Mutant analysis showed only HR was indispensable for radiation resistance, while NHEJ was not essential for survival against radiation stress (Schultzhaus *et al*., 2020). Similar DNA damage response was also observed in *C.neoformans* as reflected in the induction of hypothetical genes implicated in radiation resistance, *Rig1, 2, 3.* One of the effectors of DNA damage response is Ribonucleotide reductase (RNR), an enzyme that converts nucleoside diphosphate to deoxyribonucleosidediphosphate. In line with the function of RNRs, it was found to be upregulated in *W. deramtidis* (Robertson *et al*., 2012) and *S.pombe* (Watson *et al*., 2011). bZip transcription factors coordinate the transcription of DNA damage response proteins. Bdr1 (a bZIP TF for DNA damage response 1) was a novel transcription factor that was discovered in *C. neoformans*, and its mutants exhibited radiation sensitivity, underscoring its importance in radiation induced DNA damage response.

CONCLUSIONS

Life on Earth has developed radiation resistance due to historically high background radiation levels. Fungi, particularly from the Basidiomycota and Ascomycota phyla, have shown significant resilience to ionizing radiation (IR), notably in regions like Chernobyl and Fukushima. The radio-resistant capabilities of fungi are linked to mechanisms involving melanin, which offers protection through increased redox potential and radiotropism. IR produces harmful free radicals via water radiolysis, prompting cellular antioxidant responses. Key enzymes, such as Cu Zn SOD and catalases, contribute to protection against oxidative stress, though not all are critical for IR resistance. Radiation generates reactive oxygen species that carbonylate proteins, causing damage primarily to proline, arginine, lysine, and threonine, leading to end products like glutamic and aminoadipic semialdehyde. This carbonylation is linked to radiation-induced lethality in bacteria, with *S. cerevisiae* displaying a dose-dependent response. In *C. neoformans*, gamma radiation triggers an upregulation of UPR pathway elements and transient changes in the ubiquitin-mediated ERAD pathway, emphasizing protein degradation and folding mechanisms for recovery. Radiation also causes significant DNA damage, activating a response involving sensors such as Rad17 and kinases like Mec3 and Rad53, primarily repaired through homologous recombination. Ribonucleotide reductase contributes to this damage response, with Bdr1, a transcription factor, influencing the reaction to radiation-induced stress. Research on fungi's radiation resistance continues to evolve, underscoring the need for further study on their natural distribution and resilience mechanisms.

FUTURE SCOPE

The research and development in radio-resistant fungi are in a preliminary stage. Radiations are one of the primary sources for the evolution of new species. The presented review provides a strong background to explore further insight into the physiological and molecular basis of the properties of radio-resistant fungi. This review work will also help in designing experiments to test the radio-resistant fungi.

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