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Heat-Induced Pollen Sterility in Fruit Crops: Physiological and Molecular Perspectives

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Temperature plays a crucial role in plant growth and development, with climate change-induced heat stress posing a significant threat to fruit crop productivity. High temperatures disrupt pollen development, causing sterility and yield losses due to physiological and molecular changes. To address this, a combination of agronomic strategies, microclimate adjustments, and heat-tolerant breeding is needed for sustainable fruit production.

Keywords: Heat stress, pollen viability, fruit set, oxidative stress, heat shock proteins, fruit crops

Introduction

Temperature is a key factor affecting plant growth, with each species having its own minimum, maximum, and optimal temperature range (Hatfield et al.). With global temperatures projected to rise by 1.8–4.0°C by 2100, plants face a significant challenge, as they can't move to escape the heat. This warming can disrupt growth and development, making it crucial to understand and address heat stress to maintain plant health and productivity. Heat stress, caused by prolonged exposure to high temperatures, hampers plant growth and development. Factors like temperature intensity, duration, and rate of increase contribute to this stress. In tropical and temperate regions, heat stress leads to reduced yields, damaged leaves and fruits, and stunted growth, ultimately affecting crop productivity. (Yatinkumar N. Tandel, Vijay R. Zala and Shivanand Koti,2025)

Pollen development in fruit crops

Pollen, the male reproductive component of flowering plants, plays a crucial role in seed formation. It develops in the anther, is released, and germinates on the stigma, leading to fertilization and fruit development. This process involves microspore development (microsporogenesis) and maturation into pollen grains containing male gametes (microgametogenesis). (Bharti Chaudhary and Anjana Rustagi,2015)

Heat stress affect late stages of pollen development

As pollen grains mature, they undergo dehydration, reducing water content to 40-58%, and enter a dormant state until they land on a suitable stigma. This dehydration occurs before or after the anther releases the pollen. (Firon et al. 2012). Mature pollen has low metabolic activity, helping it survive outside the plant. Bi-cellular pollen is more dehydrated and less active than tri-cellular pollen. When the anther dries, its wall, including the endothecium, exerts pressure, opening the stomium and releasing pollen through a combination of mechanical force and programmed cell death in the connective tissue. (Wilson et al.2011; Cecchetti et al. 2017). Temperature fluctuations impact pollen desiccation, and heat stress disrupts the endoplasmic reticulum in pollen, impairing protein processing and secretion. (Ciampolini et al. 1990). Pollen swelling is linked to successful anther dehiscence, but high temperatures impair pollen swelling, reducing anther dehiscence. (Matsui and Omasa 2002). High humidity, especially with heat stress, can also disrupt anther dehiscence and pollen release. (Porch and Jahn 2001).

Physiological Responses to Heat Stress Leading to Pollen Sterility

Heat stress disrupts pollen formation in fruit crops, especially during microsporogenesis and microgametogenesis, causing sterility. It damages the tapetum, impairing nutrient supply, and affects membrane stability, leading to pollen dehydration and reduced viability. Heat stress also hampers carbohydrate metabolism, reducing energy reserves and impairing pollen germination and growth. Heat stress triggers hormonal imbalance, altering auxin, gibberellin, and abscisic acid levels, which disrupts pollen development and anther dehiscence. It also boosts reactive oxygen species (ROS), causing oxidative damage and reducing pollen viability. Combined with tapetal damage, membrane disruption, and energy deficits, this leads to pollen sterility and poor fruit yields.

Molecular mechanism underlying heat induced pollen sterility

Heat stress causes pollen sterility by disrupting gene expression and protein stability, affecting meiosis, tapetum function, and energy metabolism. It also triggers protein misfolding, oxidative damage, and epigenetic changes, ultimately reducing pollen viability and fertility. (Zinn, K. E., Tunc-Ozdemir, M., & Harper, J. F. (2010). Temperature stress and plant sexual reproduction: uncovering the weakest links. Journal of Experimental Botany, 61(7), 1959–1968.)

Strategies to Mitigate Heat-Induced Pollen Sterility

To reduce heat-induced pollen sterility, combine agronomic practices like adjusting planting times, using shade nets, and irrigation with physiological and genetic strategies. Apply growth regulators and antioxidants to protect pollen, stabilize membranes, and reduce oxidative damage, helping maintain pollen viability under heat stress. Developing heat-tolerant crop varieties is a sustainable long-term strategy. These varieties often have enhanced heat shock proteins, antioxidants, and better nutrient supply to pollen. Breeding techniques like marker-assisted selection and genome editing (CRISPR/Cas) can introduce heat tolerance traits, reducing pollen sterility and improving fruit yields in a warming climate.

Conclusion

Rising temperatures threaten fruit crop productivity, with pollen development being highly sensitive to heat stress. Heat damage causes pollen sterility, poor fruit set, and reduced yields. To combat this, adopting heat-mitigation practices and developing heat-tolerant varieties through breeding and biotechnology is crucial for sustainable fruit production.

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