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Molecular Approaches for Plant-Parasitic Nematode Management: Advances in Nematology and Agricultural Biotechnology

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Plant-parasitic nematodes (PPNs) cause substantial agricultural losses by disrupting root physiology and weakening plant defence responses. Biotechnology and molecular biology have transformed nematode research, enabling precise diagnosis, effector gene characterization, host–parasite interaction studies, and development of RNA interference (RNAi) and CRISPR-based management strategies. This paper reviews recent advances in molecular diagnostics, functional genomics, transgenic resistance, and integrated molecular nematode management, offering sustainable solutions aligned with modern agriculture.

Keywords: Plant-parasitic nematodes, Biotechnology, Molecular diagnostics, RNA interference, CRISPR, Genomics

Introduction

Plant-parasitic nematodes such as Meloidogyne, Heterodera, and Globodera species severely affect crop productivity. Traditional methods often fall short due to the hidden nature of nematodes in soil and plant tissues. Advances in molecular biology have enabled a shift from phenotype-based identification to gene-level precision, enhancing diagnostic accuracy and facilitating targeted management strategies.

Molecular Basis of Nematode Parasitism

Nematodes utilize a stylet to penetrate host roots and secrete effector proteins that manipulate host cells. Molecular studies reveal that nematodes acquire genes such as cellulases and pectate lyases through horizontal gene transfer. These effectors suppress plant immunity and modify host tissues to form feeding structures like giant cells and syncytia.

Molecular Diagnostics

PCR-based identification using ITS, COI, and 18S rRNA markers provides species-level accuracy. Real-time PCR (qPCR) allows quantification of nematode populations, while LAMP assays offer rapid field detection. Next-generation sequencing (NGS) enables nemabiome profiling, detection of mixed populations, and identification of cryptic species.

Biotechnological Approaches for Management

RNA interference (RNAi) has emerged as a powerful tool for silencing essential nematode genes. Host-delivered RNAi expressing dsRNA targeting genes such as 16D10, MAP kinases, and v-ATPases reduces nematode development and reproduction. CRISPR-Cas systems enable gene editing in hosts to eliminate susceptibility genes, contributing to stable nematode resistance. Transgenic strategies involving proteinase inhibitors, lectins, chitinases, and antimicrobial peptides have shown success in reducing nematode infection.

Omics Technologies

Genomics of major nematodes has provided insights into effector diversity and adaptation mechanisms. Transcriptomics identifies gene expression patterns during parasitism.

Proteomics reveals secreted effectors critical for host manipulation, while metabolomics helps understand nematode-induced shifts in plant metabolic pathways.

Integrated Molecular Nematode Management (IMNM)

Combining traditional and advanced approaches enhances long-term sustainability. Molecular diagnostics guide early detection, while RNAi and CRISPR-based resistance integrate well with biological control agents and cultural practices to create a comprehensive management strategy.

Conclusion

Molecular tools have revolutionized nematology, offering precise, efficient, and environmentally friendly solutions. Integrating biotechnology with classical nematode management can significantly enhance crop resilience and sustainability. Continued research and field validation will strengthen future nematode management strategies.

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