

FACTORS REGULATING REPRODUCTIVE OUTPUT IN INSECTS: PHYSIOLOGY, ENVIRONMENT, AND EVOLUTIONARY CONSTRAINTS

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Abstract

Arthropods are strong and fast flexible creature possessing great breeding proportion and concise lifespan sequence. Because of anthropogenic disturbance in farming system and universal atmospheric fluctuations, the habitat of arthropods is disrupted. Breeding is a basic process in all living organisms, containing invertebrates, in which descendants is reproduced from the parents. The young ones merged hereditary information from both parents individually and it is hereditarily special. Arthropods can be breed by two types of reproduction via, sexually or asexually, assuring rapid growth of population. Reproductive fusion including the utilizing of sex cells from each sex of arthropods, on the other hand non-sexual reproduction allows single organisms causes the biologically same offsprings. Reproductive ecology manage with the research that in what way biological features ;behavioral pattern, and ecological factors affect the insects propagation. The complications of insects breeding are highlighted by a key process called as vitellogenesis that is important for oogenesis and inherited immunity.

Introduction

Reproduction is a basic trait of all identified living beings, including the quality of sequence of concept that progeny is reproduced from their parental origin (Tariq, M. et al, (2024). Usually, there is two kinds of breeding biparental and uniparental breeding. In sexual reproduction, pair of gametes, both sexes of organisms known as gametes, that comprises on a 50% of chromosomal complements of somatic cells, and produced by meiosis, and the sperm cells merge with the egg cell of the same species to reproduce a fertilized egg. This produce a progeny from which hereditary composition is influenced by both sexes. In uniparental reproduction, living beings can be breed in the absence of contribution

of another individual involvement, that is produced a closely related genetically or alike (Hunter WB et al, 2018)

In earlier research, it is observed that arthropods utilize both types of reproduction methods, thus guaranteeing their quick rise in numbers. Ecology of reproduction handle with living beings' functional biology, activities, living and nonliving environment where it exists to identify that how reproduction occurs (LaFlamme BA et al, 2011). The female reproductive functions, physiological traits, and egg characteristics determine the percentage number of offspring a species can produce. Multiple associated components trigger limitation on the reproductive success that can be classified as barriers arise from females'

physiological condition. The nonliving environmental factors faced by the female ova, and presence of predator species (Deviene P et al, 2013).

Worldwide changes is contributing for an extensive variety of manmade and natural changes in environment. These climatic and weather fluctuations do not only impact on the condition of insect's population but also have an impact on their population growth pattern, occurrence, density, strength and their feeding pattern (Hunter WB et al, 2018). Level of change in atmospheric ecological system observed by meteorology has been indicated primary and secondary effect on the predator prey and host interaction, their defense system responses and growth rate, their fertility and multiple body functions (Sagheer, M. et al (2014)). Experiments carried out throughout 2008-2012 on different elements such as manmade living and nonliving were considered to cause the occurrence of longhorned beetle. Nonliving environmental disturbances especially higher and lower temperature influence confirm the insect reproduction, dormancy, appearance, locomotion and rate of dispersal. Apart from high temperature limit that is causing such scenarios on the other hand low temperature serve a significant role in fundamental features of insect species. (Bentz B et al, 2012).

For example, arthropods experiencing to cold stress will exhibit dark pigmentation in comparison with those inhabiting in warm regions. Moreover, to nonliving environmental factors, biological changes are similarly causing the functional behavioral pattern and anatomical modifications in the arthropods with its population variations (Mishra, M, et al, 2015). Within biological challenges of an environmental system, land-based flower performed a key role in development of multiple stages of non-aquatic arthropods such as, in their egg laying behavior and egg survival rate. Upon plant various arthropods consume pollen vector and other phytophagous. Plants exhibit different reactions toward various arthropods pest species. Specific herbivore stimulated flora unstable role of

carnivorous arthropods to invasion herbivorous species. In this research a powerful impact of floral species and their important influence caused by HIPVs emission opposite to the pollinator activity (Nealis V et al, 2012).

Reproductive potential in Insects

The theory of breeding capacity among arthropods refers to the highest capability of an insect types to reproduce within optimal conditions in which necessities like nutrition, habitat and favorable climate conditions is rich and restricting to the factors that is unavailable. (Juroszek, P., et al, 2013). It indicates the physiological capability of invertebrates to multiply quickly because of the properties including maximum breeding potential, brief life cycle, precocious maturity, and, in numerous species, the ability of several breeding cycles throughout annual season. Various insects oviposit scores or thousands of embryos throughout the life, that is significantly rises their ability to increase population. (Lomate, P. R et al, 2015) Reproductive ability is also influenced by, biological performances, courtship behavior and survival strategies like asexual reproduction or hibernation that increases chances of survival and successive generations. This theory is especially crucial in study of insects as it describe that in what way specific arthropods species reproduce rapidly and turn into cultivation related disease causing insects within a brief time. Moreover, in native ecosystem, the real population number hardly reach its maximum breeding capacity due to ecological limited elements including hunting, parasitic interaction, pathogens, interspecific competition, environmental changes, and it restricted the work supplies to stabilize and regulate the increases in population. Reproductive ability knowledge assist scientist to estimate population fluctuations, regulated pest species, and preserved beneficial species throughout the entire environmental networks. (Kiritani K et al. 2013)

Environmental factors Affecting reproduction

Ecological rudiments significantly impact the reproductive capacity of insects. The reduplication

of insects is significantly affected by external factors since they're ectothermic brutes, and their physiological functions largely calculate on environmental conditions. These environmental cues help insects in relating the optimal time for reduplication, oviposition, and the growth of their youthful (Andrewartha et al.1954).Indicated that environmental factors constantly regulate population growth by affecting the timing of reduplication and rates of survival. With changing environmental conditions, insects modify their reproductive actions to enhance the survival odds of their seed.

Among environmental factors, temperature is viewed as one of the most significant influences on nonentity reduplication. Temperature (Fig. 01) affects metabolic processes, enzyme functionality, and the speed of reproductive organ development (Chapman et al. 2013).Noted that moderate temperatures lead to quicker gonad development and enhanced fecundity in multitudinous nonentity species. In advanced temperatures, insects generally parade lesser lovemaking geste and quicker egg product. Very high temperature can stress insects and reduce their ability to reproduce on the other hand very slow temperature can slow down their metabolism and delay reproduction which can affect their overall reproductive success.

Humidity is a fresh environmental element that directly influences nonentity reduplication and survival. Sufficient moisture in the surroundings assists insects in regulating their internal water situations throughout reduplication. Multitudinous nonentity eggs are veritably responsive to humidity situations, and acceptable moisture is essential for their successful growth and emergence (Leather et al.1993).Noted that low moisture can lead to egg desiccation, which in turn decreases hatchability and overall reproductive success. Again, settings with ideal moisture situations enhance the survival of eggs and naiads, therefore leading to increased reproductive success.

Photoperiod, denoting the length of light and dark in a 24 hour period, significantly influences the regulation of reproductive cycles. Multitudinous insects depend on variations in day length as environmental signals to start or halt reproductive actions. Tauber et al.1986 proposed that extended daylight ages generally encourage reproductive conditioning, similar as lovemaking and egg laying. These changes in day length help insects match their reproduction with favourable conditions when daylight become shorter some species may go diapause a period when reproduction temporarily stops until conditions improve.

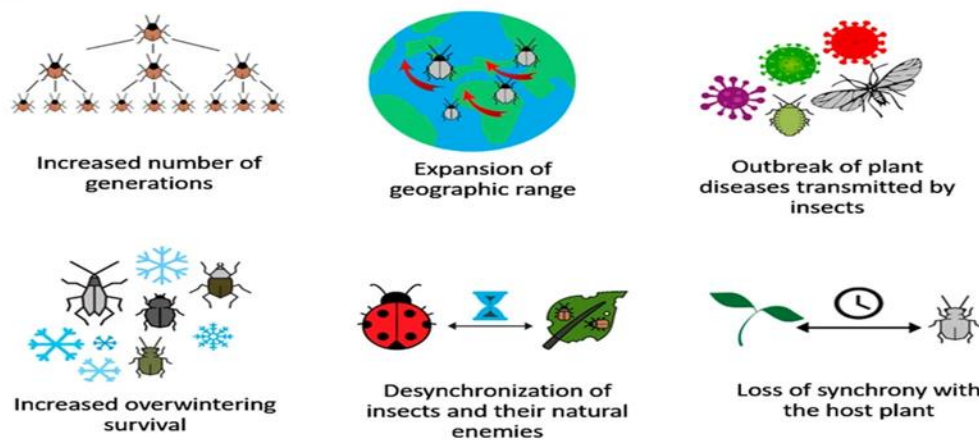


Fig. 01. Effect of temperature on density of Insect pests

Seasonal changes also affect nonentity reduplication by modifying environmental factors like temperature, moisture, and food force. Insects

generally breed in seasons that offer the stylish conditions for the survival of their youthful (Denlinger et al.2002) suggest that multitudinous

insects align their parentage cycles with seasonal variations to enhance reproductive success. For case, the spring and summer months generally promote increased reproductive exertion due to favorable temperatures and generous food inventories. In discrepancy, reproductive geste might drop in downtime or during adverse seasons when environmental conditions turn harsh and coffers come scarce.

In general, environmental rudiments significantly impact the reproductive success of nonentity populations. Variations in temperature, moisture, light duration, and seasonal trends can directly or laterally influence reproductive physiology and geste.

Nutrition is a crucial element affecting the reproductive capabilities of insects. Sufficient nutrient consumption supplies the energy and biochemical accoutrements necessary for the growth of reproductive apkins, egg product, and effective lovemaking geste. Larval diet and adult feeding patterns play a pivotal part in reproductive success. (Nation et al.2015) stressed that nutritive status directly influences fecundity, fertility, and overall reproductive health performance in insects.

The quality of host shops is pivotal for carnivorous insects since they calculate on shops as their main source of nutrients. The reproductive capability of insects that feed on host shops is told by the nutritive makeup of those shops, which includes proteins, carbohydrates, and vital micronutrients. (Slansky et al.1987) set up that insects that feed on superior host shops generally lay more eggs and show increased reproductive rates. Again, insects that consume shops with low nutritive value might suffer delayed reproductive growth and dropped fertility. The presence of applicable host shops is vital in impacting the growth of nonentity populations and their reproductive success.

The reproductive eventuality in numerous nonentity species is also greatly affected by the diet of grown-ups. In majority, insects constantly need redundant food sources like quencher, pollen, or other nutrient- thick accoutrements to support their reproductive functions (Simpson et al.1995) stated that proper nutrition for grown-ups supplies

the energy necessary for sleeping conditioning and laying eggs. When adult insects have access to superior food sources, they generally parade enhanced fertility and advanced egg product. Again, defined access to food in majority could dwindle reproductive success and dock the duration of reproductive life A significant nutritive element impacting reduplication is the availability of vital nutrients necessary for egg development and the conformation of reproductive apkins. Proteins, lipids, vitamins, and carbohydrates are essential for the effective operation of reproductive organs and for generating feasible eggs. (Behmer et al. 2009) emphasized that a balanced input of nutrients allows insects to devote acceptable coffers to reduplication while conserving their physiological stability. A lack of acceptable nutrients can lead to smaller eggs, laid over parentage, and lower seed survival.

Also, nutritive factors encountered during the larval phase can affect reproductive success in majority. Naiads that consume nutrient- thick diets generally develop into grown-ups with enhanced reproductive capabilities.(Chapman et al. 2013) noted that acceptable nutrition for naiads promotes the growth of increased body size and completely formed reproductive organs, which eventually boosts fecundity in mature insects.

Physiological and Hormonal Regulation

Physiological and hormonal regulation plays a vital role in assessing the reproductive ability of insects. Reproduction in insects occurs due to a complex interaction of their nervous system, endocrine glands, and environmental factors like temperature, nutrition, and daylight. These factors control hormonal regulation of different reproductive processes, including egg development, sperm development, mating, and egg development. These factors have been established as vital in regulating insect reproductive capabilities, as indicated by different studies (Nation et al., 2022).The insect endocrine system primarily depends on different hormones, including neurohormones, juvenile hormones,

and ecdysteroids, which control different reproductive processes, including body changes that come with reproduction (Douglas et al., 2023).

One of the biggest hormones that are a part of the reproduction of insects is juvenile hormone. This hormone is released by the corpora allata and plays a major role in controlling the development of the ovaries, the production of yolk proteins, and the maturation of the eggs in the ovaries of insects (Goodman et al., 2022). This hormone plays a major role in the development of the vitellogenin proteins, a marker for the production of yolk proteins in the fat bodies and the movement of the proteins to the eggs (Raikhel et al., 2021). High stages of juvenile hormone usually help

reproductive functions, while lower steps may slow down or stop reproductive development.

Insects use their brain as the primary control center to regulate the initiation of the hormones that control reproduction activities. This means that the brain has specialized cells that produce hormones that activate the corpora allata and the prothoracic glands, which are very vital in the development of vital hormones. The hormones are very vital in the development of reproductive maturity and ensure that the reproduction takes place at the right time when the environment is conducive for the survival of the offspring (Nijhout et al., 2021). The control mechanism in the brain controls the reproduction activities of the insects according to the changes in the environment.

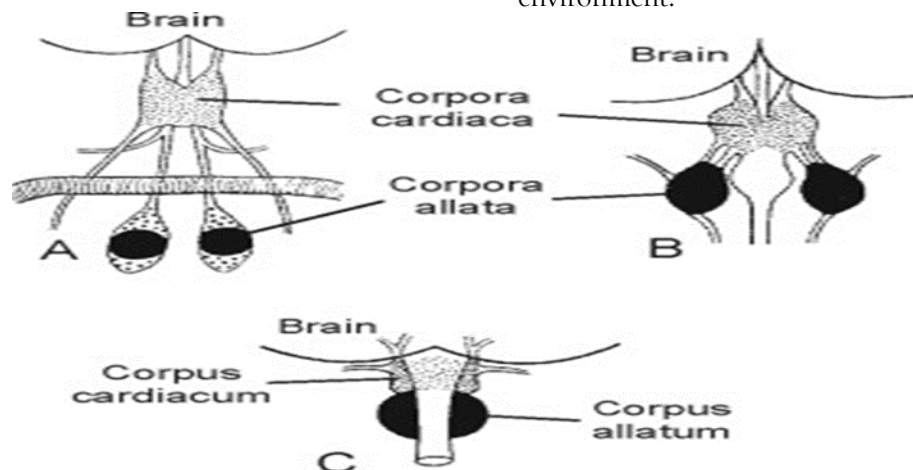


Fig. 02. Mechanism of how the brain controls the reproduction activities of the insects

Nutrition is another factor that influences the regulation of reproduction in insects by hormones. Adequate nutrition is necessary for proper endocrine functions, which in turn will promote the development of hormones that facilitate egg formation and fertility (Attardo et al., 2021). Conversely, inadequate nutrition will impede the development of hormones, thus postponing reproductive activities, which is an adaptive mechanism for insects to wait for an appropriate time when their environment is conducive for reproduction (Denlinger et al., 2020).

Temperature, day length, and seasonal changes are some of the environmental factors that influence

the role of hormones in the control of reproduction. Some insects have adapted to the seasonal changes to ensure the suitability of the environment for the hatching of their young (Saunders et al., 2020). Some insects use their nervous system to detect changes in the length of days, which are converted into hormones that either stop or start their reproduction, as explained by (Armbruster et al. 2022).

Biotic interactions have a significant effect on the reproductive capacity of insects, as these interactions are known to affect the survival, fecundity, mating, and development of insects (Ge et al., 2025). These biotic interactions are mediated by various ecological associations such as

predation, parasitism, competition, host plant, and symbiotic associations with microbes (Basit et al., 2025). These biological relationships often control insect populations, either allowing them to increase rapidly or keeping them under ecological control (Bozbuga et al., 2024).

Among the most important biotic factors is the competition between species. Insect species compete for food, shelter, and oviposition sites (Hegazi et al., 2024). When the availability of host resources is low, the reproductive performance of insects is negatively affected, and the reproduction of insects delayed due to inadequate nutrient uptake. The reproductive performance of parasitic insects is negatively affected by the competition for food, and the reproduction of females is negatively affected by the availability of fewer host species for oviposition (Khafagi et al., 2024). Such interactions also affect the reproductive strategies of insects, and the insects are forced to focus more on survival rather than reproduction (Bozbuga et al., 2024).

Predators have an essential function in governing the reproductive potential of insects through direct population reduction and indirect effects on the reproductive behavior of the insects (Basit et al., 2025). The effect of predators on the reproductive potential of insects has been reported to lead to changes in the mating behavior of the insects to avoid predation (Bozbuga et al., 2024). The changes in the behavior of the insects to avoid predators may lead to a reduction in the reproductive potential of the insects since the insects will be using more energy to avoid predators than to reproduce. The stress caused by predators affects the physiological aspects of the reproductive behavior of the insects (Basit et al., 2025).

In addition, microbial populations are also associated with the reproductive success of insects by modulating immune responses and providing protection against infectious agents (Basit et al., 2025). A balanced gut microbiome is also associated with enhanced fitness and reproductive performance in stressful environmental conditions (Ge et al., 2025). However, there is also evidence that disruption of microbial populations

is associated with low fertility rates, abnormal reproductive development, and poor egg viability (Bozbuga et al., 2024). As such, insect reproduction is related to their microbiome (Basit et al., 2025).

Decline in specie richness, mainly affecting insect pollinators, shows a vital attribute of the Anthropocene era with possibly intense outcomes for operation of ecological system and nutritional stability. Many ecological stress factors are reflected as the primary determinants of intense decrease rate of various insects. These environmental stressors most certainly interact with each other and create a complex effect that can exacerbate the effects of the various stressors. There are still gaps in the knowledge concerning the interactions between the most important stressors that can impact the health of insect pollinators. The effect of global warming on the wellbeing of insect pollinators is not well grasped but will most probably change their behavioral traits (Potts et al., 2010). Distinct the honey bees that can oversee their self-temperature, the isolated bees are vulnerable to the environmental temperatures. Investigators explored the impact of the connection among the bees reaction to thermal conditions and their native range on biological performance of the blue orchard bees, *Osmia lignaria*. The bees that were raised at a temperature that was higher than their native origin showed reduced fitness. There were also developmental differences between the bees. This could be a possible interaction between the genetic makeup of the bees and the environmental conditions that could have contributed to the fact that some bees were better adapted to the environmental changes. This research is important in predicting the effects of climate change on insect pollinators. Nevertheless, this study also shows the desire to carry out more investigation to boost our insight. (Harvey et al., 2023) Various insect populations are specifically prone to decline and portioning of habitat, as they are relying on numerous botanical assets. Intensified farming is a leading factor in the decline of native habitats, out coming in declined population and richness of plants in addition to pristine breeding sites. A

study on the conservation habitat in agroecosystems revealed that even small acreages of flower cover positively supported bee diversity and abundance in agroecosystem. (Mc Neil, 1991) It was further highlighted that importance of habitat heterogeneity as they undertook a study on pollinator taxa in eight European countries and determined that pollinators responded to landscape and climate parameters in a taxon and crop specific way. Bee population was favorably linked with habitat variation in canola fields. Lower managed habitats beneficially effected pollinator population. More tools will be required to assess the nutritional health of bees to determine their nutritional status. For example, pollen diets can increase biomarkers of oxidative stress in honey bees and thus act as a novel tool to assess nutritional deficiencies in bees (Kremen et al., 2002)

It is believed that pests and pathogens are a major factor in controlling the population of wild and domesticated species of bees. *Varroa destructor*, an ectoparasitic mite, and viruses are considered to be the biggest threat to apiculture worldwide. To reduce the adverse impact of *Varroa destructor* parasitism and possible transmission of viruses, it is important to ensure timely treatments to avoid further unsustainable losses in managed populations of honey bee colonies. Researchers have found that temporal efficacy of treatments against mites varies seasonally, with winter and spring treatments being more effective in controlling mites in colonies compared to summer and fall treatments. Experts have studied the spatial distribution of *V. destructor* infestations within the colony of the honey bee species through a population-level epidemiological approach over a period of five years and have established the presence of a stable cluster of mite infestations with other individual clusters occurring sporadically throughout the study area in Southern Ontario, Canada, with no association with environmental factors. Reducing the mite populations within the managed honey bee colony has positive downstream effects and could also have a beneficial impact on the spillover of the virus to the wild bee populations. The study on the

potential impact of the spillover of the virus from the managed populations of the honey bee to the wild bee populations showed that the Deformed Wing Virus A (DWV-A) does not replicate within the mason bee species *Osmia bicornis* is not likely to be infectious to the species. However, there exists the potential for *O. bicornis* to become a host to the DWV-A virus because the virus isolated 16 days after microinjection into the species was infectious to the managed populations of the honey bees. Besides the spillover of the viruses, the viruses could have interactions with environmental pollutants like the agrochemicals. Analysts confirmed that interaction to four fungus killing product widely utilized in blueberry farming might improve the vulnerability of honey bee larvae. (Steinhauer et al., 2021)

Reproductive strategies

In vertebrates, hormones are well known to control reproductive behavior, especially with respect to fine-tuning sensory responsiveness to sexually relevant stimuli. Insects are vertebrates and thus exhibit a large variety of reproductive behaviors such as calling, courtship, mating, and egg-laying using an efficient sexual signaling system to attract and select appropriate sexual partners. This complex sexual signaling system is well known to be regulated by endogenous signals such as hormones and hormone-like molecules like peptides and biogenic amines. Endocrine molecules mediate pheromone biosynthesis and calling behavior (Teal et al., 2000) Pheromones play an important role in the identification and attraction of sexual partners in many insect species, leading to mating behavior. Pheromones are often secondary compounds with structures derived from fatty acids or isoprenoids and may be mixtures of pheromonal compounds. Pheromone biosynthesis is mediated by exocrine glands called pheromone glands, mainly composed of a single epidermal layer present in different parts of the insect's body or epidermal secretory cells called oenocytes present in the abdomen (Wickert-thomas et al., 2009).

Instead of detailed study done throughout recent decades, the metabolic pathway of semiochemicals

and hormonal control of semiochemicals production are not still widely recognized at the cell and molecule based stage. Conversely, a number of research done specifically on *Lepidoptera* has shown that the pheromone production process is the outcome of the mechanism of a light signal, which initiates the discharge of a hormone-like material into the hemolymph (Jiang et al., 2007). It has lately been confirmed that the two primary chemical messengers of insects, juvenile hormone and 20-hydroxyecdysone, are the vital coordinators of the pheromone metabolic production in some insect taxon. It has also been illustrated on the taxon of the order *Lepidoptera* that the modulatory function of juvenile hormone on the pheromone metabolic production rely on the species. In fact, in long-lifespan moths such as the armyworm *Pseudaletia unipuncta* and the black cutworm *Agrotis ipsilon*, JH is known to stimulate the production of pheromones by releasing the PBAN, whereas, in moths with shorter lifespans such as the cotton bollworm *Heliothis armigera*, the JH is required for the primary induction of the pheromone gland to the PBAN. On the other hand, the administration of JH to adult females results in the inhibition of the specific binding to the PBAN-R as well as the production of pheromones in other moth species. In the bark beetle, the JH is known to directly stimulate the production of aggregation pheromones by upregulating the transcriptional activity of the genes responsible for the production of the pheromones. A similar stimulatory action of the JH has been demonstrated for the production

of the sex pheromones in the females of the fruit fly *Drosophila melanogaster*, through the action of the nuclear receptor for the JH, the Methoprene-tolerant. (Bilen et al., 2013).

Recently, the experiments of RNA interference-mediated silencing of the gene for the product of the *Met* gene and the nuclear partner Taiman (*Tai*) in the worst desert locust *Schistocerca gregaria* have shown that the production of phenylacetone nitrile aggregation pheromone is regulated by the JH-Met-Tai signaling pathway. So far, at least three endocrine regulators, PBAN, JH, and 20E, have been found to play the crucial roles in the regulation of pheromone production in the sexual communication of insects. Calling behavior is often associated with the production of pheromones in insects. The initiation of the calling behavior has been intensively studied in relation to external factors such as light and temperature. Conversely, a few studies emphasize the fact that the hormonal regulation of the sexual behavior exists. For example, the removal of the corpora allata, the endocrine gland that synthesizes JH, from moths and cockroaches prevents the occurrence of the female calling behavior. Conversely, the injection of the JH analog fenoxycarb into allatectomized females initiates the onset of the female calling behavior. To date, the molecular mechanisms of the regulatory effect of JH on the female calling behavior remain unknown. (Smith et al., 1990). This table 01 shows that hormones regulates the production of pheromones and reproductive behavior in insects.

Table 01: Hormonal regulation of pheromone production and reproductive behavior in insects

| Regulator | Function | Example | References |
|---|---|--------------------------------|----------------------------|
| PBAN (Pheromone Biosynthesis Activating Neuropeptide) | Activates pheromone yield in glands | Lepidoptera | Jiang et al., 2007 |
| Juvenile Hormone (JH) | Activates production of chemical signal and copulation manner | <i>Drosophila melanogaster</i> | Bilen et al., 2013 |
| Corpora allata / JH | Governs female signaling manner | <i>Supella longipalpa</i> | Smith & Schal, 1990 |
| Pheromones | Induce and detect mating partners | Various insects | Wicker-Thomas et al., 2009 |

9. Future research directions:

Insects have an immune system that is very adaptable and is affected by a number of things, such as their genes, their health, and the conditions in which they live (Rolff & Siva-Jothy, 2003). Pathogens are one of the most powerful selective forces that shape immune defense. Different species have different chances of being exposed to pathogens, which is often linked to differences in habitat, feeding habits, and behaviour (Siva-Jothy, Moret & Rolff, 2005).

Within the same species, immune responses and susceptibility to infection may vary based on biological factors such as sex, developmental stage, and social organization or caste structure (Rolff, 2001; Leech et al., 2019; Paul, Khan & Herberstein, 2022). Consequently, variation in immune defense among and within insect species signifies differences in selective pressures and may also be affected by the risk of physical injury or wounding (Subasi et al., 2024).

The functioning of immune system depend on energy just like other physiological process in body for this reason environmental and ecological condition that affect the availability of resources nutritional status and energy storage can influence the strength and performance of immune system in insects Rolff & Siva-Jothy, 2003; Horrocks et al., 2011; Vogelweith et al., 2017).

Conclusion:

Mortal conduct significantly impact the vulnerable systems of insects. Multitudinous environmental pollutants, similar as germicides and heavy essence, can disrupt vulnerable signaling pathways and weaken vulnerable responses. Also, climate-related differences, including increased temperatures and further frequent heatwaves, heighten the metabolic demands on insects. As insects are needed to expend further energy to manage these stressful situations, there are smaller coffers left to maintain effective vulnerable defenses.

Nonentity health can also be negatively affected by changes in the terrain. For case, the vacuity and nutritive value of food coffers may be lowered by increased atmospheric CO₂ attention and the

deterioration of natural territories. Insects may not get enough energy to sustain robust vulnerable responses when they're faced with scarce or crummy food

Nonentity impunity may also be impacted by substances deduced from humans, similar as antibiotics and pharmaceutical remainders. In certain cases, these composites have the capability to spark immunological responses in insects that are affected. Nonentity fitness may be significantly impacted by similar changes in immunological function. Insects are more vulnerable to infections and may have lesser rates of complaint- related mortality when environmental stress reduces vulnerable function. On the other hand, inordinate immunological exertion may take coffers down from other vital natural functions, especially reduplication.

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