



Justification of Ultra weak Photon Emission as a Biomarker for Mitochondrial Function in Plants

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ABSTRACT

Ultraweak photon emission (UPE), the spontaneous emission of low-intensity light from biological systems, is examined as a potential non-invasive biomarker for assessing mitochondrial function in plants. This review explores the biophysical mechanisms underlying UPE, its relationship with mitochondrial activity, and its application in plant research. Evidence supporting UPE as a biomarker, including correlations with established mitochondrial health indicators and findings from case studies, is synthesized. The advantages of UPE, such as non-invasive measurement and real-time monitoring capabilities, along with current limitations and challenges, are discussed. The review further highlights potential applications of UPE in stress response studies, breeding programs, and ecological monitoring, emphasizing its role in advancing our understanding of plant physiology and responses to environmental stressors.

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1. Introduction

1.1 Overview of Mitochondrial Function in Plants



Mitochondria are essential organelles in plant cells, primarily known for their role in cellular respiration and energy production[1]. They generate adenosine triphosphate (ATP) through oxidative phosphorylation, which is critical for powering various cellular processes. Beyond energy production, mitochondria are involved in numerous metabolic pathways, including the tricarboxylic acid (TCA) cycle, amino acid metabolism, and lipid biosynthesis[2]. Additionally, they play a pivotal role in regulating reactive oxygen species (ROS) levels, which are by-products of mitochondrial respiration and act as signalling molecules in stress responses and cellular homeostasis[3]. In plants, mitochondrial function is particularly significant due to the dual energy systems of photosynthesis and respiration. While chloroplasts are responsible for photosynthetic energy production, mitochondria provide energy during the night or under stress conditions when photosynthesis is limited. Furthermore, mitochondria are integral to the plant's ability to adapt to environmental stressors, such as drought, salinity, and temperature fluctuations, by modulating metabolic and signalling pathways [4].

1.2 Ultraweak Photon Emission (UPE)

Ultraweak photon emission (UPE), also referred to as biophoton emission, is the spontaneous release of photons at extremely low intensities from living organisms. This phenomenon occurs as a by-product of cellular metabolic processes, particularly those involving oxidative reactions and ROS generation[5]. UPE is distinct from other light-emission processes, such as bioluminescence or chemiluminescence, as it arises from the natural metabolic activity of cells without the involvement of specialised light-emitting molecules[6]. UPE has been observed in plants across various tissues and under different physiological conditions. It is closely linked to mitochondrial activity, as mitochondria are a major source of ROS production during respiration[7]. The photons emitted during UPE are thought to result from the relaxation of electronically excited molecules, such as singlet oxygen or excited carbonyl groups, which are generated during oxidative metabolic reactions. Studies have shown that UPE intensity correlates with mitochondrial function, making it a potential non-invasive indicator of cellular metabolic health[8].

1.3 Significance of UPE in Plant Research

The study of UPE in plants has gained attention due to its potential as a biomarker for physiological and metabolic states[5]. UPE provides a unique, non-invasive method to monitor cellular processes in real time, offering insights into mitochondrial function, oxidative stress, and overall plant health. For instance, changes in UPE intensity have been linked to abiotic stress responses, such as drought and



salinity, as well as biotic stress caused by pathogens[6]. Furthermore, UPE analysis has been proposed as a tool for early detection of stress-induced damage in plants, enabling timely interventions in agriculture and environmental monitoring [7].The historical development of UPE research in plants has laid the foundation for its application in mitochondrial studies. Early investigations demonstrated UPE from isolated plant mitochondria, highlighting its connection to ROS production and energy metabolism[8] .Recent advancements in imaging and detection technologies have further enhanced the ability to measure UPE with high sensitivity, paving the way for its integration into plant physiology and biophysics research. In this review, we explore the mechanisms underlying UPE, its relationship with mitochondrial function, and its potential as a biomarker in plant research[9]. By synthesizing current evidence, we aim to justify the use of UPE as a reliable indicator of mitochondrial health and its broader applications in understanding plant responses to environmental challenges.

2. Mechanisms of Ultraweak Photon Emission

2.1 Biophysical Basis of UPE

Ultraweak photon emission (UPE), also referred to as biophoton emission, is the spontaneous release of photons at extremely low intensities from living cells[9]. This phenomenon is primarily a by-product of cellular metabolic processes, particularly those involving oxidative reactions and the generation of reactive oxygen species (ROS). The photons emitted during UPE are thought to result from the relaxation of electronically excited molecules, such as singlet oxygen or excited carbonyl groups, which are generated during oxidative metabolic reactions [7] [6].

Mitochondria, as the primary site of cellular respiration, are a major source of UPE. During oxidative phosphorylation, electrons are transferred through the electron transport chain (ETC), and a small percentage of these electrons leak, leading to the formation of ROS such as superoxide anions and hydrogen peroxide[10]. These ROS can interact with biomolecules, such as lipids and proteins, resulting in the formation of electronically excited states. The subsequent relaxation of these excited states releases photons in the visible to near-infrared spectrum (400–900 nm)[9]. This process is distinct from other light-emission phenomena, such as bioluminescence, as it does not involve specialised light-emitting molecules like luciferase[11].

The intensity and spectral characteristics of UPE are influenced by the metabolic activity of mitochondria. For instance, increased ROS production during stress or mitochondrial dysfunction can



elevate UPE levels, making it a potential indicator of mitochondrial health[7]. Studies have demonstrated that UPE is closely linked to mitochondrial respiration, with higher photon emission observed during active metabolic states[9] [6].

2.2 Factors Influencing UPE in Plants

Several factors can modulate UPE in plants, including environmental conditions and the physiological state of the plant. These factors influence mitochondrial activity and ROS production, thereby affecting the intensity and dynamics of UPE.

1. Environmental Conditions:

- **Light:** Light exposure can significantly impact UPE in plants. Photosynthesis in chloroplasts generates ROS, which can interact with mitochondrial processes, leading to changes in UPE. Additionally, light-induced stress, such as high-intensity light, can increase ROS production and UPE levels [7]
- **Temperature:** Temperature fluctuations can alter mitochondrial respiration rates and ROS production. For example, heat stress has been shown to increase UPE due to enhanced oxidative stress and metabolic activity[12].
- **Stress Factors:** Abiotic stressors, such as drought, salinity, and heavy metals, can elevate ROS levels in plant cells, leading to increased UPE. These stress-induced changes in UPE have been observed in various plant species and are often correlated with mitochondrial dysfunction[13].

2. Physiological State of the Plant:

- **Growth Stage:** The metabolic activity of mitochondria varies across different growth stages of plants. For instance, young, actively growing tissues exhibit higher mitochondrial respiration rates and, consequently, higher UPE levels compared to mature or senescent tissues[7].
- **Health Status:** The health of the plant significantly influences UPE. Healthy plants with optimal mitochondrial function exhibit stable UPE levels, whereas diseased or stressed plants show altered UPE patterns due to mitochondrial dysfunction and increased ROS production[9].

2.3 Integration of UPE with Mitochondrial Function



The relationship between UPE and mitochondrial function has been extensively studied, highlighting its potential as a non-invasive biomarker. Mitochondria are not only the primary source of UPE but also play a central role in regulating ROS levels and oxidative metabolism. The dynamic nature of UPE, influenced by mitochondrial activity, provides valuable insights into the metabolic and physiological state of plants [9] [6]. Recent advancements in UPE detection technologies have enabled researchers to measure photon emission with high sensitivity, allowing for real-time monitoring of mitochondrial activity. These studies have demonstrated that UPE can serve as a reliable indicator of mitochondrial health, oxidative stress, and overall cellular metabolism in plants. By understanding the biophysical mechanisms and factors influencing UPE, researchers can further explore its applications in plant physiology, stress biology, and environmental monitoring. The integration of UPE analysis with mitochondrial research holds great promise for advancing our understanding of plant responses to environmental challenges and improving agricultural practices.

3. Biomarkers and Mitochondrial Function

3.1 Importance of Biomarkers

Biomarkers are critical indicators of a plant's physiological state, particularly in response to various abiotic and biotic stress factors [14]. They serve as measurable and quantifiable signals that reflect the cellular responses of plants to environmental changes, enabling early detection of stress before it manifests as visible damage. This capability is particularly vital in the context of global food security, where understanding plant stress responses is essential for developing resilient crop varieties capable of withstanding adverse conditions [15]. The significance of biomarkers has gained momentum in recent years, driven by advancements in technology that facilitate their identification and validation. These indicators can range from specific molecules, such as phytohormones and proteins, to broader biochemical changes that signify shifts in plant health and metabolic activity [16].

3.2 Mitochondrial Health Indicators

Mitochondria play a pivotal role in cellular respiration and energy production, making them essential for plant growth and development. Assessing mitochondrial function is crucial for understanding overall plant health, particularly under stress conditions. Common parameters used to evaluate mitochondrial health include ATP production, reactive oxygen species (ROS) levels, and membrane potential [17]. ATP production is often measured using bioluminescent assays that quantify light emitted from ATP-



luciferase reactions, providing insights into the energy status of the plant. Additionally, the assessment of ROS levels is critical, as these molecules can indicate oxidative stress and mitochondrial dysfunction[18]. Techniques such as fluorescent probes and colorimetric assays are employed to measure ROS, allowing researchers to gauge the extent of oxidative damage within plant cells. Membrane potential is another vital indicator of mitochondrial health, as it reflects the ability of mitochondria to maintain a proton gradient essential for ATP synthesis. Fluorescent dyes are commonly used to assess membrane potential, providing real-time insights into mitochondrial function[19].

3.3 Limitations of Traditional Methods

Despite the importance of these parameters, traditional methods for assessing mitochondrial function have notable limitations. Many of these techniques require specialised equipment that can be costly and complex, limiting their accessibility for routine use in plant research. For instance, high-resolution respirometry systems, while effective, demand precise calibration and can be sensitive to environmental conditions, leading to variability in results. Moreover, the isolation of mitochondria from plant tissues can introduce contamination from other organelles, complicating the interpretation of results[20]. This contamination can obscure the true mitochondrial activity and lead to misleading conclusions about plant health. Additionally, the dynamic nature of mitochondrial function means that measurements can fluctuate significantly based on the plant's developmental stage and environmental conditions, further complicating data interpretation[21]. The need for standardised protocols is evident, as variability in methodologies can lead to inconsistent results across studies. As such, there is a pressing demand for innovative approaches that can provide reliable, non-invasive assessments of mitochondrial function in plants. This is where ultraweak photon emission (UPE) emerges as a promising alternative, offering a non-invasive method to monitor mitochondrial health in real-time, potentially overcoming many of the limitations associated with traditional techniques[22]. In summary, while traditional biomarkers and methods for assessing mitochondrial function in plants provide valuable insights, they are often hindered by technical challenges and variability. The exploration of UPE as a biomarker for mitochondrial function presents an exciting avenue for future research, with the potential to enhance our understanding of plant physiology and resilience in the face of environmental stressors[23].

4. UPE as a Biomarker for Mitochondrial Function

4.1 Evidence Supporting UPE as a Biomarker



The validation of Ultra-weak Photon Emission (UPE) as a biomarker for mitochondrial function is supported by a growing body of evidence that demonstrates its correlation with various aspects of mitochondrial health and cellular metabolism. Recent advances between 2000 and 2020 have shown significant progress in detecting UPE signals in living tissues, establishing its potential as a valuable tool for assessing mitochondrial function [24].

4.1.1 Correlation with Mitochondrial Health Indicators

The relationship between UPE and mitochondrial health is primarily mediated through oxidative processes and stress responses. During periods of mitochondrial dysfunction, changes in oxidative stress levels lead to corresponding alterations in UPE patterns [9]. This correlation is particularly evident in the context of mitochondrial retrograde signalling, where changes in mitochondrial function trigger communication between mitochondria and the nucleus, resulting in modified gene expression patterns and stress adaptation responses [24]. The production of Reactive Oxygen Species (ROS) serves as a critical link between mitochondrial function and UPE. Research has established that UPE can effectively serve as an assay for ROS, which are closely tied to mitochondrial health and function[24]. This relationship is particularly significant as it provides a non-invasive means of monitoring oxidative stress levels, which are key indicators of mitochondrial health.

4.1.2 Case Studies and Experimental Evidence

Various experimental studies have demonstrated the utility of UPE measurements across different plant species and conditions:

1. **Stress Response Monitoring:** Studies have shown that plants under drought stress and other environmental stressors exhibit measurable changes in UPE levels, correlating with alterations in mitochondrial function[25].
2. **Growth Stage Analysis:** Research has revealed that UPE patterns vary with different growth stages and physiological states, providing insights into developmental changes in mitochondrial activity[9].
3. **Environmental Adaptation:** Investigations have demonstrated how UPE measurements can reflect plants' responses to various environmental conditions, including temperature fluctuations and light exposure[26].

4.2 Advantages of Using UPE



4.2.1 Non-invasive Measurement Techniques

One of the primary advantages of UPE as a biomarker is its non-invasive nature. Modern UPE detection systems allow for the measurement of mitochondrial function without damaging or disturbing the plant tissue[27]. This non-destructive approach enables the Continuous monitoring of the same specimen over time, Preservation of plant integrity during measurements, Reduction in experimental artifacts that might arise from tissue damage and Application in sensitive developmental studies.

4.2.2 Real-time Monitoring Capabilities

The advancement in UPE measurement technology has enabled sophisticated real-time monitoring systems that offer several advantages:

1. **Continuous Data Collection:** Modern sensor technologies allow for continuous monitoring of plant physiological states, providing immediate feedback on changes in mitochondrial function[27].
2. **Dynamic Response Assessment:** Real-time monitoring systems can capture rapid changes in UPE levels, enabling the observation of immediate responses to environmental stimuli or stress conditions.[28]
3. **Integration with Other Monitoring Systems:** UPE measurements can be combined with other non-invasive monitoring techniques to provide comprehensive insights into plant health[29].

However, it is important to note that while UPE shows considerable promise as a biomarker, there are still challenges to be addressed. The primary challenge lies in the low intensity of UPE signals, which requires sophisticated detection systems to distinguish from background noise [6]. Additionally, further validation studies are needed to establish standardised protocols and confirm the reliability of UPE measurements across different experimental conditions[30]. The integration of UPE measurements with advanced sensor technologies and imaging techniques continues to evolve, promising improved sensitivity and reliability in future applications. This ongoing development suggests that UPE will become an increasingly valuable tool for assessing mitochondrial function in plant biology research.

5. Applications of UPE Measurement in Plant Research

Ultra-weak Photon Emission (UPE) measurement has emerged as a powerful tool in plant research, enabling scientists to assess plant responses to various environmental stresses, enhance breeding programs, and monitor ecosystem health. This innovative approach provides critical insights into

mitochondrial function and overall plant health, offering non-invasive and real-time data that traditional methods often lack[22].

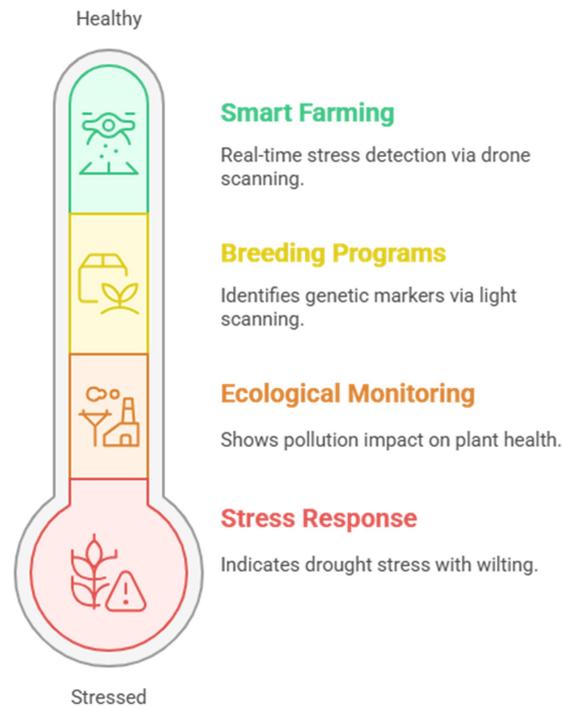


Figure 1. Monitoring plant health via ultra-weak photon emission levels.

5.1 Stress Response Studies

UPE has been particularly valuable in stress response studies, where understanding plant reactions to both biotic and abiotic stressors is crucial for improving crop resilience. Research has demonstrated that UPE levels vary significantly under different stress conditions, such as drought, salinity, and pathogen attack. For instance, UPE measurements have shown a distinct increase in photon emission during drought stress, correlating with increased reactive oxygen species (ROS) production, which acts as a signalling mechanism for stress responses [31]. Additionally, plants exposed to temperature fluctuations exhibit changes in UPE patterns, indicating their physiological adjustments to thermal stress. This capability allows researchers to monitor stress-induced changes dynamically, providing a deeper understanding of plant resilience mechanisms[32]. Moreover, UPE measurements have been instrumental in assessing cross-tolerance among various stressors. For example, studies have highlighted how exposure to one type of stress can enhance a plant's tolerance to another, with UPE serving as a



reliable indicator of these physiological changes. Such insights are essential for developing strategies to enhance plant resilience in the face of climate change and variable environmental conditions.

5.2 Breeding Programs and Genetic Studies

In the realm of plant breeding, UPE measurements offer a promising avenue for selecting resilient varieties. The integration of UPE data with modern genomic selection and marker-assisted breeding techniques allows breeders to assess physiological traits alongside genetic information. This synergy enhances the efficiency of selecting plants that can withstand environmental stresses[33]. For instance, UPE can help identify physiological markers associated with drought tolerance, guiding the selection of elite genotypes in breeding programs. Furthermore, UPE measurements have found applications in high-throughput phenotyping, where they facilitate rapid screening of large populations for desirable traits[34]. This approach has been particularly beneficial in evaluating hybrid plants for their stress responses, enabling the identification of superior hybrids that exhibit enhanced resilience. The ability to obtain real-time physiological data through UPE significantly accelerates the breeding process, providing breeders with the tools needed to develop crops that can thrive in challenging environments[35].

5.3 Ecological and Environmental Monitoring

Beyond individual plant studies, UPE measurements play a vital role in ecological and environmental monitoring. They serve as indicators of ecosystem health, reflecting the physiological status of plant communities in response to environmental changes. For example, studies have shown that UPE can be utilized to assess the impact of pollutants on plant health, offering insights into ecosystem stress levels [36]. By integrating UPE data with advanced ecological modelling techniques, researchers can gain a comprehensive understanding of how environmental factors influence plant communities and overall ecosystem dynamics. In the context of precision agriculture, UPE technology has been incorporated into smart farming practices, allowing for real-time monitoring of crop health and stress responses. This integration facilitates more informed decision-making regarding resource allocation, pest management, and irrigation practices, ultimately enhancing agricultural sustainability [37]. As UPE technology continues to evolve, its applications in ecological monitoring and smart farming are expected to expand, providing critical data for improving plant health and productivity in an ever-changing environment. The application of UPE measurements in plant research offers significant advantages across various



domains, from stress response assessment to breeding programs and ecological monitoring. By providing non-invasive, real-time insights into plant physiological states, UPE continues to emerge as a crucial tool for advancing our understanding of plant biology and enhancing agricultural practices[38].

6. Advantages and Limitations of UPE as a Biomarker for Mitochondrial Function

Ultraweak photon emission offers several compelling advantages as a biomarker for mitochondrial function in plants [9]. One of the most significant benefits is its non-invasive nature. UPE can be measured without causing any damage to the plant or requiring the introduction of external probes or labels. This allows for the continuous, real-time monitoring of physiological processes over extended periods. Furthermore, the techniques used to measure UPE are highly sensitive, capable of detecting extremely low levels of light emission. This sensitivity is crucial for capturing the faint signals emitted by biological systems. The potential for high-throughput screening is another advantage, as UPE imaging could be adapted for rapidly assessing the health or stress status of a large number of plants or samples. While the focus is on mitochondria, UPE also reflects the broader oxidative metabolic state of the cell, providing a holistic view of cellular activity[22].

Despite its advantages, there are also limitations to consider when using UPE as a biomarker for mitochondrial function[39]. The extremely low intensity of UPE necessitates the use of highly specialized and sensitive detection equipment, which can be expensive and require careful handling. Additionally, UPE is not exclusively generated by mitochondrial activity. Other cellular processes, such as chlorophyll fluorescence and delayed luminescence, as well as environmental factors, can also contribute to the overall photon emission. This means that deciphering the specific contribution of mitochondrial ROS to the total UPE signal can be complex and may require careful experimental design and controls[40]. The lack of standardised protocols for UPE measurement and data analysis across different research laboratories can also pose a challenge when comparing results from various studies. Furthermore, the emitted photons may be absorbed or scattered as they pass through plant tissues, potentially limiting the depth of information that can be obtained, especially in thicker samples[22].

Table 1. Summary of Research Studies Linking UPE to Mitochondrial Function in Plants

Plant Species	Experimental Condition	Key Findings Related to UPE and Mitochondrial Function	Reference
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Soybean cotyledons	Mechanical wounding	Observed high initial UPE intensity followed by a stable phase, potentially representing an oxidative burst and recovery. Suppression of emission under anoxic stress suggests involvement of oxygen-dependent metabolism.	[41]
Arabidopsis	Mechanical injury	Photon emission in the spectral region >650 nm, implicating chlorophyll, but also suppressed under anoxic stress, suggesting a link to oxygen-dependent processes.	[42]
Mung beans	Growth, drought, watering, growth hormones	Higher UPE in mature plants, spikes during drought and after watering, peaks during root growth, increased UPE with hydrogen peroxide and auxin, linking UPE to metabolism and stress responses controlled by mitochondria.	[43]
Plant seeds (general), cherry tomatoes	Watering with coherent water	Coherent water boosted biophoton emission, potentially reflecting enhanced mitochondrial activity. Suggests mitochondria as the primary site of biophoton production.	[44]

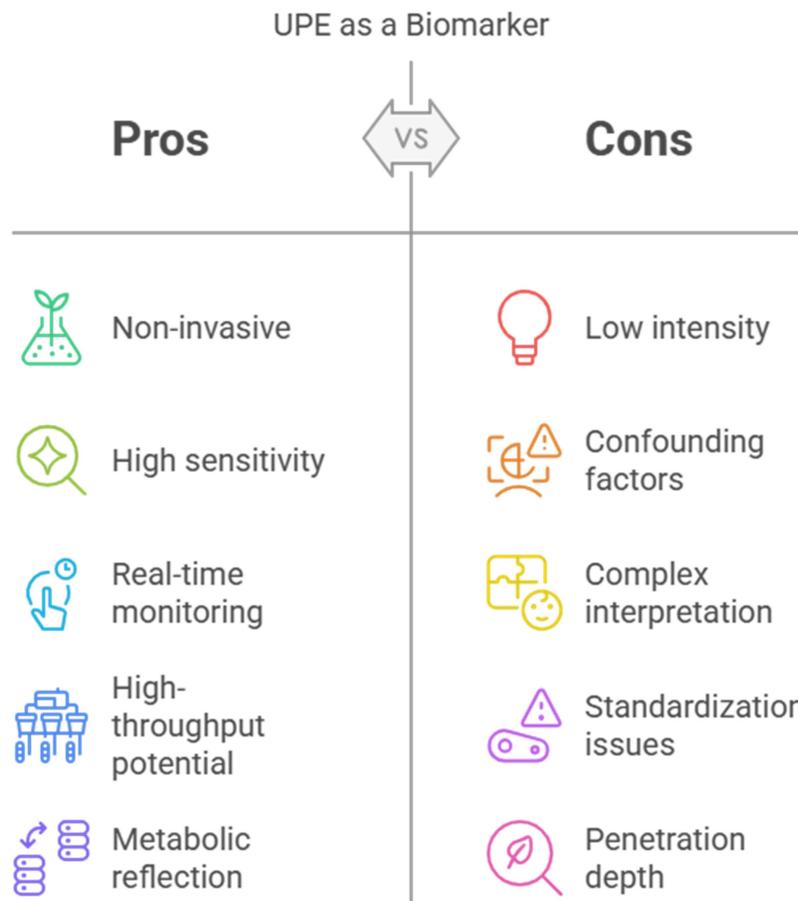


Figure 2. Pros and Cons of Using Ultra-Weak Photon Emission (UPE) as a Biomarker

7. Potential Applications of UPE in Plant Science Research

The unique characteristics of ultraweak photon emission open up a range of potential applications in various areas of plant science research[45]. In the field of stress physiology, UPE can be employed to investigate the intricate role of mitochondria in plant responses to a multitude of abiotic and biotic stresses. By monitoring UPE levels and patterns, researchers may be able to identify plant genotypes that exhibit superior stress tolerance based on their mitochondrial responses. Furthermore, UPE could be used to assess the effectiveness of different stress mitigation strategies, providing a non-destructive way to evaluate their impact at the cellular level[24].

In developmental biology, UPE offers a non-invasive window into the metabolic changes occurring during various stages of plant growth and development [Insight 25]. Studies have shown that UPE levels can fluctuate significantly during seed germination, seedling growth, flowering, and fruit ripening. For



example, peaks in UPE have been observed during periods of active root growth and in response to growth hormones. Monitoring biophoton emission from germinating seeds has also been explored as a method for assessing their overall quality. These findings suggest that UPE could provide valuable insights into the dynamic role of mitochondrial activity throughout the plant life cycle[46].

The potential for crop improvement is another exciting area of application. UPE could serve as a non-destructive tool for evaluating seed viability, vigor, and overall quality. By identifying superior plant varieties with enhanced mitochondrial function and resilience to stress, breeders could utilize UPE as a selection criterion. The suggestion that UPE and delayed fluorescence might be useful for estimating seed quality further supports this application. Monitoring biophoton emission from germinating seeds as a measure of quality has already been explored , and analyzing emission patterns to correlate with the degree of seed development shows promise[47].

Finally, UPE can be a valuable tool in toxicology for monitoring the effects of environmental toxins on mitochondrial function in plants. Changes in UPE characteristics upon exposure to various pollutants could indicate disruption of mitochondrial activity and increased oxidative stress. This non-invasive method could be used to assess the phytotoxicity of different compounds and to understand the mechanisms of their action at the cellular level.

8. Conclusion and Future Directions

In summary, the evidence presented strongly supports the justification of ultraweak photon emission as a promising biomarker for mitochondrial function in plants. The biological basis lies in the close relationship between mitochondrial respiration, the production of reactive oxygen species, and the generation of UPE. Experimental studies, including those using metabolic inhibitors, genetically modified plants, and plants subjected to various stress conditions, consistently show a correlation between altered mitochondrial activity and changes in UPE. The non-invasive nature and high sensitivity of UPE measurements offer significant advantages for studying mitochondrial function in real-time and under various physiological and environmental conditions.

Future research should focus on further elucidating the specific mitochondrial sources and mechanisms responsible for UPE generation in different plant species and under diverse conditions. The development of standardised protocols for UPE measurement and analysis is crucial to enhance the reproducibility and comparability of results across different studies. Integrating UPE measurements with other omics approaches, such as transcriptomics, proteomics, and metabolomics, could provide a more



comprehensive understanding of the intricate relationship between UPE and mitochondrial function. Further validation of UPE as a reliable biomarker by comparing it with established methods across a wider range of plant species and experimental setups is also warranted. The potential of UPE imaging for high-resolution mapping of mitochondrial activity and stress within plant tissues deserves further exploration. Investigating the spectral characteristics of UPE in greater detail may help identify specific wavelengths that are most strongly indicative of mitochondrial function. Finally, the development of portable and cost-effective UPE detection systems could pave the way for field-based applications in agriculture and environmental monitoring, unlocking the full potential of this fascinating phenomenon as a practical tool in plant science.

9. References

- [1] A. J. Roger, S. A. Muñoz-Gómez, and R. Kamikawa, “The Origin and Diversification of Mitochondria,” *Current Biology*, vol. 27, no. 21, pp. R1177–R1192, Nov. 2017, doi: 10.1016/j.cub.2017.09.015.
- [2] G. M. Cooper, “Mitochondria,” in *The Cell: A Molecular Approach. 2nd edition*, Sinauer Associates, 2000. Accessed: May 05, 2025. [Online]. Available: <https://www.ncbi.nlm.nih.gov/books/NBK9896/>
- [3] J. B. Spinelli and M. C. Haigis, “The Multifaceted Contributions of Mitochondria to Cellular Metabolism,” *Nat Cell Biol*, vol. 20, no. 7, pp. 745–754, Jul. 2018, doi: 10.1038/s41556-018-0124-1.
- [4] A. M. Vera-Vives *et al.*, “Mitochondrial respiration is essential for photosynthesis-dependent ATP supply of the plant cytosol,” *New Phytologist*, vol. 243, no. 6, pp. 2175–2186, 2024, doi: 10.1111/nph.19989.
- [5] A. Prasad, E. Mihačová, R. R. Manoharan, and P. Pospíšil, “Application of ultra-weak photon emission imaging in plant stress assessment,” *J Plant Res*, vol. 138, no. 2, pp. 389–400, Mar. 2025, doi: 10.1007/s10265-024-01600-w.
- [6] R. R. Mould *et al.*, “Ultra weak photon emission—a brief review,” *Front Physiol*, vol. 15, p. 1348915, Feb. 2024, doi: 10.3389/fphys.2024.1348915.



- [7] È. Hideg, M. Kobayashi, and H. Inaba, “Spontaneous ultraweak light emission from respiring spinach leaf mitochondria,” *Biochimica et Biophysica Acta (BBA) - Bioenergetics*, vol. 1098, no. 1, pp. 27–31, Dec. 1991, doi: 10.1016/0005-2728(91)90005-9.
- [8] S. Komatsu, A. H. M. Kamal, T. Makino, and Z. Hossain, “Ultraweak photon emission and proteomics analyses in soybean under abiotic stress,” *Biochimica et Biophysica Acta (BBA) - Proteins and Proteomics*, vol. 1844, no. 7, pp. 1208–1218, Jul. 2014, doi: 10.1016/j.bbapap.2014.04.002.
- [9] R. Van Wijk, E. P. A. Van Wijk, J. Pang, M. Yang, Y. Yan, and J. Han, “Integrating Ultra-Weak Photon Emission Analysis in Mitochondrial Research,” *Front Physiol*, vol. 11, p. 717, Jul. 2020, doi: 10.3389/fphys.2020.00717.
- [10] R.-Z. Zhao, S. Jiang, L. Zhang, and Z.-B. Yu, “Mitochondrial electron transport chain, ROS generation and uncoupling (Review),” *Int J Mol Med*, vol. 44, no. 1, pp. 3–15, Jul. 2019, doi: 10.3892/ijmm.2019.4188.
- [11] J. Qian, Z. Feng, X. Fan, A. Kuzmin, A. S. L. Gomes, and P. N. Prasad, “High contrast 3-D optical bioimaging using molecular and nanoprobe optically responsive to IR light,” *Physics Reports*, vol. 962, pp. 1–107, Jun. 2022, doi: 10.1016/j.physrep.2022.02.004.
- [12] A. S. Marquez-Acevedo, W. R. Hood, R. J. Collier, and A. L. Skibieli, “Graduate Student Literature Review: Mitochondrial response to heat stress and its implications on dairy cattle bioenergetics, metabolism, and production,” *Journal of Dairy Science*, vol. 106, no. 10, pp. 7295–7309, Oct. 2023, doi: 10.3168/jds.2023-23340.
- [13] S. Sachdev, S. A. Ansari, M. I. Ansari, M. Fujita, and M. Hasanuzzaman, “Abiotic Stress and Reactive Oxygen Species: Generation, Signaling, and Defense Mechanisms,” *Antioxidants*, vol. 10, no. 2, Art. no. 2, Feb. 2021, doi: 10.3390/antiox10020277.
- [14] O. Aina, O. O. Bakare, A. O. Fadaka, M. Keyster, and A. Klein, “Plant biomarkers as early detection tools in stress management in food crops: a review,” *Planta*, vol. 259, no. 3, p. 60, Feb. 2024, doi: 10.1007/s00425-024-04333-1.
- [15] R. K. B. M. Rathna Kumari B M, “Mechanisms and Advances in Abiotic Stress Tolerance in Crops: A Molecular and Genetic Perspective,” *Plant Science Archives*. Accessed: May 16, 2025.



- [Online]. Available: <https://plantarc.com/mechanisms-and-advances-in-abiotic-stress-tolerance-in-crops-a-molecular-and-genetic-perspective/>
- [16] A. Ahmad, M. Imran, and H. Ahsan, “Biomarkers as Biomedical Bioindicators: Approaches and Techniques for the Detection, Analysis, and Validation of Novel Biomarkers of Diseases,” *Pharmaceutics*, vol. 15, no. 6, p. 1630, May 2023, doi: 10.3390/pharmaceutics15061630.
- [17] E. S. Chang *et al.*, “Real-time assessment of relative mitochondrial ATP synthesis response against inhibiting and stimulating substrates (MitoRAISE),” *Cancer & Metabolism*, vol. 12, no. 1, p. 25, Aug. 2024, doi: 10.1186/s40170-024-00353-3.
- [18] Y. Hong, A. Boiti, D. Vallone, and N. S. Foulkes, “Reactive Oxygen Species Signaling and Oxidative Stress: Transcriptional Regulation and Evolution,” *Antioxidants*, vol. 13, no. 3, Art. no. 3, Mar. 2024, doi: 10.3390/antiox13030312.
- [19] P. M. Oak and A. S. Mali, “Advancements in Cellular Imaging: Expanding Horizons with Innovative Dyes and Techniques,” *Colorants*, vol. 3, no. 4, Art. no. 4, Dec. 2024, doi: 10.3390/colorants3040025.
- [20] P. Irigoyen, R. Sapiro, and A. Cassina, “High-Resolution Respirometry to Assess Mitochondrial Function in Human Spermatozoa,” *J Vis Exp*, no. 196, Jun. 2023, doi: 10.3791/65493.
- [21] P.-C. Liao, C. Bergamini, R. Fato, L. A. Pon, and F. Pallotti, “Isolation of mitochondria from cells and tissues,” *Methods Cell Biol*, vol. 155, pp. 3–31, 2020, doi: 10.1016/bs.mcb.2019.10.002.
- [22] A. Prasad, E. Mihačová, R. R. Manoharan, and P. Pospíšil, “Application of ultra-weak photon emission imaging in plant stress assessment,” *J Plant Res*, vol. 138, no. 2, pp. 389–400, 2025, doi: 10.1007/s10265-024-01600-w.
- [23] Y. Li *et al.*, “Assessment of mitochondrial dysfunction and implications in cardiovascular disorders,” *Life Sciences*, vol. 306, p. 120834, Oct. 2022, doi: 10.1016/j.lfs.2022.120834.
- [24] J. Selinski, S. Frings, and R. Schmidt-Schippers, “Perception and processing of stress signals by plant mitochondria,” *Plant J*, vol. 120, no. 6, pp. 2337–2355, Dec. 2024, doi: 10.1111/tpj.17133.



- [25] N. Osmolovskaya *et al.*, “Methodology of Drought Stress Research: Experimental Setup and Physiological Characterization,” *Int J Mol Sci*, vol. 19, no. 12, p. 4089, Dec. 2018, doi: 10.3390/ijms19124089.
- [26] S. B. Gray and S. M. Brady, “Plant developmental responses to climate change,” *Developmental Biology*, vol. 419, no. 1, pp. 64–77, Nov. 2016, doi: 10.1016/j.ydbio.2016.07.023.
- [27] Y. Yang *et al.*, “Methodology: non-invasive monitoring system based on standing wave ratio for detecting water content variations in plants,” *Plant Methods*, vol. 17, no. 1, p. 56, May 2021, doi: 10.1186/s13007-021-00757-y.
- [28] M. Sheikh, M. Qassem, and P. A. Kyriacou, “Wearable, Environmental, and Smartphone-Based Passive Sensing for Mental Health Monitoring,” *Front Digit Health*, vol. 3, p. 662811, Apr. 2021, doi: 10.3389/fdgth.2021.662811.
- [29] Y. Faqir, A. Qayoom, E. Erasmus, M. Schutte-Smith, and H. G. Visser, “A review on the application of advanced soil and plant sensors in the agriculture sector,” *Computers and Electronics in Agriculture*, vol. 226, p. 109385, Nov. 2024, doi: 10.1016/j.compag.2024.109385.
- [30] I. Baker, “Independent researchers determine mitochondrial test is unreliable and should not be used as test in ME/CFS | 09 August 2019,” The ME Association. Accessed: May 19, 2025. [Online]. Available: <https://meassociation.org.uk/2019/08/independent-researchers-determine-mitochondrial-test-is-unreliable-and-should-not-be-used-as-test-in-me-cfs-09-august-2019/>
- [31] O. B. Umar *et al.*, “Stresses in Plants: Biotic and Abiotic,” in *Current Trends in Wheat Research*, IntechOpen, 2021. doi: 10.5772/intechopen.100501.
- [32] T. B. dos Santos, A. F. Ribas, S. G. H. de Souza, I. G. F. Budzinski, and D. S. Domingues, “Physiological Responses to Drought, Salinity, and Heat Stress in Plants: A Review,” *Stresses*, vol. 2, no. 1, Art. no. 1, Mar. 2022, doi: 10.3390/stresses2010009.
- [33] R. Bhuvaneshwari, “Advances in Genomic Selection for Enhanced Crop Improvement: Bridging the Gap between Genomics and Plant Breeding,” *Plant Science Archives*. Accessed: May 19, 2025. [Online]. Available: <https://plantarc.com/advances-in-genomic-selection-for-enhanced-crop-improvement-bridging-the-gap-between-genomics-and-plant-breeding/>



- [34] E. L. Resende *et al.*, “High-Throughput Phenotyping: Application in Maize Breeding,” *AgriEngineering*, vol. 6, no. 2, Art. no. 2, Jun. 2024, doi: 10.3390/agriengineering6020062.
- [35] T. Begna, “Speed Breeding to Accelerate Crop Improvement,” *Advances in Crop Science and Technology*, vol. 10, no. 6, pp. 1–6, Jun. 2022, doi: 10.4172/2329-8863.1000515.
- [36] L. Dinca, V. Crisan, G. Ienasoiu, G. Murariu, and R. Drasovean, “Environmental Indicator Plants in Mountain Forests: A Review,” *Plants*, vol. 13, no. 23, Art. no. 23, Jan. 2024, doi: 10.3390/plants13233358.
- [37] A. Khang, K. C. Rath, S. Panda, P. K. Sree, and S. K. Panda, “Revolutionizing Agriculture: Exploring Advanced Technologies for Plant Protection in the Agriculture Sector,” in *Handbook of Research on AI-Equipped IoT Applications in High-Tech Agriculture*, IGI Global Scientific Publishing, 2023, pp. 1–22. doi: 10.4018/978-1-6684-9231-4.ch001.
- [38] S. Mandal, A. Yadav, F. A. Panme, K. M. Devi, and S. Kumar S.M., “Adaption of smart applications in agriculture to enhance production,” *Smart Agricultural Technology*, vol. 7, p. 100431, Mar. 2024, doi: 10.1016/j.atech.2024.100431.
- [39] E. Sharma *et al.*, “Overview of methods that determine mitochondrial function in human disease,” *Metabolism*, p. 156300, May 2025, doi: 10.1016/j.metabol.2025.156300.
- [40] R. I. Dmitriev, X. Intes, and M. M. Barroso, “Luminescence lifetime imaging of three-dimensional biological objects,” *J Cell Sci*, vol. 134, no. 9, p. jcs254763, May 2021, doi: 10.1242/jcs.254763.
- [41] M. Ghorbel, F. Brini, M. Brestic, and M. Landi, “Interplay between low light and hormone-mediated signaling pathways in shade avoidance regulation in plants,” *Plant Stress*, vol. 9, p. 100178, Sep. 2023, doi: 10.1016/j.stress.2023.100178.
- [42] A. Prasad, M. Sedlářová, A. Balukova, M. Rác, and P. Pospíšil, “Reactive Oxygen Species as a Response to Wounding: In Vivo Imaging in *Arabidopsis thaliana*,” *Front. Plant Sci.*, vol. 10, Jan. 2020, doi: 10.3389/fpls.2019.01660.



- [43] M. White, Belinda Albert, “Water potential of cherry tomato (*Lycopersicon esculentum* Mill.) placenta and seed germination in response to desiccation during fruit development | Request PDF,” *ResearchGate*, vol. 14, no. 2004, May 2004, doi: 10.1079/SSR2004174.
- [44] “Rooting out ultraweak photon emission a-mung bean sprouts,” *Journal of Photochemistry and Photobiology*, vol. 19, p. 100224, Feb. 2024, doi: 10.1016/j.jpap.2023.100224.
- [45] M. Cifra and P. Pospíšil, “Ultra-weak photon emission from biological samples: Definition, mechanisms, properties, detection and applications,” *Journal of Photochemistry and Photobiology B: Biology*, vol. 139, pp. 2–10, Oct. 2014, doi: 10.1016/j.jphotobiol.2014.02.009.
- [46] K. V. Sripathy and S. P. C. Groot, “Seed Development and Maturation,” in *Seed Science and Technology: Biology, Production, Quality*, M. Dadlani and D. K. Yadava, Eds., Singapore: Springer Nature, 2023, pp. 17–38. doi: 10.1007/978-981-19-5888-5_2.
- [47] S. Basu and S. P. C. Groot, “Seed Vigour and Invigoration,” in *Seed Science and Technology: Biology, Production, Quality*, M. Dadlani and D. K. Yadava, Eds., Singapore: Springer Nature, 2023, pp. 67–89. doi: 10.1007/978-981-19-5888-5_4.