Asian Journal of Biology

Volume 20, Issue 11, Page 11-24, 2024; Article no.AJOB.124652
ISSN: 2456-7124

Distribution Pattern of Keratinophilic Fungi in Different Ecological Conditions: A Review

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ajob/2024/v20i11445

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/124652

Review Article

Received: 22/07/2024
Accepted: 01/10/2024
Published: 04/10/2024

ABSTRACT

Keratin, an insoluble protein with numerous disulphide bonds is highly resistant to proteases and serves as one of the major defiant pollutants. The keratinophilic fungi are known to use keratinous substances such as skin, hair, nail, fur and feather for their growth and survival. The biodegradation of keratin by microbes provides a medium to remove environmental contamination and is even considered as substitute to physical and chemical treatments. The keratinolytic potential of these fungi play an important role in decomposition of keratin. The present review highlights the role of various ecological factors on the distribution pattern of keratinophilic fungi. Also, the effect of various biotic and abiotic factors on their growth is discussed. Among biotic factors growth is largely dependent on the presence of humans, birds, animals and abiotic factors include temperature, pH, humidity, organic matter in soil. Further, the potential keratinous substrates such as hairs, feathers, pellets are also described. Study of keratinophilic fungi is important as they have

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Cite as: *Rathore, Poonam, and Seema Bhadauria. 2024. "Distribution Pattern of Keratinophilic Fungi in Different Ecological Conditions: A Review". Asian Journal of Biology 20 (11):11-24. https://doi.org/10.9734/ajob/2024/v20i11445.*

application in industrial sector. Further, isolation of keratinases is also helpful in pharmaceutical and leather industry. Biotechnological uses of these fungi help in cleaning the environmental waste. This review may help as a guide to use the keratinases at industrial level that is to extend the laboratory research to industrial level.

Keywords: Keratinophilic fungi; keratinous substrate; ecological factors; decomposition.

1. INTRODUCTION

A large number of microbes exist in the world ranging from bacteria, fungi, algae, protozoan etc where fungi forms the second largest group of microorganisms after the insects [1]. Fungi are cosmopolitan in distribution; some are aquatic and others are terrestrial. Many are parasitic on plants, animals and human beings. The body consists of branched and filamentous hyphal forms, a net like structure called as mycelium. These are devoid of chlorophyll so heterotrophic in nature, hence considered as parasites, saprotrophs or symbionts.

Fungi are found in different ecological habitats and depend on particular nutrition and environmental conditions for its perpetuation [2,3]. Fungi play a very important role in environment [4,5]. Ecological factors affect the distribution pattern of fungi [6,7]. Growth and reproduction of fungi are dependent on several environmental factors and even a minute change in these requirements cannot be tolerated [8,9]. Although the sustenance needs of fungi are simple but different fungi require different physical, chemical and physiological conditions [10]. The effect of different culture media and several physiological factors on fungal growth have been studied by several workers [11,12]. One of the environmental factors which affect spore germination is temperature [13]. There is an optimum, maximum and minimum temperature for spore germination [14]. Optimum temperature for fungal growth is 15-35^0 C [15]. Not only temperature but pH also affects fungal growth directly or indirectly [16,17]. Optimum pH for the growth of keratinophilic fungi is 5-8 [12,18]. The soil acts as main reservoirs for all microorganisms including fungi [1].

The biodegradation of keratin by microbes provides a medium to remove environmental contamination and is even considered as substitute to physical and chemical treatments. The genetic level studies of keratin breakdown and identification of involved keratinases require metagenomic annotations [19]. Biological degradation of solid waste is highly effective method as it is economical, ecological and highly efficacious [20]. Biotechnological applications of keratinases include keratinous waste management, in textile industry, in leather industry for cleaning animal hides, prion decontamination, in detergents. Other applications include pearl bleaching and bird’s nest processing. They can even be used in medicines and cosmetics as callus removal, transfer accelerators, acne treatment, personal hygiene products and earwax removal. They also have commercial use [21].

2. KERATINOPHILIC FUNGI

Keratinophilic fungi are those fungi which grow and perpetuate on keratinous substances such as skin, hair, nail, fur, feather, horn, hoof and beak of the birds. They use keratin as a source of carbon [22]. Keratinophilic fungi generally colonize keratinous substrates. Some of them are keratinolytic and are ecologically important as they can decompose *α*-keratins, insoluble fibrous proteins [23]. Those keratinophilic fungi which cause most of cutaneous infections are referred to as dermatophytes [24]. The dermatophytes have the ability to take over keratinous tissue of the body such as skin, hair and nails [25].

Keratinophilic fungi grow on various keratinous materials and break them into their low-molecular-weight components. Keratinophilic fungi include a variety of filamentous fungi, mainly comprising hyphomycetes, including dermatophytic and a large number of non-dermatophytic filamentous fungi and several other taxonomic groups. Generally, keratinophilic non-dermatophytic filamentous fungi exist as saprophytes in soil and can even act as plant pathogens [26]. Keratinophilic fungi are ecologically important and exist in the nature with wide distribution patterns and cause human and animal mycological disorders [27]. Keratinophilic fungi are practically pathogenic saprotrophs that mark out as opportunistic pathogens [28]. *Microsporum gypseum, M. cookei, Chrysosporium keratynophilum* are pathogenic strains of these fungi which generally cause dermatomycoses in humans and animals.

Dermatophytes are group of fungi capable of infecting humans and other animals, growing on their keratinized tissue (skin, hair and nails) and cause dermatophytoses, commonly known as ringworm. They cause cutaneous infection and invade only non-living cornified layers as they cannot invade deeper tissues of host [29,30]. The causal organisms of dermatophytoses belong to three anamorphic genera namely *Epidermophyton, Microsporum and Trichophyton.* The genera can be distinguished on the basis of morphology and formation of conidia [31,32,33].

A correlation was found between association of dermatophytes with soil and conidia production by them, lesser the growth of a dermatophyte on the dissociated keratin, lesser are the chances to form conidia. The formation of heterothallic teleomorphs by them is also influenced by their association with soil [35]. The arthroconidium is the structure found in association with infected hairs and skin scales. They may persist in environment for long and can serve as an environmental source of contagion.

2.1 Types of Keratinophilic Fungi

Those keratinophilic fungi which invade the keratinous tissues such as skin, nails, hair and live parasitically in man and animals; share certain morphological features, constitutes a special group called dermatophytes. Deramtophytes can be classified into three ecological groups: anthropohilic, which use human being as its hosts, zoophilic, grows on animals and geophilic dermatophytes, occur in soil as saprophytes [34,26].

Anthropophilic fungi are known to infect humans and rarely infect animals [36]. Zoophilic fungi are associated with animals but can infect humans too. Geophilic fungi are dependent on keratinous waste like hairs, feathers, hooves and horns of animals after they have been shed. During the course of evolution, many of the geophilic fungi have adopted a pathogenic life cycle and are now serve as potential agents of fungal diseases in humans and animals. So, geophilic dermatophytes are known to be ancestral to the pathogenic dermatophytes as they have ability to decompose keratin and are closely associated with animals living in contact with soil [37]. These species cannot be clearly demarcated as they are interrelated to each other. Some zoophilic species can be isolated from soil as well as from fur of healthy animals [38]. Although geophiles are known to persists in soil, some geophilic dermatophytes overlap in ecology with zoophiles. Although anthropophilic species cause human dermatophytoses but there is a significant role of domestic animals also in transmission of dermatophytes to man, raising a need for humans to use appropriate measures when in contact with animals.

2.1.1 Geophilic fungi

Geophilic fungi are keratinophilic fungi that colonize keratinous substrates (feathers, hairs, animal remains) present in the soil, on soil surface and in other natural environments. They are keratinolytic fungi with special physiological function of decomposing native keratin. They utilize native keratin (chicken feathers) as carbon and energy source [39]. Geophilic dermatophytes includes *Trichophyton* Malmsten and *Microsporum* Gruby (anamorphs) and their respective teleomorphs: *Arthroderma* Berk. and *Nannizzia* Stocklade. The *Chrysosporium* group consists of two keratinolytic genera, *Chrysosporium* Corda and *Myceliophthora* Cost (anamorphs). Their teleomorphs are classified in the genera *Arthroderma* Berk., *Aphanoascus* Zukal and *Ctenomyces* Eidam. or remain unknown [40].

Two new keratinophyton species were reported namely *Keratinophyton kautmanovae* sp. nov. and *K. keniense* sp. nov., from soil samples collected from two different locations of Africa and Europe. Study utilised data collected from phylogenetic studies involving the internal transcribed spacer (ITS) region and the nuclear large subunit (LSU) rDNA, as well as their unique phenotype. Besides, the *K. keniense* constitute the first described new species for this genus from Africa [41].

3. KERATINOLYTIC POTENTIAL

Keratin is an insoluble protein having fibrous helical structure with numerous disulfide bonds making it resistant to proteases but can be easily digested by keratinase enzymes [42]. Keratin is one of the main components of hair, skin and feathers and is also found in soil [43]. Natural keratin material consists of both keratinous as well as non-keratinous components along with other simpler compounds, e.g., amino acids, urea, which is up to 10% of the substrate's dry weight [44]. This enables growth of non-keratinolytic fungi also on native keratin [45].

Keratinases are known to provide pathogenecity to dermatophytes and help them to cause dermatophytoses or ringworm disease in humans and animals [46]. Keratinases are known to have industrial applications such as they are used in leather industry, poultry feed, cosmetics, diagnostics and pharmaceuticals [47, 48, 49, 50]. There are other applications of Keratinolytic enzymes in biotechnological field such as hydrolysis of poultry feathers and dehairing of bovine pelts [51]. Keratinases have also been shown to be useful in processing waste in the poultry and leather industries [52].

The process of fungal keratinolysis can be categorized under three phases namely deamination, sulphitolysis and proteolysis [53]. Deamination is the process of removal of ammonia conditioned by an elevated level of nitrogen in native keratin upto 16% in hair [53] and a low C:N ratio in these substrates [40]. N-$NH4^+$ accumulation leads to alkalization of environment which is important for enzymatic disruption of many keratins' disulphide bridges responsible for its resistance to the activity of proteolytic enzymes. Sulphitolysis involves the disruption of S-S bonds and occurs with the help of inorganic sulphite released by the fungus [54,55]. This leads to denaturation of keratin and leads to proteolysis with alkaline or neutral proteases released by these fungi [53]. While growing saprophitically on native keratin, keratinolytic fungi leads to oxidation of 70% of carbon to CO_2, liberate 30-60% of nitrogen as ammonia and convert 30-50% of sulphur into sulphates [40]. This enables keratinolytic fungi to play a key role in recovering carbon, nitrogen and sulphur present in animal remains containing keratin.

$$\text{Keratin} \xrightarrow[\text{Oxidation}]{\text{Keratinophilic fungi}} CO_2 + NH_4^+ + SO_4^{2-}$$

An investigation was done to analyse keratinolytic activity of 37 pigmenting and non-pigmenting strains of *Trichophyton ajelloi* collected from loamy soil and chernozem. It was concluded that in loamy soils, pigmenting strains and in chernozem, non-pigmenting strains proved to be highly efficacious in degrading keratin. On comparison, it was found that the strains isolated from loamy soils have better keratinolytic activity. They also noted the continuous increase in keratinase activity and soluble proteins in cultures throughout the experiment. The results were highly significant as keratinolytic property of *Trichophyton ajelloi* can be applied to synthesise sulfur containing fertilizers for the plants. Higher amount of ammonium ions was released by pigmenting strains of the fungi obtained from loamy soils [56].

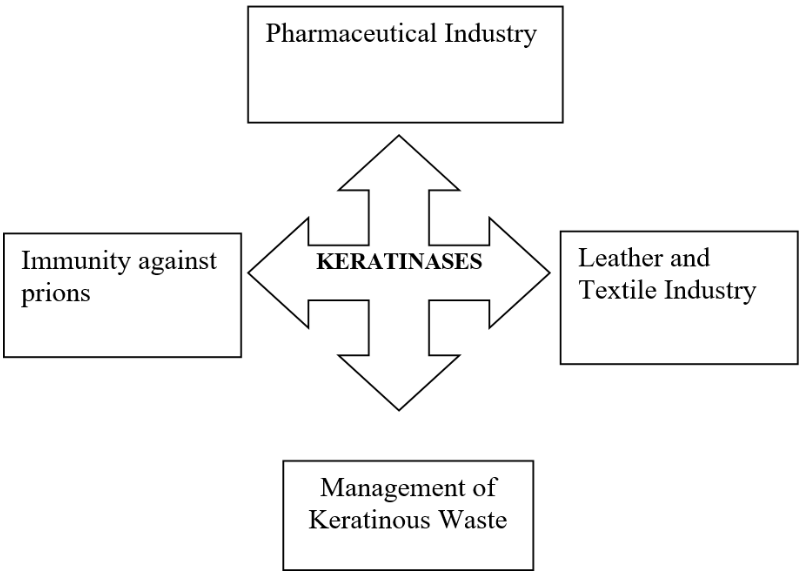

Fig. 1. Application of Keratinases

4. KERATINOUS SUBSTRATES

Birds' nests are one of the microenvironments consisting of variable amounts of keratinous substrate such as feathers, hairs, pellets, prey remains and have distinct levels of humidity and pH [57]. Some other substrates include hairs of wild animals [58,59], water [60], plant debris [61] and dung [62]. Besides, sewage sludge accommodates high quantities of keratin remnants with specific physicochemical and microbiological characteristics. So, it can be presumed that keratinophilic fungi are found in plenty in a sludge environment.

In different aquatic habitats, quantitatively and qualitatively different communities of keratinophilic fungi are found. This might be due to difference in the levels of water contamination with sewage and natural environmental pollutants [63]. The distribution and occurrence of cycloheximide-resistant, keratinophilic and other fungi in aquatic habitats, including sludge and wastewater have been studied by various investigators [64].

5. ECOLOGICAL FACTORS AFFECTING GROWTH OF KERATINOPHILIC FUNGI

5.1 Abiotic Factors

The occurrence of dermatophytes is mainly dependent on the geographical location, season or living conditions and the climates to which the susceptible animal or human is exposed [65].

The variable distribution patterns of keratinophilic fungi depends on several environmental factors including biotic and abiotic. Among biotic factors, existence of keratinophilic fungi is largely dependent on the presence of humans, birds and animals [6, 66]. Abiotic factors include temperature, pH, soil moisture, chemical composition and content of the organic matter in soil. *T. ajelloi*, is an exception which can grow in soils with low pH.

5.1.1 Soil

Vanbreuseghem was the first to report the incidence of dermatophytes in soil by using the hair bait technique [67]. Since then, studies on keratinophilic fungi of soil were carried out throughout the world [68,69,66,70,71]. The soil proves to be one of the complex microenvironments for the growth of several fungi. Fungal floras vary with the type of soils but most of them are cosmopolitan [72]. Soil is the principal habitat of fungi [73]. Soils with abundant keratinous residues act as both a permanent or occasional pool for dermatophytes and other keratinophilic fungi and are a major source of potential infection for humans and animals [23]. Keratinous substrates provide the most favourable environment for the development of keratinophilic fungi [74]. In India, several keratinophilic fungi were reported from hospital dust and soil samples collected from various public places. Reports states that out of the total dermatophytes isolated from their soil samples, *Trichophyton mentagrophytes* occurred most commonly, followed by *Microsporum gypseum* and *Chrysosporium tropicum*, *C*. *keratinophilium*, *M*. *nanum*, *T*. *terrestre* and *C*. *lobatum*. Out of the non-dermatophytes identified, *Aspergillus fumigatus* and *Penicllium chrysogenum* occurred most regularly, with each contributing 5.4% to the total fungal flora, while *Microsporum fulvum* and *Candida parapsilosis* contributed at least 1.2% [75].

Soil acts as connecting epidemiological and evolutionary link that connects geophilic, zoophilic and anthropophilic keratinophilic fungi [68]. The diversity of keratinolytic fungi was analysed in soil samples collected from Jhansi, India. The isolates include both the keratinolytic and phytopathogenic fungi and reported the significant presence of G*raphium keratinophilum, Candida albicans, Microsporum fulvum, Chrysosporium lobatum, Onocladium flavum, Alternaria alternata, Aspergillus niger, Penicillium citrinum.* 75% of the fungi belongs to the Onygenales order of division Ascomycota. They concluded that the biodiversity of fungi is affected by the different factors in addition to the existence of animals in the area [76].

5.1.2 Soil pH

Bőhme and Ziegler were the first to report the variance in species composition of keratinophilic fungi with reference to pH range. Enzymes of keratinophilic fungi are generally active at pH 6.9 [77]. The keratinophilic fungi can be divided into three groups on the basis of pH values namely acidophilic *Arthroderma uncinatum, A. curreyi* and *Chrysosporium tropicum*, neutrophilic *Nannizia incurvata* and alkalophilic *A. quadrifidum, Ctenoymces serratus* and *Chrysosporium keratinophilum* [78]. The effect of soil pH and climate types on the frequency of keratinophilic fungi was investigated by analyzing soil samples collected from Iran and concluded that there is a relation between frequency of keratinophilic fungi and the soil pH [79]. Some reports states that keratinophilic fungi are not seen in soils with low pH such as 3 to 4.5 [75]. The correlation between soil pH and spread of dermatophytes in Jaipur city was tested. From pH range 7 to 9, *Trichophyton verrucosum, Microsporum audouinii and M. canis* were isolated whereas from pH range 6.5 to 9.5, *Chrysosporium tropicum* followed by *Trichophyton mentagrophytes* were isolated. Results concluded that garden soil and roadside soil with pH 6.5 to 8.5 were most favourable for the occurrence of keratinophilic fungi except *Fusarium moniliforme* which can be isolated from acidic soil of pH 3 [80]. Fungi were recovered from neutral soil with pH 7 including *Exserophilum* sp., *Microsporum audouinii, Trichophyton verrucosum* for the first time from Jaipur, India [81]. The highest growth was reported at pH 5-7. Among which *Chrysosporium indicum* was recovered at pH 3 and remaining two isolates from pH 7 and concluded that extremes values of pH are not suitable for fungal growth [82]. *Arthroderma multifidum*, showed highest growth at pH 8 [83]. pH 7.5 proved to be optimal for mycelia growth whereas sporulation was highest at pH 6.5 [84]. Low and high pH such as 5.5 and 8.5 is not much effective for growth and sporulation. The effect of pH on the growth of keratinophilic fungi was analysed and it was found that pH 7.00 to 7.99 is the most favourable. *Chrysosporium indicum* were found from pH 8.00 to 8.99 whereas *Fusarium solani*, *Microsporum canis* and *Trichophyton mentagrophytes* from pH 7.00 to 7.99 [85]. Species generally grow in pH range of 5.8 to 9.1 [86].

5.1.3 Soil moisture

A positive correlation has been found between number of isolates and moisture content of soil [73]. *Arthroderma uncinatum* and *Ctenomyces serratus* shows highest spore germination at 90-100 % relative humidity [57].

5.1.4 Organic matter content

High distribution frequency generally occurs in rural than in urban areas and also in stables due to the high organic matter [87]. The existence of keratinophilic fungi in waterlogged soils of paddy field were examined at several stages of cultivation namely transplantation, tillering, milking and maturation. Reports identified 14 species of *Chrysosporium* all-round the cropping season. Among *them C. keratinophilum* followed by *C. tropicum* were the most prevalent geophilic species [71].

5.1.5 Chemical composition of soil

The uneven distribution is found due to dissimilar physiology and resistance to variations in environmental factors. The species diversity of keratinophilic fungi was analyzed in four different soil types having different physiological and chemical properties. Identification included *Chrysosporium* sp. and geophilic dermatophytes namely *Trichophyton ajelloi* and studies concluded that occurrence of *Trichophyton ajelloi* was high in acidic soils whereas prevalence of *Chrysosporium keratinophilum* increased with an increase in the content of humus, nitrogen, $CaCO_3$ and phosphorus in the soils [88]. Garden soils were proved to be more appropriate for fungal growth than playground soils due to high organic debris, keratinous substrates and plant litter present in these soils [89]. Higher proliferation rates of keratinophilic fungi occur in loamy soil, chernozem and rendzina which have high amount of slit and clay in comparison with sandy soil which have high content of sand.

5.1.6 Depth of soil

The relation between occurrence of keratinophilic fungi and depth of soil was studied by collecting forty soil samples from surface, 10, 20 and 30cm depth. The study revealed that number of species decreased with increased sampling depth [90].

5.1.7 Temperature

Keratinophilic fungi shows maximum growth at 25-30^0 C i.e., mesophilic in their occurrence. *Chrysosporium keratinophilum, C. tropicum, C. queenslandicum* occur at 37^{0}C. Optimum temperature range for most of the keratinophilic fungi is 25-27^{O}C and above 40^{0}C there is no fungal growth [57]. The limited heterogeneity of keratinophilic fungi was reported due to hot and arid climate [91].

Very high or very low temperature disturbs the growth of fungi [8]. Three keratinophilic fungi were isolated from Jaipur, India and highest growth was reported at 25°C to 35°C temperature. Among these *Chrysosporium indicum* was recovered from 15ºC to 35ºC temperature and remaining two isolates were observed at 35ºC. Extremes values of temperature are not suitable for fungal growth [82].

Arthroderma multifidum, a keratinophilic fungi was isolated from soils of poultry farmhouse of Rajasthan, India showing highest growth at 25^0C temperature [83]. 30^0 C temperature was reported to be the most optimal for mycelia growth and sporulation [84]. Survival period of dermatophytic and keratinophilic fungi was investigated in unsterilized soil, sterilized soil and Sabouraud's dextrose-agar medium at three different temperature conditions and verified 11±1ºC to be the most suitable temperature condition for all tested fungi up to two years of studies [92].

5.1.8 Humidity

The effect of humidity was studied on the perpetuation and reproduction of geophilic keratinophilic fungi isolated from soil samples collected from Public Park. They analyzed that a positive correlation occurs between growth and humidity. They isolated *Chrysosporium tropicum* and *Trichophyton mentagrophytes* and concluded that *Chrysosporium tropicum* manifested highest growth and sporulation at 75% and 50-95% relative humidity respectively while *Trichophyton mentagrophytes* showed highest growth and sporulation at 95% and 62-95% relative humidity respectively [8].

5.1.9 Seasonal variations

Floor dust samples were collected from January to December 2005 and following dermatophytes were obtained-*Aphanoascus fulvescens, Aphanoascus sp., Arthroderma cuniculi, Chrysosporium lucknowense, Gymnoascus uncinatus* and *Trichophyton rubrum*. Keratinophilic fungi showed a peak in April and decline in November [93].

The effect of seasonal fluctuations on distribution pattern of keratinophilic fungi was studied in 19 samples collected from Baghdad swimming pools in the course of four seasons. *Aspergillus* genus was found abundantly, followed by *Trichophyton* and *Fusarium* and conclusion was drawn that the summer season is the most favourable for fungal infection [94]. The seasonal variation and niche preference of keratinophilic fungi was also analyzed [95]. The keratinophilic fungi were observed in a wetland agro ecosystem in Kerala, India. Maximum species were recorded in North East monsoon season followed by early summer (29 species), late summer (19 species) and south west monsoon season (18 species). Due to the presence of maximum organic matter and keratinous materials Vembanadu wetland agro ecosystem proves to be the best environment for perpetuation of keratinophilic fungi. These fungi are symbolic of environmental pollution [96]. Climatic conditions during monsoon season favour the growth and sporulation of the fungi [92].

5.2 Biotic Factors

5.2.1 Birds and animals

Isolation rates of keratinophilic fungi are higher in soil samples gathered from the farm lands and poultries [52]. The distribution of keratinophilic fungi is largely dependent on physical and chemical properties of the nests such as humidity, pH. Nest is a potential source of pathogenic infections and acts as reservoirs of geophilic fungi causing dermatomycoses and systemic mycoses in humans and mammals [97]. The mycoflora of hair of cows, donkeys, rabbits, cats and dogs were evaluated and analysed the occurrence frequency of keratinophilic fungal species in these samples and reported that majority of them were either mycotic agents or isolated from animal and human lesions. Seven species of dermatophytes were recovered. They concluded that maximum dermatophytes were recovered from cats followed by cows, rabbits, donkeys, dogs and discussed that these animals play important role in transmission of these fungi [98].

The keratinophilic fungi were also studied in clovenhooves and horns of goats and sheep where *Chrysosporium* was the most commonly reported genus on the different substrates [99]. The highest frequency was reported from animal resorts as compared to street soil samples [100]. The frequency of keratinophilic fungi is higher in compost with higher feather proportion. *Chrysosporium* group was predominantly found [101]. The occurrence of keratinophilic fungi was screened in soils stressed by the presence of animals and presence of opportunistic pathogen (*Pseudallescheria boydii*) was reported. Commonly occurring fungi were *Trichophyton ajelloi*, geophilic dermatophytes *Microsporum gypseum, Chrysosporium keratinophilum* and *Chrysosporium queenslandicum* [102]. The isolation frequency of keratinophilic fungi was higher from terrestrial birds mainly water fowl and migratory birds are an important vehicle for dissemination of dermatophtyes [103]. Keratinophilic fungi occur amply in soil from fold-grazed pasture than non-fold-grazed pasture due to the occurrence of high animal activity in fold grazed pasture [104]. The presence of keratinophilic fungi and dermatophytes were analyzed from playground soils of Ujjain, India and it was observed that their occurrence is also affected by the vertebrate and human activity. On administering these fungal samples in Juvenile pteropodid bats it was found that oral candidiasis is usual in domestic pteropodid bats [105]. The occurrence of Keratinophilic and Keratinolytic Fungi was studied inside and outside of three caves in Tatra Mts., Slovakia (Brestovská, Demänovská L'adová and Demänovská Slobody). It was observed that maximum fungal species were from inside of caves and highest values of the Shannon diversity index was recorded inside the Demänovská Slobody Cave. This was the first report of *Arthroderma eboreum, Arthroderma insingulare, Chrysosporium europae, Chrysosporium siglerae, Keratinophyton wagneri, and Penicillium charlesii* in underground sites. *Arthroderma quadrifidum* was the most common fungal species in their samples. A positive correlation was specified between fungal biodiversity of this group and anthropogenic and animal activity in these sites [106].

5.2.2 Interaction with humans

The invasion of human hair by *Trichophyton mentagrophytes, T. rubrum* and *T. ajelloi* was studied. It was observed that mycelium penetrates into the cuticle and digestion of cortex was noticeable maximum by *T. mentagrophytes* [107]. Keratinophilic fungi are more in urban areas than in rural areas because in urban areas human population and their activities, substrate and source of the keratin required for keratinophilic fungi is higher than the rural area. *Engyodontium album* was isolated for the first time from Iran soil [79].

The process of keratinolysis and its morphological expression in hair digestion by some of the species showed surface erosion and radial penetration [108]. The degradation of human hair by keratinophilic fungi was studied by using the biochemical and microscopic analysis. Reports states that all test fungi employed human hair as carbon and nitrogen source. *M. gypseum* exhibited maximum activity whereas *Auxarthron conjugatum* showed minimum hair degradation activity [109]. Human hair, cattle hair, human nail, horn and feather serves as good keratinous substrates as *Chrysosporium, Microsporum, Trichophyton* genera grow on all the substrates. Management of keratinous waste is essential for lowering the risk of dermatophytosis [110]. *Chrysosporium pannicola* was the most frequent species from soils of Malwa region (M.P.) [111].

6. CONCLUSION

Dermatophytes do not cause life threatening infection but can cause hair and nail loss, inflammation, pustules, itching and scaling (dermatophytoses) as they are constantly associated parasites of humans. Keratinous waste is one of the major recalcitrant pollutants in nature. Keratinophilic fungi possess the potential biotechnological applications which can be utilized to degrade keratinous waste and to recycle the poultry waste for the protection of environment. Fungal keratinases prove to be eco-friendly alternative for decomposing and recycling pollutant in nature. Using keratinophilic fungi for hydrolysis of keratin not only proves to be ecologically safe but also economically fruitful. Keratinophilic fungi act as nature's keratin degrading machines. The keratinolytic potential of fungi is important ecologically as it allows the degradation of keratinous waste present in soil. The fermentation broth of fungi and isolated keratinases can be of potential application in leather and textile industry. The presence of keratinophilic fungi act as bioindicator of environmental pollution with animal faeces, hair, plant debris and other keratinous substrate. The hydrolyzed keratinous products can be used as fertilizers for plants (N, S) and feed for animals (amino acids). They can be used in agricultural practice due to their keratinolytic activity. There is still scope of isolation of many more keratinophilic fungi from Indian soils and there is need for further ecological studies of this important group of microbes as their distribution, disease cycle and keratinolytic potential is affected by a variety of ecological factors. Understanding the role of ecological factors on survival of these fungi can help researchers to study management of these fungi.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

ACKNOWLEDGEMENTS

The authors would like to thank Head of the Botany Department, University of Rajasthan, Jaipur for providing basic infrastructure facilities. One of the authors would also like to thank UGC-CSIR, NEW DELHI for the financial support.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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