

Climate Change and Emerging Fungal Infections in India: Ecological Niche Modeling, Epidemiological Implications, and Public Health Response

Running Title: Climate Change and Emerging Fungal Infections

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Abstract: Climate change is accelerating the emergence, distribution, and clinical burden of fungal infections worldwide. India bears a disproportionately high epidemiological impact due to its diverse climatic zones and ecological heterogeneity, which amplify these trends and produce marked geographic variation in fungal endemicity. The rising burden of serious fungal infection, estimated to affect 60 million Indians annually, surpasses that of several historically dominant infectious diseases. Increasing ambient temperatures, modified patterns of precipitation, and the heightened occurrence of extreme weather conditions are major factors altering fungal ecology, fostering thermotolerance, expanding geographic distribution, and amplifying human exposure. The contemporary prevalence of multidrug-resistant pathogens such as *Candida auris*, along with climate-sensitive infections such as aspergillosis, mucormycosis, and other dimorphic fungi, reflects both enhanced clinical complexity and mounting public health risk. These vulnerabilities were

further emphasized by pandemic-associated mycoses during COVID-19, which were driven by immune dysregulation, corticosteroid use, and comorbidities. Despite increasing disease burden, fungal surveillance infrastructure remains rudimentary. Existing gaps include underreporting, restricted diagnostic capacity, lack of standardized methodologies, and inadequate environmental monitoring. National initiatives represented by ICMR-MycoNet, AMDRCs, and AMRSN signify important but need expansion and integration with global platforms including the WHO GLASS-Fungi and CDC Fungi-Net. Building national capacity necessitates mandatory reporting of invasive mycoses, scaling up mycological diagnostics, antifungal stewardship, and interdisciplinary research that links climate parameters with fungal disease trends. The converging threats from climate change and emergence of fungal diseases call for urgent, coordinated public health action to build resilient surveillance, diagnostic, and policy systems across the country.

Keywords: Climate change, Fungal infections, India, Public health, Surveillance.

Introduction

Fungal infections constitute a substantial but frequently underestimated component of the global infectious disease burden, with India representing a particularly vulnerable epidemiological landscape [1]. The aggregated prevalence and incidence of serious fungal infections (SFIs) in India are estimated at approximately 60 million cases annually (4.1% of the population), exceeding the disease burden of tuberculosis an historically predominant infectious threat thereby warranting immediate epidemiological investigation and targeted public health intervention[1][2].

Climate Change and Fungal Pathogen Ecology

Climate change operates as a complex environmental driver modulating fungal ecology through multiple mechanistic pathways. The phenomenon encompasses long-term alterations in climatic parameters (temperature, precipitation, humidity) coupled with increased frequency and intensity of extreme weather events[3]. Fungi occupy an ecologically sensitive position at the interface of terrestrial climate dynamics, with maximum diversity and biomass concentrated within upper soil strata [1].

Anthropogenic climate change induces shifts in the geographic range of pathogenic fungal lineages through several interconnected mechanisms. Increased ambient temperatures facilitate the range expansion of thermotolerant fungi into previously unsuitable geographic areas, with corresponding increases in thermotolerance thresholds and altered phenological patterns[4]. Simultaneously, stochastic variation in precipitation patterns and humidity levels influence fungal sporulation, dispersal efficiency, and environmental persistence, thereby modulating transmission dynamics[3]. Natural disasters including heat waves, floods, droughts, and wildfires create ecological disturbances that facilitate fungal proliferation and human exposure[4]. Concurrently, population dynamics (urbanization, demographic growth), increased human longevity, enhanced international mobility, and concurrent immunosuppression from chronic diseases collectively amplify human vulnerability to pathogenic fungi.

Epidemiological Context in India

India's tropical geographic position, combined with heterogeneous ecological

zones (tropical forests, monsoon regions, arid areas, temperate highlands, and coastal regions), creates a complex epidemiological landscape for fungal disease emergence and endemicity[5]. The geo-ecological heterogeneity coupled with diverse mycobiota generates substantial geographic variation in fungal disease epidemiology, with disease burden patterns reflecting underlying distributions of fungal endemicity and ecological determinants[5][6].

Among pathogenic fungi endemic to India, several species demonstrate heightened epidemiological importance and novel resistance patterns. Recent epidemiological surveillance has identified *Candida auris*, a multidrug-resistant nosocomial pathogen, as an emerging threat capable of generating healthcare-associated clusters and demonstrating thermotolerance characteristics compatible with climate change scenarios[7]. The emergence of mucormycosis (Order Mucorales) as a high-burden infection, coupled with pandemic-associated mycoses (aspergillosis, mucormycosis during COVID-19 immunosuppression), exemplifies the dynamic nature of fungal disease epidemiology in India [7].

Clinical Epidemiology of Serious Fungal Infections in India

Burden Assessment and Epidemiological Quantification

The epidemiological burden of serious fungal infections in India is substantial and frequently underestimated. Ray et al.[2] conducted a systematic review encompassing over 400 published investigations to estimate annual incidence across the disease spectrum. Candidemia (approximately 100,000 cases annually) demonstrates ICU predominance with high attributable mortality, while cryptococcal meningitis (~27,000 cases) predominantly affects HIV/AIDS patients with CD4 counts below 50 cells/ μ L and frequently occurs concurrent with tuberculosis coinfection. Pneumocystis pneumonia affects approximately 59,000 individuals annually, with CD4 thresholds below 200 cells/ μ L demarcating clinical risk. Chronic pulmonary aspergillosis accounts for approximately 1.5 million cases but remains frequently misdiagnosed as pulmonary tuberculosis. Allergic bronchopulmonary aspergillosis and severe asthma with fungal sensitization collectively affect

approximately 3.93 million individuals, representing substantially underdiagnosed phenotypes comorbid with primary respiratory conditions. Invasive aspergillosis (~250,000 cases) predominantly affects transplant recipients, hematologic malignancy patients, and ICU-hospitalized individuals. Mucormycosis represents the highest global burden among serious fungal infections, affecting approximately 910,000 individuals annually with diabetes as a major risk factor. Fungal keratitis constitutes approximately 1.1 million cases annually and represents the principal infectious cause of corneal blindness in tropical regions. Collectively, these infections exceed tuberculosis incidence in India, representing an urgent public health priority requiring enhanced surveillance infrastructure and diagnostic capacity.

Climate-Driven Shifts in Fungal Epidemiology

Environmental and Climatic Determinants of Fungal Epidemiology

Thermotolerance represents a critical determinant of whether a fungal pathogen can transition from environmental persistence to human parasitism. The

upper thermal growth limit for most environmental fungi approximates 35-37°C, positioning human body temperature (~37°C) as a selective barrier against systemic fungal infection[8]. Climate-driven increases in ambient temperature select for thermotolerant fungal populations with elevated thermal optima, reducing the thermal exclusion barrier to human infection, with species including *Cryptococcus gattii*, *Coccidioides immitis*, and thermophilic *Aspergillus* species demonstrating expanded geographic ranges with increasing global temperatures[3].

Indian monsoon dynamics and seasonal precipitation patterns directly influence fungal sporulation, survival, and dispersal mechanisms. Increased relative humidity and altered rainfall regimes modify environmental persistence of spores and affect transmission to humans through occupational and environmental exposure routes[3]. Endemic fungal species demonstrate climate-sensitive distributional patterns; *Cryptococcus neoformans* var. *grubii* exhibits geographic clustering associated with eucalyptus distribution and tropical climate parameters, while *Coccidioides* species show ecological dependence on

specific soil parameters and temperature regimes. In India, endemic dimorphic fungi including *Histoplasma capsulatum* var. *duboisii* demonstrate clear associations with climatic and ecologic variables[1][6].

Emerging and Pandemic-Associated Mycoses

Emerging Multidrug-Resistant Mycoses

Candida auris represents a paradigmatic emerging fungal pathogen with epidemiological characteristics amenable to rapid international dissemination. This multidrug-resistant yeast demonstrates elevated minimum inhibitory concentrations to azole antifungals (fluconazole, voriconazole), emerging echinocandin resistance with reduced susceptibility patterns, and environmental thermotolerance with optimal growth at 40-42°C facilitating persistence in healthcare environments[7]. The capacity to form biofilms on abiotic surfaces complicates infection control protocols. The epidemiological trajectory of *C. auris* demonstrates healthcare-associated transmission patterns with outbreaks documented across Indian ICUs, and climate change may exert selection

pressure favoring thermotolerant strains[7].

COVID-19 pandemic-associated immune dysregulation facilitated secondary fungal infections, particularly aspergillosis (predominantly *Aspergillus fumigatus*-associated COVID-19-associated pulmonary aspergillosis, CAPA) and mucormycosis (Coronavirus-associated mucormycosis, CAM)[7]. These mycoses demonstrated substantially elevated incidence compared to pre-pandemic baseline, with geographic clustering in India consistent with potential climate-dependent factors and predominance in diabetic and immunocompromised populations. The mechanistic pathway involves pandemic-related immune suppression including lymphopenia, reduced interferon- γ production, and altered T-cell populations combined with corticosteroid use and hyperglycemia-induced immune dysfunction, resulting in high mortality despite antifungal intervention[7].

Public Health Infrastructure and Surveillance Capacity

Global and National Surveillance Infrastructure

The World Health Organization released the inaugural Fungal Priority Pathogens

List (FPPL) in 2022, categorizing fungal threats across three priority tiers based on epidemiological, resistance, and clinical burden criteria, mandating international attention to surveillance infrastructure development and diagnostic capacity enhancement in low- and middle-income countries[9]. The Global Antimicrobial Resistance and Use Surveillance System (GLASS)-Fungi represents a WHO-coordinated international surveillance infrastructure systematically collecting data on invasive fungal infection epidemiology, monitoring antifungal resistance patterns, establishing baseline epidemiological estimates for national and regional burden quantification, and facilitating international data sharing[9]. The Centers for Disease Control and Prevention (CDC) established FungiNet as a genomic surveillance platform enabling international fungal genome data sharing, facilitating molecular epidemiology, pathogenic strain detection, and geographic distribution mapping[10]. The Institut Pasteur (Paris) operates a National Reference Centre (CNR) for Invasive Mycoses and Antifungals, providing specialized laboratory services and epidemiological surveillance for severe fungal infections

across European jurisdictions since 2012[11].

Within India, the Indian Council of Medical Research (ICMR) established MycoNet in 2020 to systematically map fungal infection distribution, quantify disease impact, surveil antifungal resistance patterns, and develop standardized diagnostic and therapeutic protocols[12]. Eight Advanced Mycology Diagnostic and Research Centers (AMDRCs) were strategically established across India's geographic zones, functionally integrated with state governments and tertiary medical institutions, enabling systematic case referral and training programs. ICMR conducted systematic literature reviews and expert consultation involving practicing clinicians, mycologists, and laboratory physicians to identify priority fungal pathogens responsible for critical infectious syndromes, generating a comprehensive inventory requiring focused research and intervention capacity[12]. The Antimicrobial Resistance Research and Surveillance Network (AMRSN) operates as a Pan-Indian Clinical Registry of Invasive Fungal Infections, systematically collecting hospital-based epidemiology,

antifungal resistance patterns, and clinical outcomes data[12]. The National Centre for Disease Control (NCDC) is developing comprehensive fungal disease surveillance infrastructure integrating clinical registry database infrastructure, Integrated Disease Surveillance Project (IDSP) expansion to include fungal pathogens, antimicrobial resistance containment programming, and laboratory-based surveillance systems[12].

Epidemiological Challenges and Research Gaps

Despite established surveillance initiatives, substantive gaps persist in India's fungal disease surveillance infrastructure. Rural and remote areas remain systematically underrepresented in surveillance data, while diagnostic mycology capacity is concentrated in tertiary institutions with community and primary care laboratories inadequately equipped. Non-mandatory reporting of fungal infections results in substantial underestimation of true disease burden, and inconsistent diagnostic methodologies across institutions compromise data comparability. Direct epidemiological attribution of fungal

disease increases to climate change mechanisms remains methodologically challenging, requiring quantitative niche modeling integrating climate parameters and fungal ecophysiology, long-term prospective cohort studies examining climate-fungal disease associations, and environmental surveillance integrated with clinical epidemiology. Implementation of antifungal stewardship programs remains nascent in Indian healthcare systems, with limited standardized protocols for rational antifungal prescribing, combination therapy, and resistance containment.

Conclusions and Recommendations

The convergent epidemiological challenges of climate change and rising fungal disease burden in India demand coordinated, multi-disciplinary public health responses. Implementation of mandatory reporting systems for invasive fungal infections at national level is essential, coupled with standardization of mycological diagnostic methodologies across healthcare facilities and development of surveillance systems capturing environmental parameters alongside clinical fungal disease data. Active participation in WHO GLASS-

Fungi, CDC FungiNet, and related international surveillance initiatives will facilitate comparative epidemiology and evidence exchange. Investment in advanced mycological diagnostics (culture, identification, susceptibility testing) in secondary and tertiary institutions must be accompanied by ensuring equitable geographic access to appropriate antifungal medications and development of institutional antifungal stewardship protocols. Prospective cohort studies examining climate-fungal disease associations should be conducted concurrently with capacity-building training programs for clinicians, laboratory professionals, and epidemiologists, alongside interdisciplinary research examining climate change impacts on fungal ecology and human infection risk. Integration of fungal disease considerations into national climate adaptation strategies and disaster risk reduction frameworks, coupled with development of post-disaster fungal disease surveillance protocols following extreme weather events, represents essential public health policy priorities. Fungal infections and climate adaptation warrant recognition as major public health priorities equivalent

in urgency to historically predominant infectious diseases.

Conflict of Interest

Nil.

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