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Biotechnological Approaches to Combat Mycetoma in Farmers: Impacts and Sustainable Solutions

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Abstract

Mycetoma, a chronic, gradually debilitating condition caused by fungi or bacteria, provides enormous challenges to agricultural communities, notably in West Bengal and Andhra Pradesh, India. This research investigates the socioeconomic and environmental effects of mycetoma on tobacco and tomato producers, where the disease is common due to overreliance on agrochemicals and poor soil management. Pilot studies in Cooch Behar have shown that climatic and soil conditions ideal for tobacco production may also lead to the spread of soil-borne infections, such as those that cause mycetoma. Current research indicates that creative biotechnology solutions—such as the production of genetically engineered crops, the use of biocontrol agents, and CRISPR-based gene editing—offer viable pathways for combating mycetoma. Furthermore, quick diagnostic methods and future vaccine development are crucial for early detection and prevention, which reduces farmers' long-term socioeconomic burden. The significance of combining sustainable farming practices with these biotechnological developments cannot be emphasized, since they not only lower disease incidence but also encourage environmental preservation. Future research should focus on using genomic technology to better understand pathogen interactions in soil and developing immune-based treatments. This multidisciplinary approach will be critical in mitigating mycetoma's impact, improving impacted farmers' livelihoods, and promoting sustainable agriculture.

Keywords**:** Mycetoma in agricultural communities, Soil-borne pathogens in farmers, Mycetoma impact on tobacco and tomato farming, Biotechnological solutions for mycetoma, Sustainable farming and mycetoma prevention

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.Introduction

Tobacco production is an important part of West Bengal's agricultural landscape, particularly in districts like Cooch Behar, which are located in the Himalayan foothills. The good climate and soil conditions in this region have made it suitable for tobacco growth. Pilot testing have shown that Cooch Behar is suitable for growing high-quality cigar tobacco. The total tobacco-growing area in West Bengal is roughly 15.68 thousand hectares, with an average yield of around 1700 kg per hectare. Tobacco cultivars such as Motihari and Jati are grown largely in the state's northern regions, spanning an area of 12,000 hectares. Tobacco farmers in West Bengal have significantly greater socioeconomic standing than non-tobacco farmers (Sahadewo et al., 2020); (D. et al., 2014). They tend to possess larger pieces of land and earn better revenues, with an average net return of Rs 55,000 per acre. Despite the economic rewards, tobacco cultivation poses a number of obstacles. Farmers confront challenges such as price volatility, labor constraints, storage troubles, and sucker problems (unwanted shoots that develop on the plant). Furthermore, the health concerns linked with prolonged exposure to agrochemicals used in tobacco farming have been extensively studied. While tobacco is a profitable crop with larger returns than other regional staples such as potatoes, wheat, and jowar, its long-term impact on farmers' health and well-being is sometimes disregarded. Tobacco producers are especially prone to diseases such as **mycetoma** due to their continuous contact to agrochemicals and pathogens in the farming environment (Novotny et al., 2015).

Mycetoma is a persistent, debilitating infection that is frequent in tropical and subtropical locations where farmers are exposed to a lot of dirt, dust, and plant debris (W. W. J. Van De Sande et al., 2014); (Hutabarat et al., 2022). It primarily affects agricultural workers, particularly tobacco and tomato farmers, who come into touch with contaminated settings. India is the world's second-largest tomato grower, with Andhra Pradesh, Madhya Pradesh, and Karnataka accounting for almost 90% of the entire production. Similar to tobacco farming, tomato agriculture exposes workers to a variety of infections that can cause diseases such as mycetoma. The spread of mycetoma into rural farming communities, notably those involved in tobacco and tomato cultivation, is compounded by a lack of awareness, insufficient healthcare access, and the disease's chronic course, which can result in severe impairment. Farmers, in particular, are at increased risk of contracting this infection because of the frequent skin abrasions and injuries they experience while working. This condition is caused by soil-borne infections, either bacterial (actinomycetoma) or fungal (eumycetoma), that enter the body through small cuts or wounds (Reis & Reis-Filho, 2018).

The purpose of this review study is to address the impact of mycetoma on farmers in places such as West Bengal, including the disease's origin, clinical presentations, and biotechnological therapies. By analyzing the expanding problem of mycetoma in agricultural areas, we will highlight potential risk-mitigation measures and examine strategies to safeguard farmers, particularly those farming tobacco and tomatoes, from this painful disease.

Methodology

The information provided is comprehensive and unbiased and aims to combine relevant research results. The steps of a systematic literature review include developing a research question, searching the literature, screening and selecting relevant articles, screening and selecting the best research results, analyzing, synthesizing qualitative results, and preparing a research report. Writing the background and objectives of the study, collecting research questions, searching the literature, selecting articles, extracting articles, assessing the quality of basic studies, and summarizing the material are the steps in the systematic literature review research process.

Results

The pictures in Figure 1 illustrate the histological aspects of mycetoma lesions, allowing for a better knowledge of the disease's course and characteristics. They clearly illustrate crucial aspects such as the presence of white grains, the inflammatory response, and fibrotic encapsulation, allowing physicians and researchers to accurately identify and diagnose mycetoma. Furthermore, these visual tools help healthcare practitioners understand complex pathological ideas, which leads to better patient care and more effective treatment techniques.

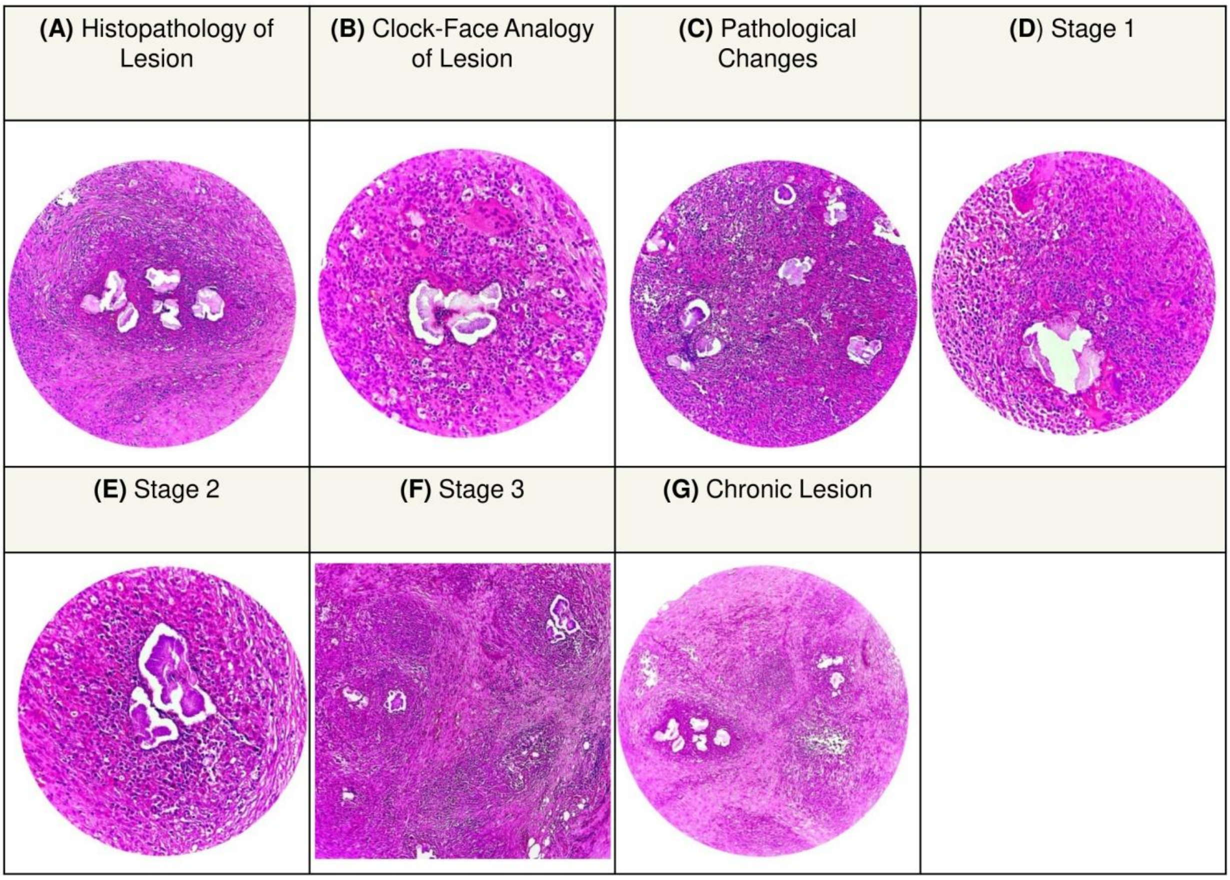

Figure 1. Micro-graphical Illustration of the Histological Aspects of Mycetoma Lesions

Table 1 depicts the histological characteristics and evolution of mycetoma lesions using numerous pictures, each exhibiting distinct aspects such as white grains, inflammatory tissue, and fibrotic responses, and is organized in a clock-face analogy for intuitive understanding. It is an invaluable resource for physicians and researchers since it aids in proper diagnosis and informs treatment methods, as well as offering a compact reference for understanding the disease's pathology. It also serves as an educational tool in medical curricula, helping researchers understand fungal and bacterial infections as well as the significance of histological examination in illness diagnosis.

Table 1. Histological Characteristics and Evolution of Mycetoma Lesions

Figure	Description	Key Features (Clock-Face Analogy)	Additional Information
Figure 1A	Histopathology of Mycetoma Lesion	• White Granules (6-9 o'clock): Central colonies of microorganisms. • Inflammatory Response (1-5 o'clock): Intense immune	Highlights the histopathological details of a typical mycetoma lesion, focusing on the interaction between the

		response with neutrophils, lymphocytes, plasma cells.	immune system and the microorganism colonies.
		• Fibrotic Capsule (4-8 o'clock): Encapsulation of grains as part of the body's defense.	
		• H&E Staining: Cell nuclei (purple) and cytoplasm (pink) highlighted.	
Figure 1B	Clock-Face Analogy of Mycetoma Lesion	• White Grains (6-9 o'clock): Colonies of microorganisms.	Uses a clock-face analogy to easily visualize the distribution of pathological features in a mycetoma lesion.
		• Inflammatory Tissue (1-5 o'clock): Active inflammation.	
		• Immune Cells (10-2 o'clock): Dark purple immune cells in high density.	
		• Fibrosis (4-8 o'clock): Fibrotic tissue forming around the infection.	
Figure 1C	Pathological Changes in Mycetoma	• White Granular Masses (12, 4, 6, 9 o'clock): Colonies of microorganisms.	Shows a more diffuse view of inflammation and immune response, along with fibrotic tissue encapsulation.
		• Diffuse Inflammation (10-3 o'clock): Intense inflammatory reaction.	
		• Encapsulation (7-9, 12-1 o'clock): Fibrotic tissue.	
		• Immune Cell Infiltration (5-8 o'clock): Dense immune cell presence.	
Figure 1D	Stage 1 of Mycetoma Lesion	• White Grains (6 o'clock): Necrotic core with grains.	Depicts early-stage mycetoma lesions with distinct areas of necrosis and fibrosis.
		• Inflammation (1, 4 o'clock): Dense immune cell infiltration around the core.	
		• Fibrosis (1, 4 o'clock): Early fibrotic response around necrotic material.	
Figure 1E	Stage 2 of Mycetoma Lesion	• Necrotic Center (3 o'clock): Microorganism colonies.	Progression of granulomatous response and fibrosis, a hallmark of chronic infection.
		• Granulomatous Response (surrounding): Heavy immune cell infiltration.	
		• Fibrosis (10, 5 o'clock): Denser fibrotic tissue forming around the grains.	
Figure 1F	Stage 3 of Mycetoma Lesion	• Granular Foci (2-5 o'clock): Scattered microorganism colonies.	Depicts a more advanced stage with extensive fibrosis

		• Fibrosis (10-4 o'clock): Thick fibrotic bands encapsulating the infection.	attempting to contain infection.
Figure 1G	Chronic Mycetoma Lesion	• White Grains: Necrotic microorganism colonies. • Granuloma Formation: Surrounding immune cells, including macrophages and giant cells. • Fibrosis: Dense encapsulation of the infection. • Inflammatory Cells: Purple-stained immune cells around necrotic grains.	Highlights the chronic phase of mycetoma with granuloma formation and dense fibrosis, indicating a longstanding infection.

Background and Epidemiology of Mycetoma

Global Distribution and Prevalence

Mycetoma is a chronic, increasingly damaging infectious illness that affects the skin, subcutaneous tissues, and occasionally bone. It is classed as a neglected tropical disease (NTD), affecting people mostly in tropical and subtropical countries, with the largest occurrence in Africa, Latin America, and portions of Asia. Sudan, Mexico, and India report among of the greatest numbers of cases each year. Mycetoma thrives in arid and semi-arid climates, particularly in rural areas where humans are constantly exposed to dirt and vegetation. Individuals engaged in agricultural operations, particularly those working on poorly automated farms, are at high risk due to direct contact with infectious organisms in the soil. Mycetoma has developed as a health concern in India, a country recognized for its rich agriculture sector. The disease spreads in areas with few medical resources, and farmers are exposed to infection-prone environments. Tobacco and tomato farmers in West Bengal and Andhra Pradesh are among the most vulnerable populations, as their regular interaction with soil and plant materials raises their chance of contracting the disease (Emery & Denning, 2020).

Mycetoma in India

Mycetoma has been recorded most frequently in rural agricultural settings in India, where barefoot farming and poor access to protective clothing are typical. The humid and warm circumstances in West Bengal, for example, provide a favorable setting for the survival and transmission of mycetoma-causing microorganisms. Tobacco producers in areas such as Cooch Behar, where tobacco production grows due to a suitable climate and soil, face increased risk due to regular interaction with soil-borne fungus and bacteria. Similarly, tomato growers in states like Andhra Pradesh, Karnataka, and Madhya Pradesh, which account for roughly 90% of India's tomato production, are at risk. Tomatoes are widely farmed in these states, frequently in open fields with manual work, leaving farmers vulnerable to abrasions and injuries that allow viruses to enter. Mycetoma is exacerbated in such situations by a lack of healthcare infrastructure and awareness, resulting in delayed diagnosis and treatment, hence increasing the disease burden (Sawatkar et al., 2019). Agricultural workers, particularly tobacco and tomato producers, make up a sizable proportion of persons affected by mycetoma, with soil contamination from these crops serving as the primary reservoir of infection. The condition impacts not only their physical health but also their socioeconomic status, thus timely interventions are critical in both area.

Pathophysiology of Mycetoma

Causative Agents: Bacterial and Fungal Etiologies

Mycetoma can be caused by bacteria (actinomycetoma) or fungal diseases (eumycetoma). The most prevalent bacterial agents include *Actinomadura*, *Nocardia*, and *Streptomyces*, whereas eumycetoma is primarily caused by *Madurella* species, among others. These infections generally enter the human body by minor cuts, abrasions, or puncture wounds, particularly in people who walk barefoot or work in soil-rich areas like tobacco and tomato farms (W. Van De Sande et al., 2018). Tobacco farmers in West Bengal, particularly in the Cooch Behar district, are extremely vulnerable to these diseases due to their frequent and direct contact with soil, which may contain mycetoma-causing bacteria. Soil polluted with organic material can serve as a reservoir for these diseases, which prefer warm, humid environments. Tomato farmers in Andhra Pradesh and Madhya Pradesh, who spend a large amount of time working with soil and crops, suffer similar hazards.

Immunological Response and Tissue Damage

When the causal agent enters the body, it activates an immune response that, in some situations, is insufficient to eliminate the pathogen. As the infection continues, the germs multiply and create nodules and sinus tracts that expel pus and occasionally blood. Tobacco producers, who are frequently exposed to agrochemicals that may affect skin integrity, are at an increased risk of bacterial invasion. The disease primarily affects subcutaneous tissues, although it can eventually infect deeper tissues such as muscle and bone. Mycetoma is characterized by granulomatous inflammation, in which the body forms granulomas or abscesses to protect itself from infectious pathogens. These granulomas, on the other hand, do not resolve the infection but rather contribute to its chronicity, frequently resulting in malformations and impairments in those affected. Farmers in high-risk areas, such as West Bengal, bear a significant economic burden from mycetoma, as untreated cases limit production and hamper their ability to work on tobacco or tomato plantations. As the infection develops, the likelihood of amputation and lasting impairment grows (Panno et al., 2021).

Clinical Manifestations

Mycetoma clinical signs are sluggish to develop, with recognizable symptoms appearing months or years later. The disease usually manifests as hard, painless nodules at the site of infection, which eventually grow into larger masses. Over time, the nodules may ulcerate, forming many sinuses that exude pus containing the disease’s grains (Fahal & Hassan, 1992). Early signs are frequently overlooked in rural India, such as West Bengal’s tobacco-growing regions or Andhra Pradesh’s tomato plantations, due to the asymptomatic nature of the initial infection and a lack of accessible healthcare. Farmers may disregard early nodules as inconsequential damage, allowing the illness to spread uncontrolled.

Epidemiology and Socioeconomic Impact of Mycetoma
Geographic Distribution and Risk Factors

Mycetoma is ubiquitous in tropical and subtropical climates, known as the “mycetoma belt.” This comprises countries from Africa, Asia, and Latin America. In India, where agriculture is the predominant vocation, mycetoma is a serious but underreported public health concern. Warm, humid environments in locations such as West Bengal, Andhra Pradesh, and Madhya Pradesh promote the proliferation of mycetoma-causing bacteria, making agricultural laborers in these areas more vulnerable. Tobacco producers in Cooch Behar, West Bengal, and tomato growers in Andhra Pradesh are frequently exposed to soil, which is a primary reservoir for these microorganisms. These people operate barefoot or with little protective clothing, which raises the danger of skin injuries that serve as entrance routes for infectious pathogens. Farmers in these locations also face the risk of being exposed to agrochemicals, which can weaken the skin’s natural defenses, increasing susceptibility to diseases such as mycetoma.

Socioeconomic Impact on Farming Communities

Mycetoma has a significant socioeconomic impact, especially in farming regions where physical work is the primary source of income. The disease primarily affects economically disadvantaged communities involved in occupations such as tobacco and tomato production. As mycetoma advances, it causes significant deformity, discomfort, and impairment, all of which limit an individual's ability to work. This is especially concerning in tobacco-growing areas like Cooch Behar, where farmers rely on tobacco harvests for higher-than-average returns when compared to other crops such as potato or wheat (Bassiri-Jahromi, 2014). Farmers in West Bengal, where tobacco production is lucrative, experience a significant loss of income due to chronic mycetoma symptoms. The disease's gradual course frequently causes delays in seeking medical attention, which can result in severe results, including amputation. This increases the economic strain on families, particularly those who already face price swings, labor shortages, and storage challenges in their agricultural operations. For tomato farmers in Andhra Pradesh, the socioeconomic consequences are similar. Tomato production, while critical to India's position as the world's second-largest producer, does not yield the same returns as tobacco farming, making the financial burden of healthcare even more daunting. Due to limited access to healthcare facilities and the high expense of therapy, mycetoma frequently advances to severe stages before intervention is sought. Furthermore, the disease's chronic nature might cause long-term disability, limiting these farmers' capacity to do physically demanding jobs and lowering overall production.

Health Risks Related to Occupational Exposure

Aside from mycetoma's direct impact, occupational contact to soil and agrochemicals poses significant health concerns. Farmers who work with harmful chemicals, such as pesticides and fertilizers, are more likely to suffer from skin damage. This increases the risk of opportunistic infections such as mycetoma. Long-term contact to soil and agrochemicals, along with high temperatures and humidity, makes infections more likely to enter the body. Tobacco production, particularly in locations such as Cooch Behar, where farmers are considered to have a higher socioeconomic position than non-tobacco farmers, generally minimizes health risks due to the financial rewards connected with tobacco cultivation. However, exposure to mycetoma-causing microbes, along with pesticide risks, poses a dual threat to these workers. Tomato producers in Andhra Pradesh are also concerned about the scenario. Tomato cultivation yields are excellent, and the crop is important to India's agricultural economy, yet it is labor-intensive and entails health dangers. Financial constraints in small-scale farming, along with the high expense of healthcare, frequently result in untreated infections and associated consequences from mycetoma (de-Assis et al., 2020).

Current Treatment Strategies for Mycetoma

Pharmacological Treatments

The treatment for mycetoma is largely determined by whether the illness is caused by bacteria (actinomycetoma) or fungi. Actinomycetoma responds better to antibiotic therapy than eumycetoma, which is a fungal infection that requires antifungal treatment. The principal medications used to treat actinomycetoma include a combination of sulfamethoxazole and trimethoprim, amikacin, and rifampicin. Because of the chronic and recurring nature of the infection, they are frequently taken for extended periods of time, sometimes ranging from 6 to 12 months. However, access to these medications is restricted in rural areas such as West Bengal's tobacco-growing districts and Andhra Pradesh's tomato agricultural areas. Farmers who develop mycetoma are sometimes ignorant of the ailment or delay seeking medical assistance because to the gradual onset of symptoms and the high costs associated with long-term care. These delays cause the condition to worsen, necessitating more aggressive and costly treatment options by the time it is recognized. Itraconazole, voriconazole, and ketoconazole are prominent antifungal medications used to treat eumycetoma. These medications target fungal cell membranes, preventing the infection from spreading. However, the treatment is frequently less effective than for actinomycetoma and requires extended use, perhaps for a year or more. In cases where the infection has progressed to bone or deeper tissues, antifungal medication may be supplemented with surgical procedures (Relhan et al., 2017).

Surgical Interventions

Surgery is frequently required in severe cases of mycetoma, especially when pharmacological therapies are ineffective or the infection has progressed widely. The surgical excision of contaminated tissue can help avoid further damage and slow the spread of disease. Surgery, on the other hand, may be a last choice, particularly if the infection has spread to bone or caused substantial deformity. For tobacco and tomato farmers, surgical therapy can have serious implications. Amputation is occasionally required in cases of severe infection, which can result in permanent disability and loss of income. This is especially bad for small-scale farmers, who rely only on their physical abilities to cultivate the field. Furthermore, in remote areas with little healthcare infrastructure, access to experienced surgeons and post-operative care might be extremely difficult (Suleiman et al., 2016).

Challenges in Treatment Accessibility

One of the most difficult issues in managing mycetoma in agricultural regions such as West Bengal and Andhra Pradesh is a lack of access to adequate medical care. Farmers, particularly in isolated locations, frequently live far from medical facilities. Even when treatment is accessible, the cost and duration of therapy can be prohibitively expensive, leading to noncompliance with medication regimens and increased risk of recurrence or consequences. For example, tobacco growers in Cooch Behar may emphasize immediate economic rewards from their crops above seeking treatment, so delaying diagnosis and allowing the disease to worsen. Furthermore, the stigma associated with mycetoma's physical ugliness can deter people from seeking care early on, resulting in late disease stages by the time medical attention is sought. Another challenge is a scarcity of trained healthcare personnel who can identify and treat mycetoma. Misdiagnoses are widespread in rural clinics, where general practitioners may lack specific expertise of NTDs. This leads to ineffective therapy, which often prolongs the disease's course and increases the risk of consequences (Emmanuel et al., 2018).

Proposed Biotechnology Solutions for Mycetoma Prevention and Treatment

Development of Soil-Based Biocontrol Agents

Given that mycetoma is predominantly a soil-borne infection, one of the most promising biotechnology solutions is the development of biocontrol agents that can minimize the presence of pathogenic fungi and bacteria in agricultural soils. By introducing helpful microorganisms into the soil, it is possible to outcompete or suppress the growth of mycetoma-causing bacteria. For example, strains of *Pseudomonas fluorescens* and *Bacillus subtilis* have been shown to have strong antagonistic effects against fungal diseases, and they might be evaluated for their usefulness in reducing the presence of eumycetoma-causing fungus in tobacco and tomato producing zones. Field trials might be done in high-risk areas such as Cooch Behar and Andhra Pradesh, where the climatic conditions and soil composition promote the proliferation of infections. Biocontrol agents could be sprayed to soil via irrigation systems or as part of organic agricultural methods to eliminate the need for chemical fungicides. This strategy is both cost-effective and environmentally friendly, as it promotes better, agrochemical-free crops while minimizing the frequency of soil-borne illnesses such as mycetoma.

Genetic Engineering of Crop Varieties with Antifungal Properties

Another method is to genetically modify crops to withstand soil-borne infections, such as mycetoma-causing fungus. Advances in gene editing technologies such as CRISPR/Cas9 enable precise alteration of plant genomes to improve disease resistance. In the case of mycetoma, research could focus on developing tobacco and tomato cultivars that express antifungal peptides or enzymes capable of neutralizing the pathogen when in contact. For example, transgenic tobacco plants could be engineered to express chitinase, an enzyme that degrades fungal cell walls. Similarly, tomato plants may be designed to produce defensins, which are tiny proteins that prevent fungus development (Sher Khan et al., 2019). These genetically engineered crops would have a dual benefit: they would protect farmers from mycetoma infections while also reducing the need for chemical fungicides, which contribute to other health risks. Field trials could evaluate the performance of genetically modified crops in terms of yield, pathogen resistance, and economic viability. These trials would also take into account the environmental impact, ensuring that the changes do not disturb local ecosystems or cause the establishment of new pathogenic strains.

Development of Rapid Diagnostic Tools

Early identification of mycetoma is crucial for preventing serious disease progression and reducing the need for surgical treatment. Current diagnostic approaches are frequently intrusive, time-consuming, and costly, posing a considerable challenge to farmers in rural locations. To overcome this, biotechnology may provide novel diagnostic methods, such as quick soil or point-of-care diagnostics. For example, lateral flow assays (similar to at-home pregnancy tests) could be designed to identify the presence of certain fungal or bacterial antigens linked to mycetoma-causing organisms. These tests might be provided to rural communities, allowing for early identification using simple, noninvasive procedures. In areas with limited healthcare resources, such as West Bengal and Andhra Pradesh, portable diagnostic instruments would serve as an important first line of defense against the disease. Soil-testing kits might also be created, allowing farmers to periodically monitor their fields for the presence of pathogenic bacteria. This would allow them to take preventive steps, such as using biocontrol chemicals or rotating crops, before illnesses might spread. By incorporating such diagnostic techniques into ordinary agricultural procedures, the total burden of mycetoma could be greatly decreased.

Vaccine Development and Immunotherapy

Given mycetoma’s chronic nature and the limited efficacy of current treatments, there is a rising interest in developing vaccinations or immunotherapeutic techniques that could give long-term disease protection. A vaccination targeting the major bacteria that cause mycetoma could provide a preventive approach, particularly for high-risk populations such as tobacco and tomato farmers. To create such a vaccine, it would be necessary to identify the most immunogenic antigens from both actinomycetoma and eumycetoma infections. Once identified, these antigens could be exploited to induce a protective immunological response in at-risk patients. Advances in biotechnology, particularly mRNA vaccine technology (as evidenced with COVID-19 vaccines), may hasten the development of a mycetoma vaccine. Immunotherapy, which includes increasing the body’s immunological response to combat illness, is another promising field of study. This could include using monoclonal antibodies to selectively target the bacteria that cause mycetoma or enhancing innate immune responses with cytokine treatment. These techniques would open up new, less intrusive therapeutic alternatives, eliminating the need for long-term antifungal or antibiotic therapy (Qadri et al., 2023).

Environmental and Socio-Economic Implications of Mycetoma Management

Impact on Farmers’ Livelihoods

Mycetoma has far-reaching socioeconomic consequences, particularly for farmers who depend on tobacco and tomato agriculture for a living. The high occurrence of mycetoma in areas like Cooch Behar and Andhra Pradesh, where tobacco and tomato production is critical to the local economy, can put a burden on finances. The chronic nature of the condition frequently necessitates long-term medical treatments, which are costly and can result in loss of productivity owing to extended illness or, in severe cases, disability from surgical operations. The cost of medical care for mycetoma, particularly in rural areas, has the potential to further impoverish already disadvantaged farming families. Farmers affected by the disease may be unable to work, resulting in diminished agricultural output and incomes. In circumstances where surgical intervention, such as amputation, is required, the loss of physical work capacity might result in permanent impairment, aggravating poverty in these areas. Furthermore, tobacco growers in particular are already under economic strain due to variable crop prices and rising input expenses such as agrochemicals. Mycetoma-related medical bills may render tobacco cultivation unsustainable for smallholder farmers. While tobacco is a profitable crop in West Bengal, giving larger yields than wheat or jowar, these gains may be offset by disease-related healthcare expenditures.

Environmental Impact of Current Agricultural Practices

The environmental factors that contribute to the incidence of mycetoma, notably in West Bengal and Andhra Pradesh, are directly related to the agricultural practices used. The widespread use of agrochemicals such as fungicides and insecticides endangers farmers' health while also disrupting the soil's natural microbial equilibrium. This imbalance can provide an ideal environment for the spread of mycetoma-causing bacteria. To sustain high yields, tobacco and tomato farmers rely significantly on chemical inputs. However, extended exposure to these pesticides might decrease farmers' immunological responses, rendering them more vulnerable to illnesses such as mycetoma. Furthermore, runoff from chemical-laden soils can contaminate local water sources, exacerbating environmental deterioration and public health concerns in these areas. The potential remedies described in the previous section, such as biocontrol agents and genetically altered crops, provide environmentally friendly alternatives to chemical-intensive farming. These measures, which reduce reliance on hazardous fungicides and pesticides, have the potential to restore soil's natural microbial balance and reduce the danger of soil-borne diseases such as mycetoma (Tudi et al., 2021).

Role of Government and Policy Interventions

To address the socioeconomic and environmental issues faced by mycetoma, both local and national initiatives must be coordinated. Government initiatives that improve farmers' access to healthcare, particularly in rural regions, are critical to effective disease management. As previously discussed, subsidizing healthcare costs or giving free diagnostic equipment could help farmers affected by mycetoma reduce their financial burden. Furthermore, agricultural policies should encourage sustainable farming practices that prevent environmental degradation and the spread of soil-borne diseases. This could include incentives for farmers to use biocontrol agents or genetically modified crops, as well as subsidies for organic farming methods that lessen reliance on hazardous pesticides. Public health efforts aiming at boosting knowledge about mycetoma and its early signs could also help farmers seek treatment before the disease progresses to a more serious stage. By combining these programs with agricultural extension services, governments may equip farmers with the information and tools they need to prevent and manage mycetoma (Carino et al., 2023).

Future Prospects and Conclusion

Future Research Directions

The future of mycetoma prevention and management is a multidisciplinary approach that combines biotechnology, environmental sustainability, and socioeconomic solutions. The study of soil-borne infections, particularly those that cause mycetoma, is still in its early phases, and there is great promise for future advances.

Genomic and Metagenomic Studies

Advanced genomic approaches, like as metagenomic sequencing, could help to better understand the microbial communities that live in agricultural soils in high-risk regions. Researchers who uncover specific genetic markers linked with dangerous fungi and bacteria may be able to develop tailored biocontrol measures or genetic engineering approaches that reduce their occurrence. Understanding how varied farming techniques and weather factors affect microbial diversity in soil is critical for designing region-specific remedies to prevent mycetoma outbreaks.

CRISPR-Based Gene Editing for Crop Improvement

Future study could concentrate on the use of CRISPR-based gene editing to develop not only antifungal but also multi-resistant crop variants. These crops would resist not only mycetoma-causing pathogens, but also other prevalent diseases and pests, reducing the overall demand for chemical inputs. This method has the potential to dramatically improve farming sustainability in regions such as West Bengal and Andhra Pradesh, where tobacco and tomato growing face severe challenges due to environmental and pathogenic pressures.

Vaccine Development and Immune-Based Therapies

Research on vaccine development for mycetoma-causing organisms, particularly *Madurella mycetomatis* and *Streptomyces somaliensis*, could lead to long-term disease prevention. While current research is limited, the possibility for vaccines targeting soil-borne diseases is a promising topic for future investigation. Furthermore, immune-based medicines, such as monoclonal antibodies and immune boosters, could be investigated as non-invasive treatments for mycetoma patients.

Conclusion

Mycetoma, a neglected tropical disease, has a significant impact on farming populations in areas where soil-borne infections are common, such as West Bengal and Andhra Pradesh. The socioeconomic load on farmers, combined with the environmental damage caused by existing farming practices, emphasizes the urgent need for long-term solutions. Biotechnology has various viable routes for combating the disease, ranging from the development of biocontrol agents and genetically altered crops to the invention of quick diagnostic tools and potential vaccines. These advances not only minimize the prevalence of mycetoma, but also promote environmentally friendly farming practices that benefit both the soil and farmers. Government policies and research activities must work together to provide adequate healthcare, raise awareness, and encourage the use of these biotechnological developments. Mycetoma demands a multifaceted approach that involves prevention, early detection, and novel treatment options. The illness can be efficiently managed with the correct combination of biotechnological treatments and legislative support, increasing farmer livelihoods and ensuring the long-term viability of agricultural practices in regions prone to soil-borne diseases.

Conflicts of Interest

The authors declare no conflict of interest.

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