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Role of Heat Shock Proteins in Insect Stress Tolerance and Survival

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Heat shock proteins (HSPs) are a highly conserved group of proteins that play a vital role in cellular adaptation to environmental stress, particularly elevated temperatures. They function as molecular chaperones by ensuring proper protein folding, preventing the aggregation of damaged or misfolded proteins, and aiding in the repair or stabilization of proteins affected by stress conditions. HSPs were first identified in *Drosophila melanogaster* through the observation of heat-induced chromosomal puffing (Ritossa, 1962, 1966). Based on their molecular weight and functions, HSPs are classified into six major families: HSP100, HSP90, HSP70, HSP60, HSP40, and small heat shock proteins (sHSPs) (Tutar *et al*., 2010; Hu *et al*., 2022). The expression of HSP genes is primarily regulated by heat shock factors (HSFs), which bind to specific DNA sequences known as heat shock elements (HSEs) located in the promoter regions of HSP genes. Upon exposure to stress, especially high temperatures, HSFs act as transcriptional activators, leading to enhanced HSP expression (Alagar *et al*., 2022). However, HSFs are not the sole regulators of HSP expression; other transcription factors also contribute in a context-dependent manner. In addition, feedback mechanisms and regulatory crosstalk integrate HSP expression into broader cellular stress response networks

Importance of Heat shock proteins in insects

Heat shock proteins (HSPs) play an important role in insect immune responses, functioning within key signaling networks. Insects mainly rely on three immune pathways *viz*., IMD, Toll, and Jak/STAT—for pathogen recognition and defense. The IMD pathway responds to Gram-negative bacteria by activating IMD, FADD, and Dredd, which induce antimicrobial peptides such as defensins and cecropins. The Toll pathway primarily targets Gram-positive bacteria and fungi, triggering a signaling cascade through Toll–Spätzle and downstream adaptors that leads to AMP production via Dorsal and Dif. The Jak/STAT pathway supports broad innate immunity, contributing to defense against diverse pathogens and to tissue repair by activating STAT-regulated immune and stress-response genes (Figure.1). Recent studies indicate that HSPs may interact closely with immune signaling pathways. Proteins such as HSP70 and HSP90 can influence immune responses by stabilizing critical signaling molecules, promoting transcription factor activation, and aiding the efficient turnover of immune components. These findings suggest that HSPs support both stress tolerance and immune robustness, highlighting their dual protective function against environmental and biological stresses.

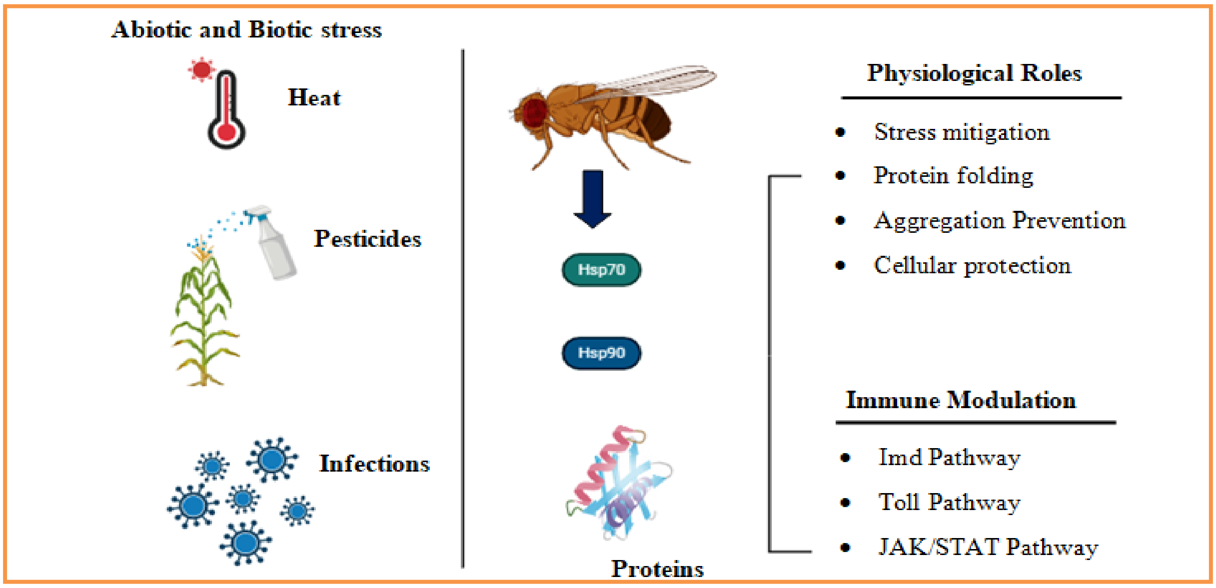

Figure 1: Roles of Heat Shock proteins in Insects

Stress Caused by Extreme Temperatures and the Role of Heat Shock Proteins

Insects are frequently exposed to extreme temperatures that disrupt protein stability, increase oxidative stress, and impair cellular homeostasis. Climate change intensifies these challenges, reducing insect survival, reproduction, and ecological functioning. Heat shock proteins (HSPs) are therefore essential, enabling rapid cellular protection under thermal stress. For example, in locust bean moth, *Ectomyelois ceratoniae*, both heat and cold stress induce HSP expression, with HSP70 mainly associated with cold stress and HSP90 with heat stress (Farhani *et al*., 2020).In bumblebee *Bombus terrestris*, extreme thermal stress (9 °C and 38 °C) cause a threefold increase in HSC (HSP70 family) and its co-chaperone Aha. Notably, this increased expression does not impair immune performance, indicating that HSP levels can be finely regulated to meet both thermal stress and immune requirements simultaneously. (Blasco *et al*., 2021). *Spodoptera litura* induces SlHSP20.4 under both heat (42 °C) and cold (5 °C) stress, while *Rhodnius prolixus* shows elevated HSP70 levels under both extremes, supporting digestion and molting (Shen *et al*., 2011). In contrast, the brown planthopper *Nilaparvata lugens* shows a biphasic thermal response: HSP70 expression remains stable at 28–40 °C, declines sharply at 5 °C, and recovers at 25 °C, indicating a sophisticated adaptive mechanism possibly involving post-translational control and interactions with co-chaperones such as HSP40 (Lu *et al*., 2017). In this regard, HSPs in particularly HSP-70 plays a crucial role in enabling insects to adapt to temperature fluctuations by offering cellular and protein-level protection against damage caused by heat stress (Jin *et al*., 2020).

Dehydration stress and role of heat shock proteins

Climate change is increasing the frequency and severity of droughts globally, as rising temperatures and changing rainfall patterns lead to reduced water availability. Heat shock proteins (HSPs) are essential molecular mediators of insect responses to dehydration and anhydrobiosis. In the Antarctic midge *Belgica antarctica*, sHSPs, HSP70, and HSP90 are rapidly induced under both dehydration and overhydration, contributing to the maintenance of cellular homeostasis (Lopez *et al*., 2009). Similarly, the sleeping chironomid *Polypedilum vanderplanki* survives extreme desiccation through anhydrobiosis, during which multiple HSPs including Pv-HSP90, Pv-HSP70, Pv-HSC70, Pv-HSP60, Pv-HSP20, Pv-p23, and the transcription factor Pv-HSF1 are strongly expressed, underscoring their protective roles in preserving cellular integrity and metabolic function.

Biotic Stresses and the role Heat Shock Proteins

Heat shock proteins (HSPs) are vital for insect survival, as they not only maintain proteostasis but also coordinate immune responses against pathogens (Pockley, 2003). In the

Chinese oak silkworm *Antheraea pernyi*, sHSP21 expression varies with pathogen type: it peaks early (3-12 h) after LPS, PGN, or glucan challenge, and later (36 h) with nucleopolyhedrovirus (NPV) (Liu *et al.*, 2018). The isoform ApsHSP21.4 further modulates immune gene expression via eicosanoid signaling during NPV infection (Zhang *et al.*, 2015). Similarly, in the red flour beetle *Tribolium castaneum*, LPS exposure upregulates HSPs alongside immune effectors like defensins and thaumatins, enhancing antimicrobial defense (Altincicek *et al.*, 2008). These findings highlight the importance of heat shock proteins as multifunctional molecular chaperones that coordinate innate immune responses with cellular repair, enabling insects to thrive in pathogen-rich environments. HSP-70 also helps stabilize cell membranes and maintain protein integrity, thereby sustaining essential cellular functions during stress. In addition to heat stress, it is induced by oxidative stress, heavy metals, and infections, highlighting its critical role in cellular defense mechanisms in insects (Zhang *et al.*, 2015).

Table . 1 Heat Shock Proteins: Stressors and Functional Roles

Stressors	HSP	Functions
Heat and cold	HSP 60/70/HSP90/ HSPs	• Enhances survival under thermal stress, infections, and insecticide challenges
Dehydration		
Rehydration	HSP 60/70/HSP90	• Facilitates protein folding of misfolded proteins during stress, preventing aggregation.
	HSPs	• Stabilizes proteins under stress conditions
Insecticides	HSP 60/70/HSP90	• Facilitates protein folding of misfolded proteins during stress, preventing aggregation
Toxins	HSP90	• Prevents aggregation of denatured proteins
	HSP 60/70	Stabilizes proteins under stress conditions
Microorganisms	HSP90	• Stabilizes proteins under stress conditions
	HSPs	• Protects against Oxidative stress
	HSP 60/70	• Prevents aggregation of denatured proteins
Parasites	HSP90	• Supports proteostasis under water stress
	HSP 60/70	• Improves thermotolerance and aids recovery after stresses • Supports water-loss tolerance, aiding survival after dehydration and anhydrobiosis • Promotes stress-signal transduction • Exhibits anti-apoptosis effects
Viruses	HSPs	• Promotes innate immune signalling and modulates immune related genes • Stabilizes the Cytoskeleton
Starvation	HSP90	• Stabilizes signaling kinases and stress-signal transduction pathways under stress • Modulates host-pathogen interactions

*HSPs - Small Heat shock proteins

Conclusion

In the era of global climate change, heat shock proteins (HSPs) play increasingly important roles, providing key insights into adaptive mechanisms that enhance biological resilience. HSPs maintain cellular stability by facilitating protein folding and repair, and they also regulate immune functions via pathways like Toll/NF-κB signaling and integrin-mediated phagocytosis. Their expression varies across developmental stages, tissues, and environments, reflecting a finely tuned system adapted to withstand temperature extremes, chemical stress, and pathogens. In addition to preserving cellular homeostasis, HSPs act as indicators of environmental change, serving as useful biomarkers for ecosystem health. They also offer potential in pest management, such as through RNA interference, providing sustainable strategies with minimal ecological impact. Ongoing research on HSP networks, including co-chaperone interactions a cross-tolerance mechanisms, is essential for forecasting insect responses to changing climates and for creating strategies that enhance agricultural productivity while conserving biodiversity

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