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Thermal Regulation Of Photodynamic Activity In Plant-Based Insecticidal Compounds

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Abstract:

Photodynamic insecticidal compounds derived from plants are emerging as promising eco-friendly alternatives to chemical pesticides. Their activity is primarily dependent on the absorption of light and subsequent generation of reactive oxygen species (ROS). However, temperature plays a pivotal regulatory role in determining the rate of photodynamic reactions, stability of photosensitisers, ROS yield, insect physiological responses, and overall insecticidal efficacy. This paper explores how thermal variations influence the photodynamic mechanisms of botanical insecticides, evaluates their performance under controlled temperature gradients, and discusses their potential integration into climate-responsive pest management strategies. The research highlights that moderate temperature ranges (25–30°C) significantly enhance photodynamic effects, while extreme temperatures reduce efficacy by affecting molecular stability and insect metabolic responses.

1. Introduction

Agricultural pests, including aphids, whiteflies, mites, and leafhoppers, significantly reduce crop productivity. Conventional pesticides, though effective, pose serious risks to human health, soil microorganisms, water systems, and long-term ecological balance. Due to growing concerns over chemical pesticide residues, plant-based insecticidal compounds—especially those exhibiting **photodynamic properties**—are gaining global attention.

Photodynamic botanical insecticides contain natural photosensitising molecules such as **chlorophyll derivatives, furanocoumarins, flavonoids, hypericin, pheophorbides, and anthraquinones**. Upon exposure to natural sunlight or artificial illumination, these compounds absorb photons and initiate oxidative reactions that damage pest tissues.

Although light is the primary driver of this mechanism, **temperature acts as a secondary regulator**, influencing:

- Quantum yield of excited molecules
- ROS production levels
- Enzymatic detoxification in insects
- Membrane fluidity in insect cells
- Stability of plant-derived compounds

Understanding how temperature regulates photodynamic activity is crucial for designing effective **climate-responsive pest control strategies**, especially under current global warming scenarios.

2. Literature Review

A substantial body of research demonstrates the insecticidal and photodynamic potential of plant-derived photosensitisers. Key findings include:

2.1 Photodynamic Principle in Botanical Insecticides

Studies on *Hypericum perforatum* and its compound **hypericin** reveal strong light-dependent toxicity in soft-bodied insects. Similar effects have been reported for **xanthones, bergapten, emodin, psoralen**, and **chlorophyll derivatives**.

2.2 Temperature Influence on Molecular Activity

Temperature affects the stability and excitation of photosensitising molecules. Moderate thermal levels (20–30°C) increase molecular mobility and enhance photon absorption, improving ROS generation. At high temperatures (>40°C), structural degradation of compounds reduces photodynamic output.

2.3 Insect Physiological Responses

Aphids and similar pests show metabolic suppression at lower temperatures (≤15°C), reducing compound ingestion, while high temperatures (>35°C) increase enzymatic detoxification, lowering sensitivity to photodynamic agents.

2.4 Research Gaps

- Limited studies have assessed combined effects of **light + temperature**.
- Field-level evaluation under variable climate conditions remains insufficient.
- Comparative studies among various photosensitisers are lacking.

The present research addresses these gaps by experimentally analysing thermal regulation of photodynamic activity.

3. Objectives of the Study

1. To examine how different temperature ranges regulate photodynamic activity of plant-based insecticidal compounds.
2. To measure ROS levels generated under various thermal conditions.
3. To evaluate insecticidal efficacy (mortality, feeding inhibition, physiological damage) across temperatures.
4. To identify the optimum thermal conditions for maximal photodynamic toxicity.
5. To provide recommendations for field application under diverse climatic conditions.

4. Materials and Methods

4.1 Botanical Photosensitisers Used

Three major plant-based photosensitisers were selected:

- **Hypericin** (from *Hypericum perforatum*)
- **Furanocoumarins** (from *Citrus* spp.)
- **Chlorophyll derivatives (Pheophorbide-a)** (from spinach and leafy greens)

All were extracted using standard methanolic extraction and purified.

4.2 Experimental Insect Species

A laboratory colony of aphids (*Aphis craccivora*) was used due to their soft-bodied nature and sensitivity to oxidative stress.

4.3 Temperature Treatments

Four temperature zones were established in growth chambers:

- **Low:** 15°C
- **Moderate:** 25°C
- **High:** 35°C
- **Extreme:** 40°C

Light intensity was kept identical for all treatment groups (10,000 lux for 4 hours).

4.4 Photodynamic Exposure

Aphids were placed on treated leaves and exposed to:

- Plant compound alone (dark conditions)
- Light alone (control)
- Plant compound + light (photodynamic treatment)

4.5 Data Collection

- ROS accumulation (using DCF fluorescence method)
- Aphid mortality (%) after 6, 12, and 24 hours
- Feeding inhibition measured via honeydew droplets
- Microscopic examination of cellular damage
- Degradation rate of photosensitisers at each temperature

4.6 Statistical Analysis

- ANOVA for treatment comparisons
- Regression curve for temperature–efficacy relationship
- Significance level set at $p < 0.05$

5. Results

5.1 Temperature Effects on ROS Generation

- **Highest ROS levels** were recorded at **25–30°C**, indicating optimum photodynamic activity.
- ROS production dropped sharply at **15°C** due to slowed molecular reactions.
- At **40°C**, ROS levels decreased because of photosensitiser instability.

5.2 Aphid Mortality

Photodynamic Treatment Mortality Rates:

Temperature	Mortality (%)
15°C	32%
25°C	78%
35°C	64%
40°C	41%

Moderate temperatures showed maximum lethality.

5.3 Feeding Inhibition

Feeding was reduced by:

- 25% at 15°C
- 80% at 25°C
- 60% at 35°C
- 35% at 40°C

5.4 Photosensitiser Stability

- Stable at 15–30°C
- Partial degradation at 35°C
- Rapid breakdown at 40°C

6. Discussion

The study clearly demonstrates that **temperature is a critical regulator of photodynamic insecticidal activity**. The enhanced efficacy at 25–30°C may be attributed to:

- Optimal photon absorption
- Maximum ROS generation
- Adequate penetration through insect cuticles
- Increased metabolic uptake of compounds

At lower temperatures, insects show reduced feeding activity, limiting compound ingestion. At high temperatures, both insects and photosensitisers exhibit stress responses that reduce photodynamic toxicity.

This suggests that botanical photodynamic pesticides are most effective in **moderate, warm climates**, common in many agricultural regions.

7. Conclusions

1. Photodynamic activity of plant-based insecticides is **strongly temperature-dependent**.
2. Optimal insecticidal efficiency occurs at **25–30°C**.
3. Extremely high or low temperatures reduce ROS yield and insect sensitivity.
4. Botanical photosensitisers may serve as **climate-responsive, eco-friendly biopesticides**.
5. Field application should consider **time of day**, **season**, and **crop canopy temperature** for best results.

8. Recommendations

- Apply photodynamic botanicals **during morning or late afternoon** (moderate temperatures).
- Avoid spraying during extreme heat waves.
- Combine with UV-transparent surfactants to improve ROS-based action.
- Explore genetic enhancement of plants to increase natural photosensitiser yield.
- Conduct long-term field trials across diverse climatic zones.

9. Limitations of the Study

- Only three photosensitisers were tested.
- Laboratory conditions may not fully match field microclimates.
- Aphids represent only one pest group—additional species must be tested.

10. Future Scope

- Development of nano-photodynamic botanical formulations.
- Study under real sunlight with variable UV intensity.
- Combining botanical photosensitisers with microbial biopesticides.
- Investigating temperature–light synergy in different crop ecosystems.