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Adaptation of Living Organisms to Environmental Change Physiologically: Mechanisms of Integration, Molecular Processes, and Ecology

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Abstract

The environmental changes (slow or rapid) put some selective pressure in living organisms and require the establishment of dynamic physiological changes that will establish homeostasis and survival. Physiological adaptation is a multi-level process that incorporates molecular signaling systems, cellular responses, system, and organism plasticity. This is a review that summarizes existing information on physiological mechanisms of adaptation to stressors across taxa, and includes molecular mechanisms including stress protein induction, hormonal regulation, epigenetic regulation, and metabolic reprogramming. We also analyze adaptation to temperature changes, hypoxia, salinity stress, drought and anthropogenic disturbances. A combination of ecological, molecular, and evolutionary views, this article highlights the significance of the physiological plasticity in determining species resilience in the face of an escalating global environmental change.

Keywords: Physiological adaptation; Environmental stress; Homeostasis; Phenotypic plasticity; Stress response; Climate change

1. Introduction

Living organisms are in dynamic and usually unpredictable environments that are typified by constant changes in temperature, oxygen content, water cycle, salinity, pH, radiation, and nutrient levels. These environmental factors may change daily, seasonally or geologically with complex physiological demands on cells and tissues. The very survival in such circumstances includes the capability of organisms to maintain internal stability an organizing principle initially formulated by Claude Bernard in his concept of the milieu intérieur, and subsequently formalised as homeostasis by Walter Cannon. These theoretical frameworks formed the conceptual foundation of the study of how the biological systems are at functional equilibrium in the face of external perturbations[1].

Physiological adaptation is not simply a question of mere stability but is an active process of maintaining in a dynamical way in that organisms can modify their internal conditions depending on environmental change. Instead of being constrained by strict constancy, the living systems are constrained by flexible set-points, feedback and anticipatory regulatory systems and are optimally able to operate under prevailing conditions of change. This adaptive ability is facilitated by orchestrated cellular communications between molecular signaling pathways, metabolic networks, endocrine systems and neural circuits, to create a hierarchy of responses that work at both cellular and organismal levels[2].

The environmental stressors may be classified as either abiotic and biotic. Abiotic stressors involve extreme temperatures, hypoxia, osmotic effects, drought, and chemical substances whereas biotic stressors involve pathogens, predators, competitors and symbiotic relationships[3]. The responses of each type are different but usually

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superimposing. As an example, thermal stress can initiate the induction of heat shock proteins, membrane remodelling, and metabolic reprogramming and hypoxic stress stimulates the regulation of oxygen by pathways and facilitates changes in respiratory and circulatory performance[4].

The difference between physiological responses and acclimation and adaptation further broadens our knowledge regarding physiological responses. Acclimation Acclimation is a short-term reversible process that takes place within the lifetime of an organism that is usually mediated by a change in gene expression or enzyme activity. Conversely, evolutionary adaptation is a heritable changes that are subject to natural selection over generations causing population-wide variation in physiological properties. Phenotypic Plasticity mediates such two dimensions and allows organisms to adopt different phenotypes under different environmental conditions. Plastic responses can promote survival in the immediate and in other instances, determine the course of evolutionary routes like genetic accommodation[5].

Over the last few decades, it has been found that physiological adaptation is supported by very conserved genetic and biochemical pathways due to recent breakthroughs in molecular biology and systems physiology. Organisms can quickly adjust cellular activity by having stress-responsive transcription factors, epigenetic changes and post-translational protein regulation. Furthermore, new data indicate that exposures to the environment can cause long-term changes in the epigenome, which are transmitted throughout generations and that begs the question of whether transgenerational plasticity may contribute to adaptive potential[6].

The increasing rate of the worldwide environmental change has increased the importance of physiological adaptation studies. The ecosystems are changing at alarming rates due to the anthropogenic climate change, habitat fragmentation, pollution and resource depletion. Increasing temperatures in the world, ever-growing occurrence of extreme weather conditions, acidification of oceans, and depleting oxygen levels in the water systems all pose a threat to the adaptive capacity of most species. Knowledge of physiological thresholds, resilience ability and plastic response of organisms is thus important in anticipating trends in species persistence, distribution changes and extinction risk[7].

Physiological characteristics determine the ecological makeup of species and determine their ability to utilize resources, evade stress and rivalry in groups in an ecological context. The level of thermal tolerance, water-use efficiency, metabolic flexibility and the regulation of stress hormones are all factors that determine the interaction of organisms with their surroundings. In turn, physiological adaptation is not only a mechanistic process but also a determinant of the structure of ecosystems, biodiversity preservation, and evolution processes[8].

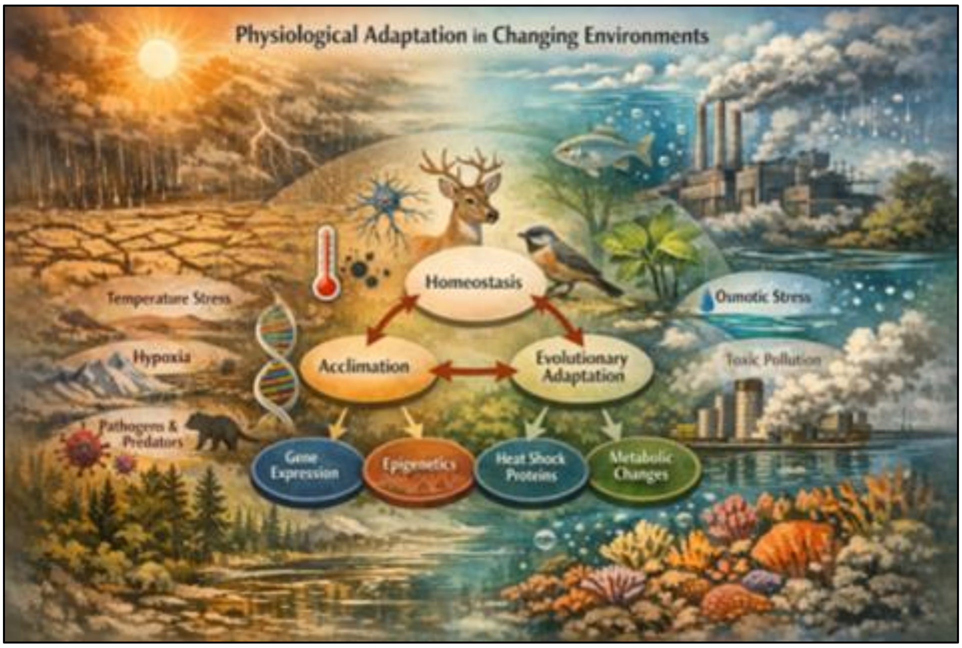

Figure 1 Conceptual framework of physiological adaptation to environmental stressors

2. Conceptual Framework of Physiological Adaptation

2.1. Homeostasis and Allostasis

Homeostasis is defined as the dynamic regulation of physiological stability inside the body despite the constant changes in the environment. This theory focuses on the controlled factors that include body temperature, osmotic pressure, blood glucose and the acidbase balance. Organisms respond to deviations of optimal internal states by a complex set of coordinated feedback processes involving the systems of the neural, endocrine and cellular systems. Nonetheless, homeostasis is not the strict constancy but a flexible balance acting in biological acceptable ranges. Allostasis expands this model by noting physiological set point adjustments which are specifically performed by organisms in anticipation of predictable stresses and thus, can be enhanced by adaptive efficiency in the face of recurrent environmental demands[9].

2.2. Acclimation vs. Adaptation

The acclimation refers to short-term, reversible physiological changes that take place during the lifetime of a given organism due to change in the environment. Such changes can include changed enzyme activity, gene patterns of expression, metabolic rate, or hormonal secretion that has allowed quick functional compensation. Conversely, adaptation is a concept that is used to describe hereditary characteristics that evolve as a result of natural selection over a series of generations resulting in population-wide changes in physiological capacity. Whereas acclimation increases survival in the short term, adaptation demonstrates long-term biological adaptation of biological systems [10].

2.3. Phenotypic Plasticity

Phenotypic plasticity is a characteristic of an organism to produce phenotypes that vary with environmental influences despite having a specific genotype. With this kind of flexibility, it allows the organisms to change their morphology, physiology, growth or behavior without necessarily modifying their genes. The regulatory networks mediate the plastic response by integrating environmental signals with the gene expression and metabolic pathways. This plasticity is capable of buffering populations against environmental change in a short period of time, and this may contribute to the evolutionary change to provide genes to accommodate. In such a manner, the phenotypic plasticity plays an essential role as a boundary between the physiological adaptation in the short run and evolutionary adaptation[11].

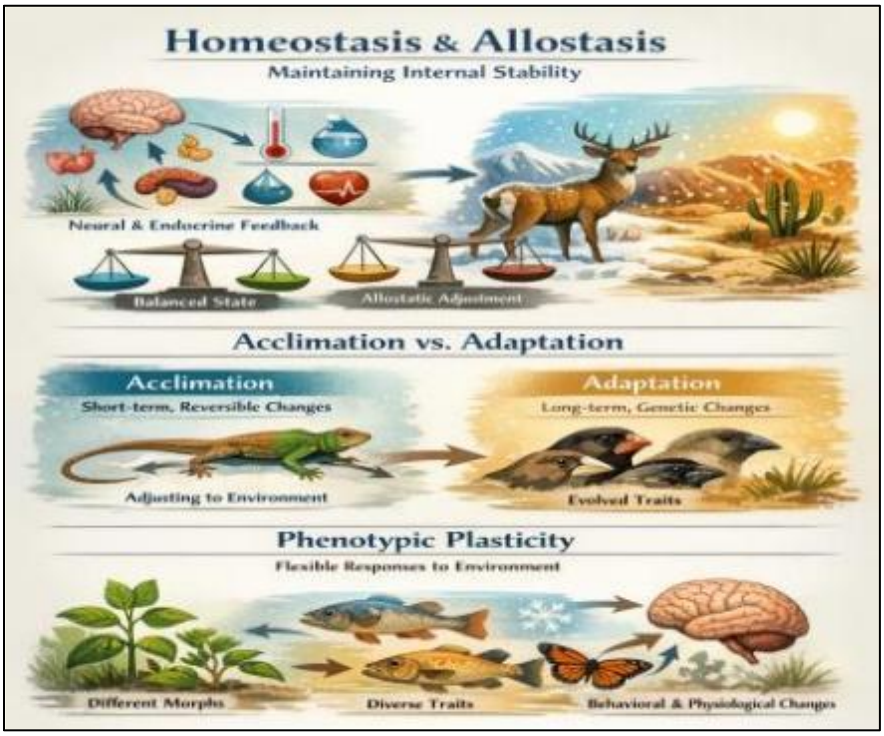

Figure 2 Mechanisms of Physiological Regulation and Environmental Adaptation

3. Molecular and Cellular Mechanisms

3.1. Heat Shock Response and Stress Proteins

Heat shock proteins (HSPs) are highly conserved molecular chaperones that help in proper protein folding and also prevent aggregation of proteins when the cell experiences stress. Their expression is activated fast due to high temperatures, oxidative stress, toxins, or other environmental issues. HSPs are important in the stabilization of essential enzymes, the repair of damaged proteins, and proteome integrity. This system is seen in all areas of life such as bacteria, plants and animals demonstrating the evolutionary significance. In addition to protection of stresses in a short term, HSPs are also involved in the regulation of apoptosis and immune responses through signaling pathways [12].

3.2. Oxidative Stress and Antioxidant Systems

Enzymatic antioxidants used by organisms include superoxide dismutase, catalase and glutathione peroxidase in oxidizing ROS and reducing cellular damage. Other antioxidants that are not enzymatic such as glutathione, vitamin C, and vitamin E are also essential as they can scavenge the free radicals. Redox homeostasis is dependent on the balance between ROS generation and antioxidant defense. The system may lead to a non-regulated state that causes oxidative stress, which is an indicator of aging, disease, and stress tolerance. To maintain cellular functions, organisms have the ability to adaptively regulate the antioxidant expression in reaction to varying environmental factors[13].

3.3. Hormonal Regulation

In vertebrates, the hypothalamic-pituitary-adrenal (HPA) axis coordinates the responses to the stress by releasing glucocorticoids, which influence metabolism, immune system and the distribution of energy. The hormones that control drought, salinity, and attack by pathogens in plants include abscisic acid (ABA), ethylene, and jasmonic acid. The environmental cues and cellular processes are combined in hormonal signaling to initiate transcriptional and metabolic changes. Feedback mechanisms make the responses of hormones in proper scale and reversible. Co-ordinated hormonal control helps organisms to achieve homeostasis as they adapt to various stressors[14].

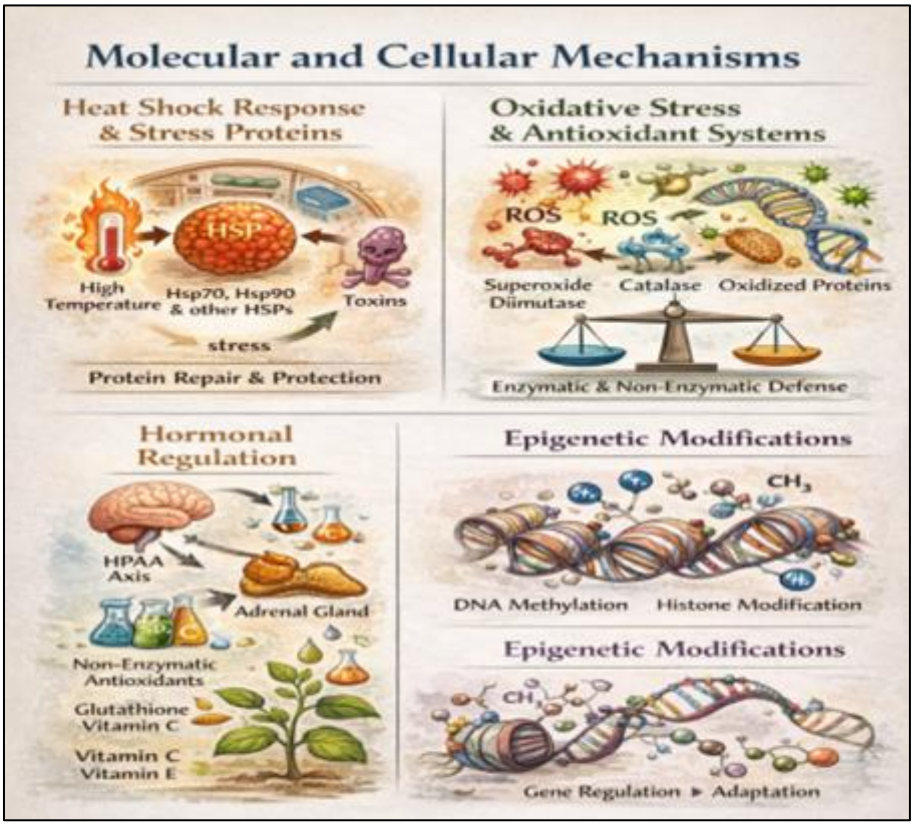

Figure 3 Molecular and Cellular Mechanisms of Environmental Stress Response

3.4. Epigenetic Modifications

The epigenetic mechanisms offer a quick and adaptable way of controlling the level of gene expression when reacting to environmental cues, which does not involve modifications on the underlying DNA sequence. Specific genes to be activated or silenced by DNA methylation, histone modifications, and non-coding RNAs, are related to stress tolerance. These changes can enable the cells to respond to the variability by changing protein production, metabolic processes, and developmental programs. Other changes in the epigenetic code may be fixed through cell division and even passed on to the next generation, which means that it provides a method of transgenerational adaptation. Epigenetic regulation is of significant importance in both the short-term acclimation and long-term evolutionary mechanisms by allowing the occurrence of phenotypic plasticity at the molecular level[15].

4. Physiological Adaptation to Major Environmental Stressors

4.1. Temperature Extremes

One of the most widespread environmental stressors in the physiology of organisms is temperature oscillations. Animals that are ecothetically active adapt the lipid makeup of their cellular membranes in order to preserve the membrane fluidity, which is called homeoviscous adaptation. This guarantees functions of membrane and actions of enzymes across different thermal settings. In contrast, endotherms maintain internal temperature by adjusting the rate of metabolism, blood flow, and behavioral patterns (e.g. seeking shade or huddling). Evolutionary adaptations to cold and hypoxia in high altitudes in humans and animals can be observed in terms of their combined adaptation, which is observed in people inhabiting Andes and Tibetan Plateau. These adaptations involve an improved oxygen uptake, a greater capillary density and a shift in metabolic enzyme activity. All three of these, together, indicate that cellular, systemic, and behavioral processes are all integrated to uphold homeostasis in the face of thermal stress. [16].

4.2. Hypoxia

The lack of oxygen poses a significant physiological issue especially in the high altitudes or in the water bodies. Hypoxia adaptation is associated with the up-regulation of hypoxia-inducible factors (HIFs) that control the expression of oxygen-carrying and angiogenic and energy-producing genes. Red blood cell count is increased with a related increase in oxygen carrying capacity due to disease increased erythropoiesis. Moreover, cardiovascular and respiratory adaptations, including increased ventilation of the lungs and cardiac output, aids in the oxygenation of the tissues. Changes at the cellular level involve mitochondrial remodeling and adaptation of the cell towards more efficient energy pathways. Hypoxia adaptation is a multi-level phenomenon that is an example of the interplay of molecular, organ level, and whole-organism responses to a severe environmental challenge[17].

4.3. Water Availability and Drought

Lack of water puts tremendous limits to survival especially in arid and semi arid ecosystems. The desert mammals have developed very effective kidney concentration mechanisms that minimize the loss of water by the urine and the necessary solutes are conserved. Xerophytic plants would have structural and physiological responses such as lower surface area of the leaf, cuticles being thick and the regulation of stomata to slow down the amount of transpiration. Osmoprotectants and compatible solutes build up to an additional degree of protecting cells against dehydration [18].

4.4. Salinity Stress

Unstable levels of salinity, especially in the marine, estuarine as well as the coastal environments, presuppose the osmotic equilibrium of the living organisms. Special ion transporters, including Na +K +ATPases, and osmoregulatory gills, kidneys, or salt glands help marine and estuarine organisms to maintain their internal ionic concentration. Osmotic stress is alleviated by cellular accumulation of compatible solutes, and by structural adaptation of membranes and transport proteins alleviates resilience. Adaptation to salinity usually necessitates the existence of coherent responses in multiple organ systems to assure the balance of water, ion homeostasis and metabolic activity. This shows that the coping with osmotic challenges requires the involvement of integrative regulation involving the physiological mechanism[19].

4.5. Anthropogenic Environmental Change

The new and rapid selective forces on organisms are present in the anthropogenic environmental changes of pollution, habitat fragmentation, urbanization, and climate change. As a solution to these challenges, most species evolve increased behavioral and physiological plasticity (e.g. a shift in stress hormone regulation, changes in metabolism or changes in foraging behavior). Urban adaptation, e.g. among birds, insects and small mammals has been observed to allow the ability of organisms to rapidly adapt to new environmental conditions. These evolutionary changes hold significance in the study of the adaptation of species to these challenges and how the biodiversity in a world that is increasingly dominated by human beings can be controlled[20].

5. Integrative Systems Physiology

The occurrence of physiological adaptation occurs in numerous levels of hierarchy beginning with the molecular processes up to the whole body behavior. The adaptation mechanisms based on the change of gene expression, synthesis of proteins as well as post-translational changes are the mechanisms of adaptive changes at the molecular level. Cellular adaptation involves organelle optimization, metabolic re-arrangement and signaling of stress. On the organ level, structural remodeling and functional remodeling will ensure system-wide functionality e.g. better lung volume or kidney efficiency. Whole- organism level supplementation Differences in behavior and life-history adaptations support physiological processes to promote survival and reproductive success. The existing systems biology practices are giving a combination of transcriptomics, proteomics and metabolomics in a holistic approach that gives a full picture of how the organism behave in response to the environmental forces[21].

6. Ecological and Evolutionary Implications

Physiological flexibility has great importance in the distribution of species, the breadth of ecological niche, and extinction susceptibility. The organisms which have low thermal or osmotic tolerance are very susceptible to sudden changes in the environment, e.g. global warming or degradation of habitats. On the other hand, those species with a high adaptive capacity are able to live in larger ecological niches and to adapt to environmental changes in a more adaptive way. At the eco system level, adaptive physiology is known to influence trophic relationships, competition, and community structure which eventually influences stability of the ecosystem. Evolutionarily, physiological plasticity may be used to direct natural selection such that a population may endure in a changing environment and to form a substrate of long-term evolutionary change[22].

7. Methodological Approaches in Studying Physiological Adaptation

To understand physiological adaptation, one needs to adopt a mixture of controlled laboratory experiments, field observations, as well as molecular studies to elicit response at various levels of biological organization. The experiments carried out in controlled environmental chambers enable the strict control of temperature, humidity, oxygen and other factors to determine the responses of organisms to the definite stresses[23]. Field-based ecological monitoring supplements lab research by giving the data on organismal reaction to natural and shifting environments in a realistic adjustment of behavior and physiology. There is stable isotope analysis, which gives evidence of how energy is metabolized, how it changes in response to diet and how it is used in times of environmental stress. [24]. Comparative phylogenetic analyses enable researchers to determine common adaptive characteristics as well as evolutionary patterns in taxa. Experimental validation of individual genes as part of adaptation, straddling mechanistic knowledge and evolutionary background, is now easily done using emerging tools, such as CRISPR-based functional genomics[25].

8. Future Perspectives

The research on physiological adaptation in the future will have to be directed at the combination of the molecular, ecological and evolutionary approaches to the problems of the rapidly changing environmental conditions[26]. The connection of epigenetic plasticity to transgenerational inheritance is one of the priorities, and the impact of environmentally induced changes on offspring resilience is to be examined. In conservation planning and management, the predictive modeling of species resilience under climatic change conditions can be used. Combining physiological knowledge with conservation biology will enable the selection of species that are most endangered and the establishment of techniques to increase adaptation capabilities. Lastly, one has to be aware of the adaptive capacity limits in organisms, where organisms reach a point of failure in the physiological mechanisms. Incorporating these lines of research will enhance our capacity to forecast, control, and reduce the effects of environmental change on the globe and its biodiversity and ecosystem regulation[27].

9. Conclusion

Physiological adaptation is a multi-scale process that is dynamic and that determines the ability of organisms to survive in changing environments. Living organisms have homeostasis and increase the ecological tolerance thresholds through their coordinated molecular, cellular and systemic responses. Due to the rapid increase in global environmental change, the further development of our knowledge on adaptive physiology will be essential to the preservation of biodiversity and the management of ecosystems.

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