Spin, Radicals, and Melanin: Quantum Interfaces in Fungal Adaptability

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Resumo
A radiação ionizante representa um dos mais desafiadores estresses ambientais para organismos vivos, mas certos fungos melanizados exibem notável resistência e até crescimento favorecido em ambientes radioativos. Essa capacidade singular está relacionada à presença de melanina, pigmento com propriedades químicas, estruturais e quânticas que conferem proteção contra radiação e potencial para processos de radiossíntese. Evidências recentes sugerem que fungos melanizados podem não apenas tolerar radiação, mas utilizá-la como fonte energética, modulando processos bioquímicos e apresentando crescimento direcionado em resposta a fontes radioativas (radiotropismo). Estudos destacam ainda a importância da estrutura tridimensional da melanina, seu efeito atenuador comparável ao chumbo, interações eletrônicas que aumentam a redução de NADH e possíveis mecanismos quânticos, como transições singlete-triplete em pares radicais sensíveis a campos magnéticos. Esses avanços revelam a melanina como pigmento multifuncional, com potencial para aplicações em biomateriais radioprotetores e implicações em astrobiologia e biotecnologia de ambientes extremos.

Palavras chaves: Fungos melanizados, Micorremediação, Radiação ionizante, Melanina, Radiotropismo.

Abstract
Ionizing radiation represents one of the most challenging environmental stresses for living organisms, yet certain melanized fungi exhibit remarkable resistance and even enhanced growth in radioactive environments. This unique capability is related to the presence of melanin, a pigment with chemical, structural, and quantum properties that provide protection against radiation and potential for radiosynthesis processes. Recent evidence suggests that melanized fungi may not only tolerate radiation but also use it as an energy source, modulating biochemical processes and exhibiting directed growth toward radioactive sources (radiotropism). Studies further highlight the importance of melanin's three-dimensional structure, its attenuation effect comparable to lead, electronic interactions that increase NADH reduction, and possible quantum mechanisms such as singlet-triplet transitions in magnetic-field-sensitive radical pairs. These advances reveal melanin as a multifunctional pigment with potential applications in radioprotective biomaterials and implications for astrobiology and biotechnology in extreme environments.

Keywords: Melanized fungi, Mycoremediation, Ionizing radiation, Melanin, Radiotropism.

1. Introduction

Ionizing radiation constitutes one of the most severe environmental stressors for living organisms, causing DNA breaks, oxidative damage, and genomic instability that often result in cell death or mutagenesis [1]. Surprisingly, certain melanized fungi, such as *Cryptococcus neoformans* and *Cladosporium sphaerospermum*, demonstrate not only resistance but also enhanced growth in radioactive environments, a phenomenon described as positive radiotropism [2,3,4]. Studies conducted in locations like Chernobyl have revealed that melanized fungi intensively colonize contaminated areas, suggesting evolutionary adaptation to high radiation fluxes [1,2].

These fungi use melanin as a physicochemical shield capable of attenuating ionizing radiation with efficiency comparable to dense materials like lead, thanks to Compton scattering enabled by its electron-rich structure [5]. Melanin exhibits multifunctional properties, such as broad and continuous absorption across the electromagnetic spectrum and the ability to dissipate energy through photothermal effects, in addition to acting as a scavenger of free radicals generated by water radiolysis [3,6]. Studies have shown that melanin undergoes oxidation under radiation, but melanized fungi compensate for this wear by producing reducing agents, suggesting active mechanisms for functional recovery of the pigment [5].

At the molecular level, the preferential binding of radionuclides such as UO_2^{2+} to phosphate groups in the fungal cell wall, forming highly stable uranyl-phosphate complexes, highlights the potential of these fungi for mycoremediation of environments contaminated with radionuclides [4,7]. In parallel, genomic analyses of *Saccharomyces cerevisiae* and *Ustilago maydis* have revealed activation of genes involved in DNA repair, recombination, and chromosomal stability, corroborating the adaptive plasticity of these organisms in response to genotoxic stress [1].

Additionally, recent studies in quantum biology suggest that processes involving quantum coherence and radical pair mechanisms could influence biochemical reactions in fungi, particularly through the presence of stable radicals in melanin, such as semiquinones, which could interact with weak magnetic fields to modulate the cellular response to radiation [8]. Hypotheses of radiosynthesis, based on biomass increases and melanin's ability to attenuate radiation while promoting intracellular redox reactions, indicate that melanized fungi may capture energy from ionizing radiation to drive biochemical processes, functionally analogous to photosynthesis [3,9].

Given recent advances in understanding the interactions among melanin, ionizing radiation, extremophilic fungi, and quantum phenomena, this review article aims to integrate the available knowledge, discuss experimental evidence and current hypotheses, and identify gaps that could guide future research. The relevance of this topic is justified by the potential to develop new strategies for mycoremediation of contaminated areas, creation of radioprotective materials inspired by fungal melanin, and a broader understanding of adaptation to extreme environments, with implications for biotechnology, human health, and astrobiology.

2. Methodology

This review article was developed based on a comprehensive literature search in the PubMed, Scopus, Web of Science, and Google Scholar databases, using keywords such as "radiation fungi," "melanin radiosynthesis," "radiotropism," "quantum biology fungi," and "fungal radioprotection." Peer-reviewed articles published between 1978 and 2025 were prioritized, including experimental studies with melanized fungi in radioactive environments, investigations into the physicochemical properties of melanin, genomic analyses of radiation response, and theoretical reviews on potential quantum mechanisms involved. Data were organized into thematic axes: mycoremediation of radionuclides, radiation-induced damage and repair in fungi, structural and electronic properties of melanin, and potential quantum processes of energy transduction.

3. Results and Discussion

3.1. Radiotrophic Mycoremediation for Decontamination and Protection in Irradiated Environments

Mycoremediation of radiation-contaminated environments emerges as a promising strategy due to the unique characteristics of radiotrophic fungi, which are capable of withstanding and interacting with radioactive contaminants. These fungi, notably the melanized ones, exhibit a remarkable ability to absorb, accumulate, and sequester radionuclides such as ^{137}Cs, ^{95}Nb, ^{100}Ag, ^{238}U, and others, removing them from the environment through their live or dead biomass, as evidenced by Tibolla et al. [4]. Pioneering studies conducted in places like Chernobyl identified these organisms as radiotrophic, thriving in highly radioactive environments, with metabolism enhanced by exposure to ionizing radiation - a phenomenon known as radiotropism, in which hyphal growth occurs toward the radioactive source [4]. This unique adaptation, associated with the melanin present in their cell walls, provides additional protection against radiation-induced damage while contributing to radionuclide retention.

The mechanisms underlying mycoremediation include processes of biosorption, bioaccumulation, biotransformation, and biomineralization. According to Shourie et al. [10], during biosorption and bioaccumulation, metal ions and radionuclides are bound to functional groups present in the cell wall, as observed in *Schizophyllum commune*, where UO_2^{2+} strongly binds to phosphate groups, forming highly stable uranyl-phosphate complexes, while chitin plays a less significant role in sorption [7]. These mechanisms enable pollutant immobilization, facilitating their removal from the environment via fungal biomass.

In the biotransformation process, fungi alter functional groups responsible for toxicity into more water-soluble and less toxic compounds through reactions such as oxidation, hydroxylation, sulfoxidation, and demethylation, reducing toxicity and enhancing elimination. Shourie et al. [10] described the action of laccase from the fungus *Pycnoporus sanguineus* in the biocatalysis of compounds like diclofenac, β-naphthol, and 2,4-dichlorophenol, demonstrating the enzymatic versatility of fungi in degrading persistent organic pollutants.

Biomineralization, another central mechanism, transforms metal pollutants and radionuclides into insoluble elemental or mineral forms, reducing their bioavailability. Fungi such as *Saccharomyces cerevisiae* have demonstrated the ability to precipitate uranium in the form of crystalline fibril layers, reaching concentrations of up to 50% of the cells' dry weight, as reported by White et al. [11]. This process, often dependent on phosphatase activity to solubilize phosphates, contributes to the definitive immobilization of radionuclides in the environment.

Among certain fungal species, *Rhizopus arrhizus* and *Aspergillus niger* have stood out as highly effective biosorbents for thorium, with loading capacities of 0.5 and 0.6 mmol g^{-1}, respectively. However, the presence of other inorganic solutes negatively affected the efficiency of *A. niger*, while *R. arrhizus* maintained consistent performance [11]. The melanin present in many of the studied fungi not only provides protection against ionizing radiation but also plays a role in interacting with radionuclides, modulating their electronic and redox properties, as evidenced by changes in the electron spin resonance (ESR) signal and up to a fourfold increase in the NADH redox rate in irradiated melanins [4].

Shourie et al. [10] emphasize that fungi are fundamental organisms in nutrient cycling and possess unique abilities to metabolize organic and inorganic compounds such as polycyclic aromatic hydrocarbons, pesticides, pharmaceuticals, synthetic dyes, heavy metals, and radionuclides, employing both physical and enzymatic mechanisms. This capability is due to the metabolic, morphological, ecological, and physiological diversity of fungi, mainly from the phyla Basidiomycota and Ascomycota, with particular emphasis on white-rot fungi such as *Trametes versicolor* and *Pleurotus ostreatus*, which produce ligninolytic enzymes (laccases, manganese peroxidases, and lignin peroxidases) that are effective in degrading persistent organic pollutants.

Fungi like *Aspergillus niger*, *Penicillium chrysogenum*, and *Pycnoporus sanguineus* have demonstrated efficiency in degrading petroleum hydrocarbons, industrial dyes, and pesticides in soils and effluents, showing the applicability of mycoremediation in different contaminated matrices. Studies report the complete removal of chlorpyrifos and its toxic metabolite 3,5,6-trichloro-2-pyridinol (TCP) by A. niger strains even in the absence of additional nutrients, highlighting their effectiveness in low-fertility environments [10].

Melanized radiotrophic fungi, in turn, have been studied not only for the decontamination of areas affected by nuclear accidents but also as protective agents for humans and equipment, including in extraterrestrial environments. Tibolla et al. [4] demonstrate that layers of fungal biomass with a high melanin content can significantly reduce incident radiation in environments such as Mars, with potential applications in space habitats by leveraging in situ materials, such as Martian regolith, to reinforce shielding against ionizing radiation.

3.2. Fungal Responses to Ionizing Radiation: Cellular Mechanisms, Radiotropism, and Possible Quantum Interactions

Radioactivity, defined as the ability of unstable nuclei to seek stability through the emission of particles or energy during nuclear decay, represents a critical environmental factor for fungi. The most common radioactive emissions include alpha (α) and beta (β^-) particles, and gamma (γ) rays, each with distinct characteristics regarding composition, penetration power, and materials required for shielding. Alpha particles, composed of two protons and two neutrons, have low penetrating power and are easily blocked by skin or paper, but pose a high risk if inhaled or ingested, as exemplified by polonium-210. Beta particles, consisting of high-energy electrons, have intermediate penetration, capable of causing damage to superficial cells and burns. Gamma rays, in turn, are high-energy photons that readily pass through tissues and air, requiring dense materials like lead for shielding and causing extensive damage, such as DNA strand breaks that can lead to mutations and cancer [4].

The interaction of fungi with ionizing radiation has been the focus of intensive studies aiming to understand their cellular responses, particularly in organisms like *Saccharomyces cerevisiae*. Microarray analyses of yeast exposed to X-rays and gamma rays have highlighted the upregulation of genes related to crucial processes such as cell cycle, DNA repair and processing, cellular defense, and carbohydrate metabolism. Notably, gene alterations induced by gamma rays occur later than those triggered by X-rays, a difference attributed to the higher linear energy transfer of gamma rays, which causes more persistent cellular damage. Complementing these findings, genes such as RAD50 and RAD51 (repair), HRP1 (recombination), and CHL1 and CTF4 (chromosomal stability) are fundamental for the resistance of *S. cerevisiae* to ionizing radiation, as well as genes involved in protein degradation and transcriptional regulation [1].

In another fungal model, *Ustilago maydis*, known for its high radiation resistance, survival at high doses depends on a robust set of DNA repair proteins. Unlike *Deinococcus radiodurans*, a model bacterium for radioresistance that uses specialized recombination, *U. maydis* relies on efficient homologous and non-homologous repair pathways. Interestingly, many genes involved in resistance in *U. maydis* have homologs in humans, opening avenues for research into radiation-assisted cancer therapies [1].

Radiation-induced damage mechanisms include single-strand breaks (SSBs), double-strand breaks (DSBs), nitrogenous base damage, and DNA cross-links. In eukaryotes, DSBs are predominantly repaired through homologous recombination but also by non-homologous end joining (NHEJ). Microhomology-mediated recombination (MHMR) in *S. cerevisiae* irradiated with 50 Gy of gamma rays demonstrates that this pathway can generate large-scale genomic rearrangements, enabling the emergence of genetic variants adapted to genotoxic stress conditions. This adaptive plasticity helps explain the radioadaptability observed in melanized fungi described by Zhdanova et al. [2], although it does not account for the rapid growth of some melanized strains following irradiation [1].

In the context of radionuclide mobilization, Tibolla et al. [4] demonstrated through bioleaching experiments that *Aspergillus hollandicus* and Penicillium citrinum are efficient at removing uranium from contaminated rocks. *A. hollandicus* showed greater efficacy at low uranium concentrations, while P. citrinum exhibited superior resistance and capacity at higher concentrations, underscoring the potential of fungi in mobilizing and recovering radioactive metals.

At the molecular level, the interaction between radioactive ions and fungal cellular components is complex. Günther et al. [7] demonstrated that the UO_2^{2+} ion preferentially binds to phosphate groups in the cell wall of Schizophyllum commune, forming uranyl-phosphate complexes with pentagonal bipyramidal geometry, with two axial oxygens and up to four equatorial oxygens bound to phosphates, with bond distances of approximately 3.59 Å. The strong stability of these complexes, confirmed by spectroscopy, highlights the high capacity of fungi to efficiently sequester uranium.

Extremophilic fungi, including radiotolerant species, exhibit extraordinary abilities to survive in lethal environments such as radiation-contaminated zones, polar regions, deserts, and ocean floors. Das et al. [12] emphasize that this resilience results from evolutionary strategies such as genetic modulation induced by abiotic stress, specialized biochemical mechanisms, and physiological plasticity, enabling these organisms to colonize extreme niches and play key roles in bioremediation, astrobiology, and biotechnology.

The possibility that fungi employ quantum processes to cope with radiation is suggested by recent findings in quantum biology. Cao et al. [13] discussed how biological systems can exploit quantum coherence to optimize energy transfer in processes like photosynthesis. Although coherence is not exclusive to the quantum domain, the ability of certain systems to modulate excitonic interactions for energy efficiency raises the hypothesis that analogous mechanisms could occur in melanized fungi interacting with radiation, a hypothesis that requires further investigation.

This connection among ecology, cell biology, biochemistry, and quantum physics is even more evident in observations by Zhdanova et al. [2], who documented directional growth of hyphae toward beta and gamma radiation sources in fungi isolated from the vicinity of Chernobyl. In 86% of observed cases, positive growth occurred toward radioactive sources even without chemical contact with the substrate, indicating positive radiotropism. The hypothesis raised points to the potential role of melanin and quinones present in the fungal cell wall as ionizing radiation sensors capable of protecting cells and possibly triggering biochemical responses that alter growth patterns.

On the biophysical level, Matarèse et al. [14] reviewed how non-targeted effects (NTEs) can be mediated by quantum mechanisms, including entanglement and tunneling, involving signals such as calcium fluxes, photon emissions, and exosomes, provoking responses in cells not directly irradiated. These phenomena, associated with processes of hormesis and genomic instability, highlight the need to integrate quantum physics concepts to fully understand fungal responses to radiation. This understanding encompasses electron transfer, mitochondrial bioenergetics, and ultra-weak bioluminescence emission (biophotons), suggesting a role for bioelectrical and biophotonic fields in cellular signaling and adaptive responses to extreme environmental stresses.

3.3. Melanin in Fungi: Structure, Radiosynthesis, and Quantum Perspectives on Radiation Protection

Melanin, a highly complex biopolymer derived from precursors such as acetyl-CoA and malonyl-CoA, plays an essential role in the adaptation and protection of fungi in environments with high doses of ionizing radiation, such as X-rays and gamma rays. In fungi like *Cryptococcus neoformans* (Cn), melanin is deposited in successive layers adhered to the cell wall, forming so-called “ghosts,” structures that preserve cellular morphology even after the degradation of internal contents. These layers act as physical shields capable of attenuating ionizing radiation with an efficiency equivalent to half the capacity of lead, thanks to the Compton effect, which promotes progressive energy loss of photons as they interact with the electrons present in melanin. This attenuation is enhanced by the spatial arrangement of melanin, as demonstrated by numerical and experimental simulations revealing better radioprotective performance compared to other forms, such as isolated or packed spheres, highlighting the importance of the three-dimensional packing of the pigment for protective effectiveness [5].

The chemical composition of melanin is also a determining factor: pheomelanin, richer in electrons per gram than eumelanin, shows greater Compton scattering capacity, resulting in superior radiation attenuation. This set of characteristics reveals that the physical, chemical, and structural properties of melanin are fundamental to its interactions with ionizing radiation, reinforcing its relevance as an adaptive mechanism in fungi inhabiting extreme environments. These multifunctional properties of melanin - from broad and continuous light absorption to energy dissipation via photothermal effects, combined with its structural organization favoring radiation scattering - support potential applications in radioprotective materials and advanced photonic devices [5].

Studies have shown that during the exposure of melanized fungi to gamma radiation, melanin undergoes oxidation and reacts with hydroxyl radicals generated by water radiolysis, phenomena that play a crucial role in cellular protection. Xie et al. [5] described that although melanin undergoes degradation through carbon–carbon bond cleavage, fungi compensate for this oxidation by producing reducing agents that partially restore pigment function. Furthermore, melanin participates in the oxidation of intracellular NADH, possibly increasing electron transfer or sequestering free radicals, which contributes to the observed drop in ATP levels in irradiated cells. These processes suggest increased energy consumption, possibly related to radiosynthesis phenomena, in which melanin captures energy from radiation to drive biochemical pathways. Although still hypothetical, such mechanisms highlight the complexity of melanin’s functional role in the response to radiation [5].

In the context of quantum biology, Zadeh-Haghighi and Simon [8] extensively reviewed how weak magnetic fields, with energies far below average thermal energy, modulate biological processes through the radical pair mechanism. In this model, radicals with correlated spins transition between singlet and triplet states under the influence of magnetic fields and hyperfine interactions, affecting specific chemical reactions and cellular functions. This mechanism, originally studied in bird magnetoreception, has been proposed to explain phenomena ranging from lithium’s effects in psychiatric disorders to alterations in neurogenesis induced by hypomagnetic fields. In fungi, the possibility that melanin contains stable radicals, such as semiquinones, suggests that similar processes might occur, potentially modulating the radiation response or even enabling energy capture in extreme environments. Magnetic sensitivity could impact functions such as DNA/RNA methylation, receptor activation, and neurotransmitter dynamics, but identifying the exact radicals involved remains a challenge requiring interdisciplinary investigations [8].

Studies by Dadachova et al. [3] showed that melanin undergoes changes in its electronic properties when exposed to ionizing radiation, with increased electron spin resonance (ESR) signal and greater capacity to reduce NADH, suggesting an energy transduction function similar to photosynthesis—a process termed radiosynthesis. Experiments with *Cn*, *Wangiella dermatitidis*, and *Cladosporium sphaerospermum* revealed significant increases in biomass and incorporation of ^{14}C-acetate after irradiation, indicating heightened metabolic activity. These results support the hypothesis that radiation can be used as an energy source by melanized fungi, corroborated by the capacity of isolated *Cn* melanin to attenuate up to 41% of X-rays, highlighting its potential as a radioprotective material [3,4].

The phenomenon of positive radiotropism reinforces this hypothesis, as evidenced by Zhdanova et al. [2], who observed the preferential growth of C. sphaerospermum hyphae toward beta and gamma radiation emitters, suggesting that melanin or quinone pigments act as sensors capable of modulating biochemical pathways in response to radiation. In parallel, Cao et al. [13] demonstrated in photosynthetic complexes that excitonic interactions and dissipative processes can promote highly efficient energy transfer, raising the possibility that melanin in fungi could play an analogous role, although there is no direct experimental confirmation yet.

Casadevall et al. [9] reinforced the idea that melanins can transduce electromagnetic radiation into biochemical energy, supporting the radiosynthesis hypothesis in melanized fungi inhabiting extreme environments. Paleobiological evidence, such as the abundance of melanized fungal fossils from the Cretaceous period - a time coinciding with high cosmic radiation - suggests that melanin was evolutionarily selected as a protective pigment under radiative stress conditions [3]. Felix et al. [6] demonstrated that irradiated melanins generate reactive oxygen species like superoxide and hydrogen peroxide, acting as radical scavengers or generators, which contributes to their protective function and highlights the complexity of their chemical interactions with radiation.

At the genetic level, Dadachova and Casadevall [1] reported that ionizing radiation activates recombination pathways in *Saccharomyces cerevisiae* and *Ustilago maydis*, producing rearrangements that generate adaptive variants under genotoxic stress, but the rapid growth response observed in melanized fungi points to a more direct role of melanin in adaptation. Studies by Grishkan [15] documented a high prevalence of melanized fungi in habitats exposed to intense solar radiation, such as deserts and irradiated slopes, where DOPA-type melanin, with properties of amorphous semiconductivity and radical stabilization, provides protection against UV-B radiation.

At the molecular level, Kim et al. [16] reviewed the importance of free radicals and radical pairs in biological processes sensitive to magnetic fields, suggesting that melanized fungi could exploit similar quantum mechanisms to capture radiation energy. Kishida et al. [17] detailed that the ratio of eumelanin to pheomelanin, defined by dopachrome and dopaquinone reactions, directly influences the pigment's optical and electronic properties. In lichens, Leksin et al. [18] showed that UV-B exposure induces cortex darkening through activation of melanogenesis genes and production of protective metabolites, demonstrating a sophisticated adaptive response.

Finally, Xie et al. [5] highlight that melanin exhibits broad and continuous absorption across the electromagnetic spectrum, with energy dissipation occurring mainly non-radiatively via photothermal effects, and the capacity to generate reactive oxygen species - attributes that reinforce its protective function and suggest potential applications in radioprotective biomaterials. These results support melanin as a multifunctional pigment, central to the adaptation of fungi to extreme environments, connecting biology, quantum physics, and evolution.

4. Conclusion

Melanized fungi represent a fascinating model of adaptation to extreme environments, demonstrating a unique ability to resist and even exploit ionizing radiation as a potential energy source. Melanin, the central pigment in this adaptation, possesses structural and electronic properties that allow it to attenuate radiation with an efficiency comparable to dense materials like lead, in addition to participating in biochemical processes suggestive of radiosynthesis. Evidence of radiotropism and increased biomass following radiation exposure further supports this hypothesis. The convergence of biology, quantum physics, and biochemistry - highlighted by the possible involvement of coherence-based mechanisms and radical pairs sensitive to magnetic fields - points to new frontiers in understanding fungal adaptive responses and developing radioprotective biomaterials. These findings also open promising avenues for applications in the mycoremediation of contaminated environments, astrobiology, and radiation protection technologies.

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