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Biochemical and Molecular Evaluation of *Ficus racemosa* Linn Leaf Galls Induced by Insect *Pauropsylla depressa*

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Abstract

Leaf galls are fascinating plant-insect interactions resulting in abnormal outgrowths on plant tissues. This review focuses on the biochemical and molecular evaluation of *Ficus racemosa* Linn leaf galls induced by the insect *Pauropsylla depressa*. The study aims to understand the changes in biochemical compounds and gene expression during different stages of gall development. By compiling similar studies, this review highlights the significance of such research in understanding plant defense mechanisms and the potential applications in agriculture and pharmacology.

Keywords: *Pauropsylla depressa*, *Ficus racemosa*, Gene expression, Leaf galls, Plant-insect interactions

1. Introduction

The interaction between plants and insects often results in unique structures known as galls. Galls are abnormal growths that occur on plants due to the activity of insects, mites, fungi, or bacteria (Patel *et al.*, 2018). These structures are formed as a result of the manipulation of the plant's metabolic pathways by the gall-inducing organisms (Oliveira *et al.*, 2016).

Gall diseases in plant leaves can be caused by various organisms including fungi, bacteria, nematodes, and mites. Fungi such as *Exobasidium* and *Taphrina* lead to abnormal growth, creating galls on leaves (Sharma *et al.*, 2017). Bacteria such as *Agrobacterium tumefaciens* can cause crown gall disease, which may also affect leaves (Gohlke & Deeken, 2014). Certain nematodes such as *Meloidogyne* species, invade plant tissues and disrupt their functions, resulting in galls or knots (Escobar *et al.*, 2015). Additionally, eriophyid mites inject chemicals into leaf tissues while feeding, triggering gall formation. These pathogens disrupt normal plant growth and metabolism, leading to economic losses in agriculture and horticulture. Among the fascinating examples of such interactions are the leaf galls of *Ficus racemosa* Linn, induced by the insect *Pauropsylla depressa* (Dsouza & Ravishankar, 2014).

Leaf galls study provides insights into the complex biochemical and molecular changes that occur during gall formation. Galls are of interest not only for their ecological significance but also for their potential pharmacological and biochemical applications (Banc *et al.*, 2023). This review article focuses on the biochemical and molecular evaluation of *Ficus racemosa* leaf galls at various stages, with a particular emphasis on the role of *Pauropsylla depressa* as the inducing agent (Dsouza & Ravishankar, 2014). We explore the physiological changes in the plant, the metabolic shifts during gall formation, and the potential implications of these findings.

2. Ficus racemosa Linn and Its Significance

Ficus racemosa Linn, commonly known as the cluster fig or India fig tree, is a multipurpose plant widely distributed in tropical regions (Krishna & Borges, 2018). *Ficus racemosa* is an important medicinal plant applicable in traditional healing systems like Ayurveda, Unani, and Siddha. Each part of the plant such as bark, leaves, fruits, (shown in the **Figure 1**) and latex has therapeutic properties (Pahari *et al.*, 2022).

Figure 1: Fruits, leaves, and Trunk of *Ficus racemosa* (Mohmmad, 2017)

The bark is known for its astringent, anti-inflammatory, and antibacterial effects, making it useful for treating wounds, diarrhea, and dysentery (Kumar *et al.*, 2024). The fruits are rich in beneficial compounds such as flavonoids and vitamins, offering antioxidant and liver-protective benefits (Chaware *et al.*, 2020). The latex has anthelmintic properties and is used for skin disorders and ulcers (Chandrashekhar *et al.*, 2008). The leaves help reduce fever and cough (Ahmed & Urooj, 2010). Additionally, *Ficus racemosa* can help regulate blood sugar levels, aid digestion, and support liver health, making it a versatile plant with significant medicinal potential (Rizvi & Mishra, 2013). The tree hosts several insect species, including *Pauropsylla depressa*, which induces characteristic leaf galls.

Galls formed on *Ficus racemosa* leaves are morphologically distinct and undergo dynamic bio-chemical and molecular changes during development. These changes reflect the interaction between the plant's defense mechanisms and the insect's ability to manipulate plant growth and metabolism (Borges, 2021).

3. *Pauropsylla depressa*: The Gall-Inducing Insect

Pauropsylla depressa is a psyllid insect that specifically targets *Ficus racemosa*.

Female psyllids lay eggs on the underside of young leaves (Shown in the **Figure 2**), and upon hatching, the nymphs initiate gall formation by feeding on the plant's phloem and injecting salivary secretions (Dhiman & Shalu, 2010).

These secretions contain plant growth regulators (PGRs), such as auxins, cytokinins, and phenolic compounds, which alter normal plant tissue development and create galls (Rizvi & Mishra, 2013).

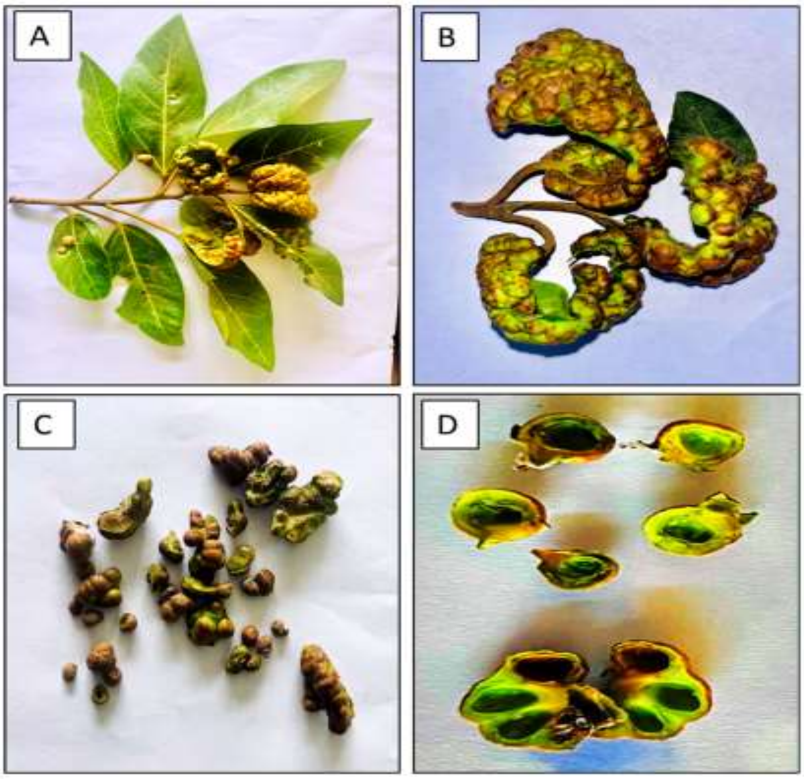

Figure 2: *Ficus recemosa* with gall (Sabira *et al.*, 2024)

The gall structure provides both nutrition and shelter for the developing insect. Understanding the biochemical and molecular pathways activated during this process is essential to unravel the intricacies of plant-insect interactions (Giron *et al.*, 2016).

4. Biochemical Changes in Gall Formation

4.1. Alterations in Primary Metabolites

Gall formation significantly impacts the primary metabolism of the host plant. Studies have shown that the carbohydrate, protein, and lipid content of gall tissues differ from those in normal leaf tissues:

- **Carbohydrates**: Gall tissues exhibit increased levels of soluble sugars, which provide an energy source for the insect and developing gall.
- **Proteins**: Enhanced protein synthesis occurs in gall tissues, likely to meet the metabolic demands of the growing insect and gall structure.
- **Lipids**: Lipid accumulation is observed, as these molecules are vital for membrane formation and energy storage.

The tissues impacted by galls caused by cyanids on oak trees and psyllids on eucalyptus exhibit changed amounts of lipids, proteins, and carbohydrates. Due to the metabolic needs of the organisms that cause gall formation, resources are diverted toward gall growth, which is the cause of these alterations. Galls produced by *Myrmecophilous aphids* cause starch to accumulate and photosynthetic activity to decrease, according to research on Tamarix species (Chen, 2024). Similarly, *Procontarinia matteiana*-induced mango leaf galls in Mangifera indica show higher levels of amino acids in their gall tissues than healthy leaves. In order to comprehend plant-insect or plant-pathogen interactions and their ecological relevance, it is imperative to investigate these mechanisms further. These findings demonstrate that gall development uniformly alters the host's metabolic pathways (Augustyn *et al.*, 2013).

4.2. Role of Secondary Metabolites

Secondary metabolites, such as phenolics, flavonoids, and tannins, play a crucial role in the defense response of the plant and the development of the gall shown in **Table 1**:

Table 1: Secondary metabolites and their role in gall development and defense

S. No.	Secondary Metabolite	Role in Defense Response	Role in Gall Development	Reference
1	**Phenolics**	Act as antimicrobial agents, inhibit pathogen growth, and strengthen cell walls by lignification.	Provide structural support to gall tissues and limit further infestation.	Sharma *et al.*, 2012
2	**Flavonoids**	Serve as antioxidants, neutralize reactive oxygen species (ROS), and provide UV protection.	Promote localized defense signaling and support gall tissue development.	Zahra *et al.*, 2024
3	**Tannins**	Exhibit astringent properties, reduce herbivory, and deter feeding by insects or pathogens.	Accumulate in galls to create a hostile environment for secondary invaders.	Saini *et al.*, 2024

4.3. Antioxidant Activity

Superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) levels were raised in *Quercus infectoria* galls caused by wasps, suggesting an adaptive response to fight reactive oxygen species (ROS). Similarly, as part of the plant's defense system, Rosa species galls generated by Diplolepis gall wasps showed elevated phenolic content and antioxidant activity. Because *Pongamia pinnata* works to neutralize ROS and preserve cellular integrity, studies on the plant have also shown increased activity of antioxidative enzymes in gall tissues. Plants frequently exhibit increased antioxidant activity in their gall tissues, which serves as a defense mechanism against oxidative stress and a home for organisms that cause gall formation (Liu *et al.*, 2014).

5. Molecular Mechanisms Underlying Gall Formation

5.1. Gene Expression Changes

Gall formation involves extensive reprogramming of the plant's gene expression. Key genes associated with growth regulation, secondary metabolism, and stress responses are differentially expressed. Auxin-responsive genes are important for gall tissues because they are activated to promote cell division and growth. **Cytokinin-responsive genes** also play a role by enhancing cell proliferation and helping form nutritious tissues within the gall (Hirano *et al.*, 2023). Additionally, **stress-responsive genes** are highly expressed, indicating the plant's efforts to balance growth and defense against stress. These genes help the plant manage the challenges posed by gall formation while ensuring it can still grow and thrive. Understanding these genetic responses is crucial for studying how plants interact with insects and pathogens, as well as for developing strategies to improve plant resilience in the face of environmental stresses (Georgieva & Vassileva, 2023).

5.2. Phytohormonal Crosstalk

The **interplay** between various plant **hormones**, including **auxins**, **cytokinins**, **gibberellins**, and **jasmonic acid**, is crucial for gall development. The **salivary secretions** of the insect modify these hormonal pathways to create a suitable environment for both gall formation and insect growth. Understanding this interaction is important for studying how insects affect plants and their ecosystems (Erb *et al.*, 2012).

5.3. Epigenetic Modifications

Emerging evidence suggests that **epigenetic changes**, such as **DNA methylation** and **histone modification**, play a significant role in gall formation. These changes can alter the **chromatin structure** and **gene expression**, which helps in the developmental reprogramming of gall tissues (Tuscher & Day, 2019). Comparative studies on leaf galls reveal interesting insights into different plant-insect interactions. For example, **cynipid gall wasps** on oak trees induce metabolic shifts similar to those seen in

Ficus racemosa, resulting in increased carbohydrate and protein content along with higher phenolic levels (Borges, 2021). Additionally, **eriophyoid mites** cause leaf galls on various plants, leading to an upregulation of defense-related enzymes and secondary metabolites. Galls induced by aphids on poplar and other plants show enhanced antioxidant activity and hormonal imbalances (De Lillo *et al.*, 2018). These findings highlight the conserved biochemical and molecular mechanisms underlying gall formation across diverse plant-insect interactions, emphasizing the need for further research to understand these complex relationships better. Understanding these mechanisms can provide insights into how plants respond to insect attacks and may help develop strategies for managing gall-inducing pests in agriculture.

6. Potential Applications of Gall Studies

6.1. Pharmacological Potential

Gall tissues are rich in **bioactive compounds** like **phenolics**, **flavonoids**, and **tannins**, which have important **medicinal properties**. Extracts from **Ficus racemosa** galls show strong **antioxidant**, **antimicrobial**, and **anti-inflammatory** activities, making them promising candidates for **drug development**. These compounds help protect cells from damage, fight infections, and reduce inflammation, which are crucial for maintaining health (Eshwarappa *et al.*, 2015). The presence of these beneficial compounds in gall tissues suggests that they can be valuable in creating new medicines. Researchers are increasingly interested in studying these galls to uncover their potential uses in healthcare. By exploring the properties of these bioactive compounds, scientists hope to develop effective treatments for various diseases. This highlights the importance of understanding plant-insect interactions and how they can lead to valuable resources for human health. Overall, the medicinal benefits of gall tissues emphasize their significance in both agriculture and medicine, encouraging further research into their applications.

6.2. Insights into Plant-Insect Interactions

Understanding how galls form at a molecular level helps us learn about the co-evolution of **plants** and **insects**. This knowledge is important for developing better **pest management** strategies and supporting **conservation** efforts. Galls are abnormal growths on plants caused by various organisms, including insects. When these organisms invade a plant, they manipulate its resources to create a suitable environment for their development (Patel *et al.*, 2018). This interaction can lead to significant changes in the plant's metabolism, affecting its growth and health. By studying these processes, researchers can identify ways to protect crops from harmful pests while promoting healthy ecosystems. Additionally, insights gained from this research can help create sustainable agricultural practices that minimize chemical use and enhance biodiversity. Ultimately, understanding gall formation not only sheds light on the complex relationships between plants and insects but also provides valuable information for improving agricultural productivity and environmental conservation.

6.3. Agricultural and Industrial Applications

Biochemical compounds derived from galls have many **potential applications** in agriculture and industry. In agriculture, these compounds can be used as **biopesticides** (Mawcha *et al.*, 2024). They help control pests without harming the environment, making farming more sustainable. For instance, certain compounds found in galls can deter harmful insects, reducing the need for chemical pesticides that can damage crops and ecosystems.

In addition to biopesticides, gall-derived compounds can also be utilized in **industry** as **natural dyes** (Pawłowska & Stepczyńska, 2022). These dyes are often more environmentally friendly than synthetic alternatives, providing vibrant colors for textiles and other materials. Furthermore, these compounds possess **antioxidant properties**, which can be beneficial in food preservation and health products (Alegbe & Uthman, 2024). Antioxidants help protect cells from damage caused by free radicals, making them valuable in the cosmetic and pharmaceutical industries.

7. Future Perspectives

Future studies should focus on **high-throughput techniques** like transcriptomics, proteomics, and metabolomics to identify the key molecules involved in gall development. Additionally, **functional studies** using gene editing tools such as **CRISPR-Cas9** can help validate the roles of candidate genes. It is also important to investigate the role of **epigenetic modifications** in gall formation, as these changes can influence gene expression without altering the DNA sequence itself. Furthermore, exploring the **ecological and evolutionary implications** of plant-insect interactions in gall systems will provide valuable insights into how these relationships affect both the plants and the insects involved. By addressing these areas, researchers can deepen our understanding of gall formation and its broader impacts on ecosystems, ultimately contributing to more effective management strategies for agricultural and natural systems affected by galls.

8. Conclusion

The leaf galls of Ficus racemosa induced by Pauropsylla depressa represent a fascinating model for studying plant-insect interactions. Biochemical and molecular analyses reveal significant changes in primary and secondary metabolism, gene expression, and hormonal pathways during gall formation. These findings have broad implications for understanding the mechanisms of plant development, defense, and co-evolution with insects. Furthermore, the pharmacological potential of gall tissues offers exciting prospects for biotechnological and therapeutic applications. Continued research in this area will deepen our understanding and unlock new possibilities for utilizing galls in science and industry.

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