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Melatonin Reduces Aluminum Toxicity in Alfalfa, According to Physiological and Transcriptomic Analysis (*Medicago sativa* L.)

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Abstract

Aluminum (Al) toxicity is a major constraint in plant growth and development, particularly in acidic soils where solubility and bioavailability of aluminum ions increase. This study investigates the potential alleviative effects of melatonin on aluminum toxicity in alfalfa (*Medicago sativa L.*). Physiological parameters and transcriptomic analysis were employed to elucidate the molecular mechanisms underlying melatonin-mediated alleviation of aluminum stress. Results demonstrate that melatonin application mitigates aluminum-induced oxidative stress, enhances antioxidant enzyme activity, and improves plant growth in alfalfa. Transcriptomic analysis reveals the differential expression of genes associated with aluminum detoxification, antioxidant defense, and stress response. The findings suggest that melatonin plays a crucial role in enhancing aluminum tolerance in alfalfa through modulation of key molecular pathways.

Keywords: Aluminum toxicity • Melatonin • *Medicago sativa* L • Whole virus

Introduction

Aluminum toxicity poses a significant threat to crop production, particularly in acidic soils where the solubility of aluminum ions increases, leading to adverse effects on plant growth and development. Alfalfa (*Medicago sativa L.*), a widely cultivated forage legume, is not exempt from the detrimental impact of aluminum stress. Understanding the molecular mechanisms underlying aluminum toxicity and identifying potential mitigating agents is crucial for sustainable agriculture. In recent years, melatonin, a versatile molecule with various roles in plants, has gained attention for its potential to alleviate abiotic stress, including heavy metal and metalloid toxicity. This study explores the alleviative effects of melatonin on aluminum toxicity in alfalfa through a comprehensive analysis of physiological and transcriptomic responses [1].

Literature Review

Aluminum toxicity disrupts various physiological processes in plants, including oxidative balance, nutrient uptake, and overall growth. Alfalfa plants exposed to aluminum exhibit characteristic symptoms of stress, such as reduced root elongation, inhibition of nutrient absorption, and oxidative damage. However, pre-treatment with melatonin has been shown to mitigate these effects. Aluminum stress inhibits root elongation in alfalfa due to the interference with cell division and elongation processes. Melatonin, acting as a protective agent, counteracts this inhibition, promoting root growth even in the presence of aluminum. This suggests that melatonin may play a role in maintaining root architecture and facilitating nutrient uptake under aluminum stress conditions [2].

Aluminum stress induces oxidative stress by promoting the generation of Reactive Oxygen Species (ROS) in plant cells. Melatonin, known for its antioxidant properties, acts as a scavenger of ROS, thereby reducing oxidative damage. This is reflected in increased activities of antioxidant enzymes such as Superoxide Dismutase (SOD), Catalase (CAT), and Peroxidase (POD) in melatonin-treated alfalfa plants under aluminum stress. These enzymes play a crucial role in detoxifying ROS and preventing cellular damage. Photosynthetic processes are adversely affected by aluminum stress, leading to a decline in chlorophyll content and a decrease in photosynthetic efficiency. Melatonin application helps maintain chlorophyll levels and promotes photosynthetic activity, ensuring sustained energy production even in the presence of aluminum. This is essential for overall plant growth and biomass accumulation [3].

Discussion

To unravel the molecular mechanisms underlying the melatonin-mediated alleviation of aluminum toxicity in alfalfa, transcriptomic analysis was conducted. RNA sequencing revealed significant changes in gene expression patterns, shedding light on key pathways involved in the plant's response to aluminum stress and melatonin treatment. Several genes associated with aluminum detoxification were found to be upregulated in melatonin-treated alfalfa plants. These genes encode transporters involved in the exclusion of aluminum ions from the root apoplast, limiting their entry into the plant. The enhanced expression of these genes suggests that melatonin contributes to the regulation of aluminum uptake and accumulation in alfalfa [4].

The transcriptomic analysis revealed a modulation of genes associated with stress response pathways. Melatonin-treated alfalfa plants exhibited upregulation of stress-responsive genes, including those involved in signal transduction, transcriptional regulation, and the synthesis of stress-related proteins. This indicates that melatonin not only mitigates aluminum-induced stress but also primes the plant for a more robust response to environmental challenges. The physiological and transcriptomic responses observed in this study collectively contribute to a better understanding of the mechanisms by which melatonin alleviates aluminum toxicity in alfalfa. The promotion of root elongation, maintenance of photosynthetic activity, and activation of detoxification and antioxidant pathways collectively result in improved plant growth and aluminum tolerance [5].

Melatonin's positive impact on root elongation suggests its potential role in improving root system architecture, which is crucial for nutrient acquisition and overall plant performance. The enhanced root growth observed in melatonin-treated alfalfa plants under aluminum stress may contribute to improved access to soil nutrients and water. The maintenance of chlorophyll levels and

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photosynthetic efficiency in melatonin-treated plants under aluminum stress has direct implications for biomass production. Sustained photosynthesis ensures a stable energy supply, allowing the plant to allocate resources for growth and development even in the presence of aluminium. The upregulation of genes associated with aluminum detoxification indicates that melatonin contributes to the exclusion of aluminum ions from plant tissues. By limiting aluminum uptake and accumulation, melatonin helps reduce the direct toxic effects of aluminum on cellular processes [6].

Conclusion

The modulation of stress-responsive genes suggests that melatonin primes alfalfa plants for a more effective response to environmental stresses. This priming effect may extend beyond aluminum stress, enhancing the plant's overall resilience to various biotic and abiotic challenges. While this study provides valuable insights into the melatonin-mediated alleviation of aluminum toxicity in alfalfa, further research is warranted to explore additional aspects. Investigating the long-term effects of melatonin treatment on plant growth, yield, and reproductive success under aluminum stress will provide a more comprehensive understanding of its practical applications in agriculture.

Moreover, the specific mechanisms by which melatonin interacts with cellular processes involved in aluminum detoxification and antioxidant defense need further elucidation. Advanced molecular techniques, such as proteomics and metabolomics, could complement transcriptomic analyses to unravel the intricacies of melatonin-mediated responses at the protein and metabolite levels. In conclusion, melatonin emerges as a promising agent for mitigating aluminum toxicity in alfalfa, as evidenced by its positive effects on physiological parameters and gene expression patterns. The multifaceted role of melatonin in promoting root growth, sustaining photosynthesis, and modulating stress-responsive pathways underscores its potential for enhancing aluminum tolerance in crops. Harnessing the insights gained from this study could pave the way for the development of sustainable agricultural practices, particularly in regions with acidic soils prone to aluminum toxicity.

Acknowledgement

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Conflict of Interest

None.

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