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Keratinophilic Fungi as Eco-Friendly Agents for Poultry Waste Biodegradation: Mechanisms, Applications, and Sustainable Management Strategies

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ABSTRACT

The rapid expansion of the poultry industry has resulted in the accumulation of large quantities of keratin-rich waste such as feathers, nails, and skin, which pose significant environmental challenges due to their recalcitrant nature. Conventional disposal methods, including incineration and chemical treatment, are energy-intensive and potentially harmful to ecosystems. Keratinophilic fungi offer an eco-friendly alternative through their ability to produce keratinase enzymes that degrade insoluble keratin into valuable amino acids and peptides. This study investigates the biodegradation potential of keratinophilic fungi isolated from poultry waste, focusing on their keratinase production, activity, and potential applications in sustainable waste management. The findings highlight promising fungal strains capable of efficient keratin degradation, underscoring their potential role in circular bioeconomy strategies and industrial applications such as animal feed production, fertilizer formulation, and leather processing.

INTRODUCTION

According to the United Nations, the global human population is projected to reach 10.1 billion by 2060 [1]. Such rapid growth poses serious challenges for humanity, including the persistent issue of hunger. In 2020, approximately 690 million people, around 9% of the global population, were undernourished and lacked access to sufficient and nutritious food [2]. Achieving food security, improving nutrition, and ending hunger are among the core Sustainable Development Goals (SDGs) [3]. However, factors such as climate variability, pest outbreaks, and, more recently, the COVID-19 pandemic have hindered the establishment of resilient and efficient food systems. One promising approach to addressing these challenges is the promotion of sustainable agricultural practices [4]. As the human population expands, the demand for agricultural products continues to grow, leading to a corresponding increase in agricultural waste. Among these wastes, keratin-rich materials such as poultry feathers are particularly problematic due to their resistance to natural degradation. Presently, most protein-based agro-

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industrial by-products are disposed of through incineration, landfilling, or chemical hydrolysis. While these methods are effective for waste reduction, they conflict with sustainable economy principles, often causing environmental damage and missing opportunities for resource recovery. In contrast, biodegradation, the use of living organisms and their enzymes to decompose waste, offers an eco-friendly alternative. This method not only minimizes environmental impact but also yields valuable hydrolysis products, such as amino acids and peptides, which can be used in fertilizers, animal feed, and other biotechnological applications. Such an approach supports a circular economy model, making waste management both sustainable and economically viable [5]. Although both bacteria and fungi produce keratinases, bacterial strains are often favored in industrial applications due to their faster growth rates and relatively simpler enzyme purification processes. In contrast, fungal keratinases generally exhibit broader substrate specificity and greater resilience under harsh conditions [6]. This review aims to investigate the biodegradation potential of keratinophilic fungi isolated from poultry waste, focusing on their keratinase production, activity, and potential applications in sustainable waste management.

Keratinophilic Fungi: Biology, Ecology, and Pathogenicity

Keratinophilic fungi are saprotrophic microorganisms capable of degrading highly recalcitrant keratinous structures, including feathers, hair, nails, and skin. Their keratinolytic capacity allows them to utilize keratin as the sole source of carbon and nitrogen. These fungi are classified ecologically into three groups: geophilic, zoophilic, and anthropophilic. Geophilic species inhabit soils rich in keratin debris and are mostly saprophytic. Zoophilic species are associated with animals and can cause infections in keratinized tissues, while anthropophilic species primarily infect humans. Among the notable keratinophilic fungi are members of the genera *Trichophyton*, *Microsporum*, and Epidermophyton. Although most species are harmless in their natural habitats, some act as opportunistic pathogens capable of causing dermatophytosis in humans and animals. To ensure safe application in industrial and environmental processes, several mitigation strategies are recommended. Non-pathogenic or low-risk strains such as *Chrysosporium keratinophilum* should be prioritized. Fungi should be cultivated under controlled conditions, including regulated temperature, pH, and containment, to prevent accidental release. Laboratory and industrial personnel must use appropriate personal protective equipment (PPE) such as gloves, masks, and protective clothing. Residual fungal biomass should be inactivated post-application via autoclaving or chemical sterilization, and adherence to biosafety protocols with routine culture monitoring under BSL-1/2 guidelines is essential. Implementing these measures allows the safe integration of keratinophilic fungi in waste management, enzyme production, and other biotechnological applications without compromising human or animal health [7]. Beyond their biotechnological potential, keratinophilic fungi play a significant ecological role in keratin turnover, contributing to nutrient cycling and the biodegradation of otherwise persistent organic matter [8]. Their ecological versatility has encouraged exploration of diverse environments, including poultry waste, to identify strains capable of efficient keratin degradation.

Keratinolytic Fungi from Different Environments

Chicken-associated microbes, particularly fungi, actinomycetes, and certain bacteria, are effective keratin-degrading organisms due to their production of diverse proteolytic and keratinolytic enzymes [9]. Poultry feathers are rich in nitrogen (15–18% dry weight) and sulfur (2–5% dry weight) and are highly resistant to degradation because of strong disulfide bonds. Only specialized organisms, including dermatophytes, Chrysosporium species, and some molds like Fusarium spp., can biologically break down keratin [10]. Keratin-degrading dermatophytes include anthropophilic species (*Trichophyton rubrum*), zoophilic species (*Trichophyton verrucosum*), and geophilic species (*Trichophyton terrestre*, *Trichophyton georgie*, *Trichophyton ajelloi*, *Microsporum gypseum*, *M. fulvum*). Geophilic dermatophytes and saprophytic Chrysosporium species are widespread in soils enriched with keratinous materials and are also found in bird nests and pellets. Among them, *Chrysosporium keratinophilum* (*Aphanoascus keratinophilus*) is particularly effective, producing keratinolytic and proteolytic enzymes that release nutrients such as ammonia and sulfates [11]. The ecological significance of fungal keratinases lies in their ability to degrade otherwise persistent keratin, contributing to nutrient cycling. Often, this degradation involves a complex interplay of enzymes produced by multiple cooperating microorganisms [12].

Keratin Structure and Degradation Mechanism

There is a huge quantity of keratin waste produced by the poultry processing industry in the form of chicken feathers, consisting of up to 90 percent keratin protein [13, 14]. Keratin is a very stable, fibrous protein, usually rich in a dense lattice of disulfide-bonded structures and the hydrogen bonds, and hydrophobic interactions altogether, of which it is insoluble and resistant against degradation caused by ordinary proteolytic enzymes [15, 16]. Accumulation of such waste material continuously leads to environmental pollution and requires sustainable strategies of management. Structurally, keratin can be classified into α-keratin, β-keratin, and γ-keratin. α-keratins, found in all vertebrates, possess α-helical secondary structures; β-keratins, predominant in reptiles

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and birds, form β-sheet structures stabilized by non-covalent interactions, making them especially resistant to hydrolysis [17-19]. The high cysteine content in keratin contributes to its recalcitrance, as cysteine residues form strong disulfide bridges that maintain the rigid protein structure. Certain microorganisms, particularly keratinolytic fungi, have evolved mechanisms to degrade keratin through the secretion of keratinases and associated proteases[11]. Notably, members of the phylum Ascomycota, such as *Onygena corvina*, are recognized for their potent keratin-degrading capabilities [20]. Indigenous fungal isolates from poultry waste, therefore, represent a valuable, yet underexplored, biotechnological resource. Keratin degradation generally proceeds via two key stages: sulfitolysis and proteolysis. In the sulfitolysis phase, disulfide bonds are cleaved either enzymatically (e.g., by sulfide reductases) or chemically (e.g., by reducing agents), converting cysteine residues into more accessible forms and loosening the keratin matrix [21-23]. This destabilization enables the next stage of proteolysis, whereby keratinases cleave the exposed peptide bonds to give rise to soluble peptides and free amino acids [24]. Keratinases may also act synergistically with other accessory enzymes, and crude enzyme preparations may prove to be more efficient in keratin degradation as compared to pure keratinase. The realization of the structural complexity of keratin and the enzyme reactions provoking its degradation is essential in the realization of effective, eco-friendly techniques of converting poultry wastes into useful products like biofertilizers, livestock feed, and bioactive molecules [25]. Subsequently, proteolysis takes place after the staining sulfitolysis whereby the exposed peptide bonds are broken and soluble peptides and free amino acids are released by keratin conductivity. There are frequently greater rates of Keratin degradation by crude enzyme preparations as compared with purified Keratinase alone, indicating that there is an interaction between Keratinase and other accessory enzymes. This two-step enzymatic process is essential for the complete biodegradation of keratin-rich materials [26]. Understanding these mechanisms also informs the strategies for isolating and screening keratinophilic fungi capable of producing potent keratinases, thereby bridging laboratory studies with practical applications.

Isolation and Screening of Keratinophilic Fungi

Keratinophilic fungi are specialized microorganisms capable of degrading keratin, the highly stable structural protein found in feathers, hair, nails, and other keratinized tissues. Their enzymatic keratinolytic activity enables the breakdown of keratin into amino acids and peptides, making them valuable for biotechnological applications, including poultry waste management [27, 28]. These fungi are commonly isolated from soils, poultry litter, and keratin-rich environments using keratin baiting techniques, where materials such as hair, feathers, or nails serve as selective substrates. Dominant genera include *Chrysosporium*, *Trichophyton*, *Microsporum*, *Aspergillus*, and *Penicillium* [29, 30]. Strains are screened for keratinase activity using keratin agar or quantitative feather degradation assays, and potent isolates are selected for further studies under controlled fermentation conditions. Several studies have demonstrated the potential of keratinophilic fungi in poultry waste biodegradation. For instance, Shestakova *et al.* [5] highlighted the environmental advantages of microbial keratin degradation over conventional disposal methods like incineration or landfilling, emphasizing its role in sustainable waste management and circular economy practices.

Biodegradation of Waste: Microbial Approaches

Building upon laboratory studies of microbial keratin degradation, these fungi can be further utilized in industrial and agricultural settings to transform poultry feather waste into value-added products such as animal feed, fertilizers, and bioactive compounds. Poultry feathers are a significant by-product of the poultry industry, comprising about 5–7% of chicken weight and accounting for several million tons of waste generated annually [32]. These wastes are composed of approximately 90% keratin, a structural protein characterized by high stability due to disulfide bonds [33]. While feathers possess desirable properties such as warmth retention, sound insulation, flexibility, and low density, their accumulation in landfills poses environmental concerns due to their resistance to natural degradation [34, 35]. Microbial degradation of feathers offers an eco-friendly solution for waste management. Various microorganisms, particularly keratinolytic fungi, can hydrolyze keratin into soluble proteins and amino acids by producing keratinase and protease enzymes [11]. These fungi play a crucial role in converting recalcitrant keratin into value-added products, with potential applications in agriculture, biotechnology, and other industries that utilize keratin-containing raw materials [27]. The Ascomycetes group, including species such as *Onygena corvina*, is well known for its keratin-degrading abilities [21]. Despite promising results, the practical application of fungal biodegradation faces several hurdles. The efficiency of degradation can be influenced by environmental factors such as temperature, pH, and moisture content. Additionally, the degradation products may be toxic or accumulate in the environment, posing further ecological risks. The economic viability of large-scale fungal biodegradation processes also remains a significant challenge [36] (Table 1).

Table 1: Common Keratinophilic Fungi Isolated from Poultry Waste and their Keratinolytic Properties

Fungal Genus / Species	Sources	Keratinase Activity	Optimum pH	Optimum Temp (°C)	References
Scopulariopsis brevicaulis	Poultry farm soil, feathers	~3.2 KU/mL; ~79% feather degradation	alkaline (≈ 8)	~35°C*	[37]
Trichophyton mentagrophytes	Poultry soil, feather waste	~2.7 KU/mL; ~72% feather degradation	~7.0–8.0	~30–40°C	[38]
Aspergillus flavus (strain K-03)	Feather meal compost/medium	Moderate to high; purified keratinase active up to 2.39× purification, broad activity	~8.0	~45°C	[39]
Chrysosporium keratinophilum	Poultry litter-enriched soil	Potent keratinase producer under submerged culture†	~7–9	mesophilic (28–37°C)	[40]

Applications of Keratinolytic Biodegradation in Poultry Waste Management

Wastes generated from livestock industries such as poultry, swine, and cattle farming are rich in keratin. Among these, chicken feathers represent the largest source, accounting for nearly 9% of a bird's total body weight, with global production estimated at approximately 11.85 million tonnes annually. Despite this abundance, most feathers are discarded, and only a small proportion is reprocessed into products such as feather meal or fertilizers. Improper disposal can make feather residues reservoirs of pathogenic microorganisms, including *Salmonella* spp., *Staphylococcus* spp., and *Clostridium* spp., as well as carriers of veterinary drugs, antibiotics, and chemical contaminants, all of which contribute to soil and water pollution [41]. Current feather disposal practices, such as incineration, eliminate waste but release greenhouse gases and prevent resource recovery [42]. Other non-biodegradation methods similarly pose environmental drawbacks and fail to align with sustainable waste management goals. In contrast, biodegradation using microbial keratinases presents a green alternative, transforming feather waste into value-added products such as fertilizers, animal feed additives, bioelectricity, and biofuels [43]. Both bacteria and fungi produce Keratinases (EC 3.4.21/24/99); while initially linked mainly to pathogenic dermatophytes, non-pathogenic keratinolytic strains have since been identified [44]. Using poultry feathers as a growth substrate for keratinase-producing microorganisms not only lowers enzyme production costs but also supports circular economy practices and reduces the environmental footprint of poultry farming [45].

CONCLUSION

Keratinophilic fungi isolated from poultry waste represent a promising and eco-friendly solution for the biodegradation of highly recalcitrant keratinous materials. Through their keratinase activity, these fungi can efficiently convert feathers, nails, and other keratin-rich waste into valuable by-products such as amino acids, peptides, and biofertilizers, supporting both environmental sustainability and circular bioeconomy strategies. Beyond waste valorization, their application can reduce reliance on energy-intensive or chemically harsh disposal methods, mitigating environmental pollution and greenhouse gas emissions. However, the presence of opportunistic pathogenic strains highlights the need for careful strain selection, controlled cultivation, and strict adherence to biosafety protocols to prevent human or animal health risks. Future research should focus on optimizing fermentation and degradation conditions, developing non-pathogenic or genetically safe strains, and integrating keratinophilic fungi into large-scale industrial processes. Moreover, combining fungal biodegradation with other biotechnological approaches such as microbial consortia or enzyme engineering may enhance efficiency and expand the range of feasible applications, including sustainable animal feed, biofertilizers, and novel bioproducts. Ultimately, strategic deployment of keratinophilic fungi offers a scalable, environmentally responsible pathway to transform poultry waste into high-value resources.

Authors Contribution

Conceptualization: TB, TH
Methodology: TB, A, AAK, HI
Formal analysis: TB, AM
Writing review and editing: TB, TH, AM

All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

All the authors declare no conflict of interest.

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