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Rediscovering Fungal Biocontrol Agents in Forestry for Sustainable Pest Management in the North of Argentina

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Abstract: *Forestry in Argentina, particularly in regions dominated by Eucalyptus and Pinus plantations, faces significant challenges in pest management. While bacterial biocontrol agents like Bacillus have been traditionally used, not all pest management needs can be met by these microbes. This highlights the potential for fungal biocontrol agents in forestry pest management. The north of Argentina harbors hotspots of rich biodiversity remnants, making it a promising location to search for potential fungal biocontrol agents. However, there is currently a lack of information regarding the isolation and characterization of fungi with biocontrol capacities in this region.This work aims to address this gap by exploring the use of new, poorly studied, and alternative fungi for biocontrol purposes. Fungi such as Clonostachys, Paecilomyces, and Escovopsis have shown promising biocontrol capabilities against pests in other regions and could be valuable additions to the pest management strategies in the forestry of Argentina.The manuscript discusses the importance of diversifying biocontrol strategies beyond Trichoderma and entomopathogenic fungi. It emphasizes the need for further research and exploration of fungal biodiversity in the region to identify novel biocontrol agents. The findings presented here contribute to the broader scope of forestry, pest management, and biodiversity management, providing valuable insights for sustainable pest management practices for countries with extensive forestry plantations like Brazil, Argentina, Paraguay and Chile.*

1. Introduction

Forestry plays a crucial role in Argentina's economy and ecology, particularly in the northern regions where vast plantations of *Eucalyptus* and *Pinus* trees are cultivated (Weber, 2005; Olemberg & Lupi, 2024). These forests contribute to the country's timber industry and serve as important carbon sinks, helping to mitigate climate change by absorbing carbon dioxide from the atmosphere. However, the sustainability of these plantations is threatened by various factors, including pest infestations. Also, one of the main challenges faced by forestry in Argentina is the management of insect pests, with ants of the genera *Atta* and *Acromyrmex* being particularly problematic (Folgarait et al., 2011; Della Lucia & Amaral, 2020). These ants are known to cause extensive damage to trees by stripping off leaves and transporting them to their underground nests. This behavior not only reduces the aesthetic value of the plantations and forests but also affects the health and growth of the trees, leading to significant economic losses for forest owners and managers.

Traditional pest management strategies in forestry have relied extensively on the use of chemical pesticides, which can have negative environmental impacts and may contribute to the development of pesticide resistance in pest populations (Furlan & Kreutzweiser, 2015). As a result, there is a growing interest in exploring alternative pest management approaches that are more sustainable and environmentally friendly. Fungi, with their potential as biocontrol agents against many insect pests and diseases, present a promising avenue for addressing pest issues in forestry (Shah & Pell, 2003; Folgarait et al., 2011; Amerio et al., 2020: Ayaz et al., 2023).

Fungi have emerged as valuable biocontrol agents in forestry pest management due to their diverse mechanisms of action and environmental adaptability (Terhonen et al., 2018). One key advantage of using fungi is their specificity towards target pests, which minimizes non-target effects often associated with broad-spectrum chemical pesticides (Brodeur, 2012). Furthermore, fungi exhibit a remarkable ability to adapt to different environmental conditions, making them suitable for diverse forestry ecosystems (Sønstebø et al., 2022).Fungi have evolved to thrive in diverse habitats, from temperate forests to tropical rainforests, making them well-suited for application in various forestry ecosystems. This adaptability enhances their effectiveness as biocontrol agents, as they can persist and function efficiently in the presence of fluctuating environmental factors (Singh et al., 2017). Additionally, fungi can often establish long-term relationships with their host plants, providing continuous protection against pests over extended periods.

The potential of fungi as biocontrol agents is particularly significant when considering indigenous or locally isolated strains (Canassa, 2019). Indigenous fungi have evolved alongside their host plants and pests, potentially developing specialized adaptations that enhance their biocontrol efficacy. Local isolation of fungi also ensures their compatibility with the existing environmental conditions, increasing their chances of establishment and persistence in the target ecosystem. By utilizing indigenous or locally isolated fungi, forestry pest management strategies can leverage the natural biodiversity of the region, promoting a more sustainable and ecologically friendly approach.

Moreover, fungi offer a renewable and environmentally sustainable alternative to conventional pest management strategies in forestry (Archana et al., 2022). Unlike chemical pesticides, which often persist in the environment and pose risks to non-target organisms, fungi are biological (organic) and have minimal impact on non-target species. Additionally, fungi can be produced on a large scale using organic substrates, reducing the reliance on synthetic chemicals and promoting a more sustainable agricultural system. Overall, the use of fungi as biocontrol agents holds great promise for enhancing pest management practices in forestry while minimizing the ecological footprint of these activities.

Fungi exhibit a high degree of specificity towards their target pests, minimizing harm to non-target organisms and reducing the risk of ecological disruption. This specificity is often attributed to the complex interactions between fungi and pests, which can involve the production of toxins, enzymes, or other compounds that disrupt pest development or physiology (Daguerre et al., 2014).

The north of Argentina harbors several biodiversity hotspots, including the Yungas and the Atlantic forest regions, which are recognized for their high levels of species richness and endemism (Myers et al., 2000). These regions are characterized by diverse ecosystems, ranging from humid forests to dry woodlands, providing a wide array of ecological niches for various organisms, including fungi. The high biodiversity of these hotspots suggests the presence of untapped fungal diversity, some of which may have biocontrol capabilities.

Exploring these biodiversity hotspots is crucial for identifying novel fungal species with biocontrol potential. Fungi play key roles in natural ecosystems, including acting as natural enemies of pests (Ganley et al., 2004). The diverse ecological conditions found in the north of Argentina offer an ideal environment for the evolution of fungi with specialized biocontrol mechanisms. Additionally, the unique plant species and pest communities in these regions may drive the evolution of unique fungal adaptations, further highlighting the importance of exploring these areas for biocontrol agents.

Overall, the biodiversity hotspots in the north of Argentina represent promising areas for the discovery of novel fungal biocontrol agents. By conducting targeted explorations and sampling efforts in these regions, researchers can uncover new fungal species with biocontrol capabilities, ultimately contributing to the development of sustainable pest management strategies in forestry.

The study on rediscovering fungal biocontrol agents in forestry for sustainable pest management in the north of Argentina holds significant importance for the development of sustainable pest management practices in forestry. Currently, the forestry industry in Argentina relies heavily on chemical pesticides for pest control, which can have detrimental effects on the environment and human health (Viglizzo et al., 2011). By introducing alternative biocontrol agents such as fungi, this study offers a more sustainable and environmentally friendly approach to pest management.

The potential impact of this research extends beyond the forestry industry to biodiversity conservation in the region. The use of fungi as biocontrol agents can help reduce the reliance on chemical pesticides, thereby minimizing the negative impacts on non-target organisms and promoting biodiversity conservation (Frąc et al., 2018). Additionally, by exploring the biodiversity hotspots in the north of Argentina for novel fungal species, this study contributes to the understanding and conservation of the region's unique biodiversity.

Overall, this study has the potential to contribute deeply to pest management practices in the forestry industry, leading to more sustainable and environmentally friendly approaches. By promoting the use of new fungi as biocontrol agents and highlighting the importance of biodiversity conservation, this research lays the foundation for a more sustainable future for forestry in Argentina.

Fungal biocontrol agents have shown great potential in forestry for sustainable pest management, offering a promising alternative to chemical pesticides. Current research has focused on identifying and characterizing fungal species with biocontrol capabilities, particularly against insect pests such as ants (Bich et al., 2021a). Studies have demonstrated the effectiveness of certain fungi, such as *Beauveria bassiana* and *Metarhizium anisopliae*, in controlling pest populations in forestry ecosystems (Meyling & Eilenberg, 2007). However, there is still a need for further research to expand the range of fungal biocontrol agents available and improve their efficacy in different forestry settings.

One of the key challenges in fungal biocontrol research is the development of effective formulation methods to ensure the viability and stability of fungal spores under field conditions (Keswani et al., 2016; Wong et al., 2019). Current formulations often face limitations in terms of shelf life and application efficiency, highlighting the need for innovative approaches to enhance the delivery of fungal biocontrol agents. Future research efforts could focus on developing novel formulations, such as microencapsulation or nanotechnology-based approaches, to improve the efficacy and durability of fungal biocontrol agents in the field (Behl et al., 2024).

Another area for future research is the exploration of microbial interactions within forestry ecosystems to enhance biocontrol efficacy. Fungi often exist in complex microbial communities, and understanding the interactions between fungi and other microorganisms could help improve the effectiveness of fungal biocontrol agents (Guetsky et al., 2002). All these advancements could significantly enhance the sustainable pest management practices in forestry, reducing reliance on chemical pesticides and minimizing environmental impacts.

Overall, the current state of fungal biocontrol in forestry shows promise but also highlights the need for further research to overcome existing challenges and maximize the potential of fungal biocontrol agents. By focusing on innovative formulation methods, understanding microbial interactions, and genetic enhancement of fungi, future research can contribute to the development of more sustainable and effective pest management practices in forestry, benefiting both the industry and the environment.

Trichoderma species are among the most extensively studied fungal biocontrol agents in forestry due to their versatile mechanisms of action and environmental adaptability (Amerio et al., 2020). These fungi are known for their ability to colonize the rhizosphere and phyllosphere of plants, where they can compete and antagonize with plant pathogens through various mechanisms, including mycoparasitism, antibiosis, and induced systemic resistance (Harman et al., 2004). *Trichoderma* species have been shown to effectively control a wide range of plant pathogens, including fungi, bacteria, and nematodes, making them valuable biocontrol agents in forestry ecosystems (Harman, 2006).

Studies have demonstrated the potential of *Trichoderma* species in enhancing plant growth and promoting plant health in forestry (Vinale et al., 2008). The use of *Trichoderma* species in forestry holds great promise for enhancing sustainable pest management practices and promoting the health and productivity of forest ecosystems. Future research efforts could focus on optimizing the application of *Trichoderma*-based biocontrol products in forestry, including developing effective formulation methods and exploring their interactions with other microorganisms in the rhizosphere. Additionally, further studies are needed to elucidate the mechanisms underlying *Trichoderma*-mediated biocontrol and plant growth promotion in forestry, which could lead to the development of more targeted and efficient biocontrol strategies for forestry pest management.

Entomopathogenic fungi are a group of fungi that can infect and kill insects, making them valuable biocontrol agents in forestry for managing insect pests. These fungi, such as *Beauveria bassiana* and *Metarhizium anisopliae*, have been extensively studied for their ability to effectively control a wide range of insect pests and play additional roles in nature (Vega et al., 2009). Entomopathogenic fungi typically infect insects through the cuticle, where they proliferate and eventually cause the death of the host insect. This mode of action makes them highly specific to insects and minimizes their impact on non-target organisms, making them an environmentally friendly alternative to chemical pesticides (Lacey et al., 2015).

In forestry, entomopathogenic fungi have been used successfully to control various insect pests, particularly in nurseries and young plantations. Studies have shown that application of entomopathogenic fungi can significantly reduce the population densities of pest insects, leading to improved tree health and growth (Dara et al., 2019). Furthermore, entomopathogenic fungi have been found to have minimal impact on beneficial insects, such as pollinators and natural enemies of pests, making them a suitable option for integrated pest management (IPM) programs in forestry (Danfa & Van der Valk, 1999; Ibrahim et al., 2011).

Overall, entomopathogenic fungi offer a sustainable and environmentally friendly solution for managing insect pests in forestry. Further research is needed to optimize their application methods to a particular pest and plantation, enhance their efficacy against target pests, and understand their interactions with non-target organisms and the environment. Incorporating entomopathogenic fungi into integrated pest management strategies can help reduce reliance on chemical pesticides and promote the health and sustainability of forest ecosystems.

Rediscovering or exploring poorly studied fungi for their biocontrol potential in forestry and pest management can provide new insights and solutions to pest issues. Genera such as *Clonostachys*, *Escovopsis*, and *Paecilomyces* are among those that have been overlooked but hold promise for biocontrol applications.

Clonostachys spp. are known for their diverse biological activities, including antagonism against plant pathogens and insect pests (Bich et al., 2021b). Studies have shown their potential as biocontrol agents against various plant diseases and pests, making them valuable candidates for integrated pest management strategies in forestry (Bengtsson, 2020).

Escovopsis is a fungus that parasitizes the fungal cultivar of leaf-cutter ants. While it is primarily studied in the context of ant-fungal mutualisms, its biocontrol potential against other pests has been largely unexplored. Given its specialized adaptations for parasitizing fungi, *Escovopsis* could be investigated for its potential to control fungal pests in forestry ecosystems (Folgarait et al., 2011; Barengo et al., 2023).

Paecilomyces is another fungal genus that has shown biocontrol potential against a wide range of insect pests. Its effectiveness as a biopesticide has been demonstrated in various agricultural settings, but its application in forestry remains underexplored (Moreno-Gavíra et al., 2020). Research on *Paecilomyces* spp. could uncover their potential as biocontrol agents against forest insect pests, contributing to sustainable pest management practices.

Overall, the rediscovery and exploration of overlooked fungi such as *Clonostachys*, *Escovopsis*, and *Paecilomyces* offer exciting prospects for enhancing biocontrol strategies in forestry and pest management. Further research is needed to elucidate their biocontrol mechanisms, assess their efficacy under field conditions, and integrate them into sustainable pest management programs. These efforts could lead to the development of innovative and environmentally friendly solutions for pest issues in forestry.

In conclusion, the exploration of poorly studied biocontrol fungi, such as *Clonostachys*, *Escovopsis*, and *Paecilomyces*, holds significant promise for enhancing pest management strategies in forestry. These fungi offer unique biological activities and mechanisms that can be harnessed for sustainable pest control practices. Their specificity towards target pests, adaptability to different environmental conditions, and minimal impact on non-target organisms make them valuable assets in integrated pest management programs.

Furthermore, the biodiversity hotspots in Argentina, particularly in the northern regions, represent untapped resources for discovering novel fungal species with biocontrol capabilities. By leveraging the biotechnological potential of these biodiversity-rich areas, researchers can uncover new biocontrol agents that can effectively manage insect pests in forestry while preserving the ecological balance of forest ecosystems. This approach not only contributes to the development of innovative pest management solutions but also promotes the conservation of biodiversity in these critical regions.

Moving forward, further research is needed to fully elucidate the biocontrol mechanisms of these fungi, optimize their application methods, and assess their efficacy under field conditions. Collaboration between researchers, forest managers, and policymakers is essential to facilitate the integration of these novel biocontrol agents into sustainable forestry practices. By harnessing the biotechnological potential of poorly studied biocontrol fungi and the biodiversity hotspots in Argentina, we can pave the way for a more sustainable and environmentally friendly approach to pest management in forestry.

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