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An Overview of Reproduction in Insects

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Authors' contributions

This work was carried out in collaboration among all authors. Authors GY and IA conceptualized the study. Authors MA and IA did the methodology. Author IA wrote and prepared the original draft of the manuscript. Authors IA and MT wrote, reviewed and edited, visualized the study. Authors GY and MA supervised the study. Authors GY and MA did the project administration. Author GY did the funding acquainted. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Reproduction is a fundamental process in all life forms, including insects, in which offspring are produced from the parent organisms. The offspring combines genetic information from each of its parents and is genetically unique. Insects reproduce through both sexual and asexual reproduction, ensuring rapid population increase. Sexual reproduction involves the use gametes from both male and female insects, whilst asexual reproduction permits solitary creatures to lead to genetically identical progeny. Reproductive ecology deals with the study of how physiological characteristics, behavioral, and environmental elements impact on insect reproduction. The complexity of insect reproduction is focused by important processes known as vitellogenesis, which is required for egg development and transgenerational immunity. The i5k initiative planned to

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sequence more than 5,000 insect genomes to increase our understanding, yet challenges remain due to genome assembly issues and budgetary limitations. Understanding the reproductive morphology and methods of insects, as well as oviposition-related genes, is critical for effective pest management and biological control measures. Insect reproductive research contributes immensely to evolutionary biology, conservation, and agricultural productivity by understanding life cycles, reproductive behaviors, and pollination roles. Insect neurobiology, microbiome and environmental entomology are three most important study fields that will come up with new insights into basic biological processes as well as anticipated pest management and conservation measures in the face of environmental changes in the coming future.

Keywords: Pest management; reproduction; vitellogenesis; oviposition; evolutionary; neurobiology; microbiome.

1. INTRODUCTION

Reproduction is a fundamental characteristic of all known life of organisms, encompassing the natural process through which offspring are produced from their parents [1]. Generally, there are two forms of reproduction: sexual and asexual reproduction. In sexual reproduction, two reproductive cells, the male and female organisms called gametes, which contain half the number of chromosomes of normal cells, are created by meiosis, and the male gamete fertilizes the female gamete of the same species to create a fertilized zygote. This produces an offspring whose genetic makeups are derived from those of the two parental organisms. In asexual reproduction, an organism can reproduce without the involvement of another organism, creating a genetically similar or identical [2-4].

In previous studies, it was noted that insects employ both sexual and asexual reproduction strategies, thus ensuring their rapid increase in numbers [5-7]. Reproductive ecology deals with the organism's physiology, behaviors, and the abiotic and biotic environments in which it lives to determine how it reproduces [8]. The female reproductive functions, physiological traits, and egg characteristics determine the percentage number of offspring a species can produce. Numerous interconnected factors causes restrictions on this reproductive outcome, which can be categorized as limitations arising from the female's physical condition, the abiotic conditions faced by the female and her eggs, and the presence of natural predators [9].

Female insect reproduction starts with vitellogenesis a process of accumulation of yolk protein during oocytes formation. The fusion of vitellogenesis has been reported in follicle cells [10], hemocytes [11-12], nurse cells [13-14], and in some insect species. Furthermore, in honey bees, vitellogenesis acts as a pathogen receptor and transfers pathogen-derived fragments into the offspring to attain trans-generational immunity [15-16]. In the small brown planthopper, vitellogenesis integrated by hemocytes can expedite the upright transmission of rice stripe virus [12]. Generally, the number of vitellogenesis genes varies between one to three across different insects. [17].

Vitellogenesis is important for egg development during adulthood and embryonic development after oviposition. Vitellogenesis also acts to safeguard the queen and the worker bees from oxidative tension and extends the lifespan of honey bees [18-20]. Moreover, vitellogenesis plays an important role in recognizing fat body sugars and gustatory insight in the worker bees [21]. This review explores reproduction strategies, reproductive organs, genomes, and their functions in insects. Understanding these aspects is crucial for designing effective biological control measures and enhancing our understanding of insect oviposition [22-24] Oviposition comprises all physical and biological processes from egg laying to egg hatch, which is essential to the survival and fitness of all insect species.

1.1 Importance of Insect Reproduction

Ecosystems rely on the essential functioning of insects as the most important and major herbivores of most terrestrial communities in the world. An important pillar of the food web is supported by insects, which transfer plant energy further up the food chain. Many fish species, birds, mammals, amphibians, reptiles, and birds rely mostly on insects for food and sustenance. During the breeding season, birds rely on insects to provide food for their young [25], to ensure species survival of new individuals in the population. This leads to the asexual replication of genetic copies of organisms. The emergence of new species promotes the evolution of organisms, which is essential for their survival due to the constant change in their environment [9]. To produce species variations since no two people are alike and because each person inherits certain genetic traits from both parents, resulting in a somewhat different version of themselves and over hundreds of years, these minute differences add to generate new species [26-28].

1.2 Sexual and Asexual Reproduction in Insects

Asexual reproduction consists of several types in the animal kingdom, these include budding, fission, fragmentation, and parthenogenesis. Parthenogenesis is the commonest form in insects and it occurs when an unfertilized egg develops into an offspring. There are mainly two asexual production, that is diploid and haploid depending on the species. Sexual reproduction is a type of production that occurs when the female insect produces eggs, which are fertilized by the male sperm cell, and then the eggs are usually placed near the required food for nutrition.

2. INSECT REPRODUCTIVE ANATOMY

2.1 Overview and Functions of the Male Reproductive Parts

The most important part of the male reproductive system is a pair of testes, mostly located closer to the back of the abdomen. Testis development, including spermatogenesis, is affected by developmental stages, temperatures, nutritional conditions, and hormones [29-31]. In the yellow dung fly (*Scathophaga stercoraria*), the testes disappear after mating [32]. Similarly, in *Meign* (*Drosophila melanogaster*), there was a significant reduction in the testes size after five successive mating [33]. Testis development is closely related to spermatogenesis [34] and testis size usually increases as spermatogenesis becomes more active [35]. However, the relationship between testis size and spermatogenesis depends on the species and developmental stage. The shape of the testis is circular, oval, or elongated, perhaps corresponding to sperm length, probably because sperm develop greatly during spermiogenesis [36-38]. Sperm are produced at the follicles, an example of the functional unit, located within the testis. An insect testis consists of hundreds of follicles, usually arranged parallel to each other. Near the distal end of each follicle, group of germ cells known as spermatogonia, that divide by mitosis and increase in size to form spermatocytes [39-40]. These spermatocytes migrate toward the basal end of the follicle, pushed along by continued cell division of the spermatogonia [41].

Each spermatocyte undergoes meiosis, resulting in four haploid spermatids that undergo development into mature spermatozoa within the follicle. The mature sperm then exit the testes through short ducts known as vasa defferentia and accumulate in storage chambers called seminal vesicles, known to be enlarged sections of the vasa [42-43]. These seminal vesicles are connected to similar ducts known as vasa deferentia, which converge near the body's midline to form a single ejaculatory duct that facilitates the release of sperm through the male's copulatory organ, known as an aedeagus. Additionally, the male reproductive system is often accompanied by one or more pairs of accessory glands, these glands produce seminal fluid to nourish sperm and spermatophores, protective protein structures that encase sperm and aid in their transfer to the female during copulation [44].

2.2 Functions of the Female Reproductive Parts

The female reproductive system is present in the abdominal cavity of female insects. The female reproductive system of insects consists of the following organs or parts: ovaries, lateral oviduct, median oviduct or vagina, spermatheca, accessory glands, and gonopophysis. The following are the functions of the various female reproductive parts:

Ovaries: An insect's intestine is above its anterior abdominal chamber, which houses a single pair of ovaries. It is situated on both sides of female insect's abdomen which is inside the tergum. The insect's two ovaries, which are mesodermal in origin, generate eggs. Many ovarioles, or functional units, make up each ovary. Every ovariole is muscular, elongated, and coated in an epithelial layer [45]. Each ovariole of an insect consists of several parts, including pedicel, terminal filament and germarium oocytes. A long, tubular structure known as the terminal filament is located in the ovariole's anterior region. Germarium apical consisting of oogonia. The outer sheath of the ovariole covers the basal vitellarium and it consists of a variety of oocyte types, including primary, secondary, and tertiary oocytes. Vitellin, sometimes known as the yolk, is

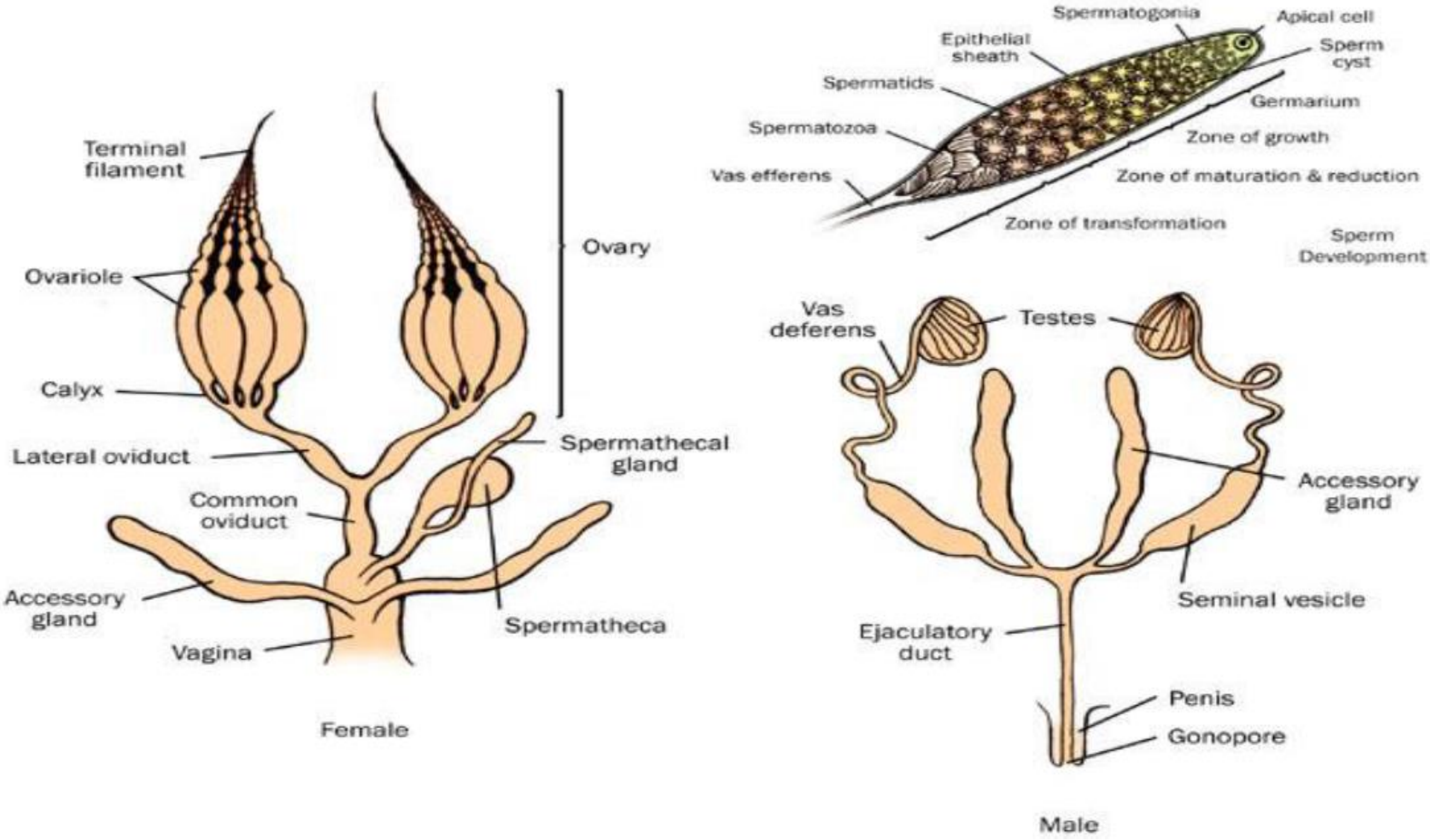

Fig. 1. Diagram of the reproductive parts of male and female insects [46,30]

produced in the adipose tissue, released into the hemolymph, and then absorbed by the oocytes via endocytosis. The terms panoistic type and meroistic type refer to two kinds of ovarioles that are primarily seen in insects. Panoistic type ovariole: A type of ovariole that is most basic and has fewer cells. It is seen in orthopterans and beetles (coleopteran). Lepidoptera and Hymenoptera insects are the primary hosts of meroistic type ovarioles. A nursing cell is present in this form of ovariole to nourish the oocytes [46].

Lateral Oviduct: The pedicel of an insect's ovariole forms one pair of lateral oviducts. Every ovariole's pedicel opens into the lateral oviduct. Different types of eggs are transported by lateral oviducts. All lateral oviduct changes in the formation of a median oviduct below the colon after extending postero-ventrally along the lateral margin of the proctodeal. The lateral oviducts originate from the ectoderm and are muscle-derived.

Median Oviduct or Vagina: A common oviduct, median oviduct, or vagina is formed posteriorly by the posterior union of the two lateral oviducts. As a result, the two lateral oviducts meet at a unique "Y" shape. In comparison to the lateral ducts, the median tube is relatively wider. Because of its ectodermal origin, it is muscular and has a modified cuticle lining it. It moves posteriorly and opens ventrally between the plates of the ovipositor. It is also called Barsa copulatrix in moths [45].

Spermatheca: The term refers to a sac-like tubular structure located at the posterior end of the common oviduct. The spermatheca, which consists of a long, coiled duct and a circular chamber, is located in the abdominal cavity near its posterior end, in the midline, below the hindgut. It opens into the genital chamber and has a creamy white color. Spermatheca serve as an insect's storage chamber, holding sperm throughout the copulation period. Within the common oviduct, the egg is fertilized by these sperm. Insect spermatheca also function as glands that secrete spermathecal fluid, which feeds sperm [45].

Accessory Glands: A single pair of accessory glands is usually observed in insects, although some insects possess two pairs. These glands are typically located at the apex of the common oviduct. They are responsible for secreting adhesive material that aids in attaching the egg to the substrate. In certain insects, such as grasshoppers, the secretion from the accessory glands contributes to the formation of egg pods. Moreover, in numerous aquatic insects, these glands produce gelatinous fluids that protect the eggs. Wasp species utilize the secretion from their accessory glands to immobilize their prey.

Gonopophysis: The posterior part of the female insect's abdomen features an opening known as the gonapophysis. This structure is also referred to as the ovipositor of the female insect. Enclosed by a chitinous framework. The gonopophysis plays a crucial role in the process of egg deposition and the creation of egg pods [41].

3. TYPES OF REPRODUCTION IN INSECTS

There are generally seven types of reproduction through which insects produce their young ones. These are listed and explained below:

Viviparity: Viviparity in insects as the process in which they “give birth to living offspring which have hatched from the egg within the mother’s body. Ovoviviparity is a related term of which author described it as when some species deposit eggs with embryos in different stages of development and considered this behavior a different phenomenon. Later, a new classification where the viviparity of insects is classified into four groups, based on the modifications related to the strategies utilized to nourish the embryo during development.

- **Ovoviviparity:** The egg contains enough yolk to nourish the embryo till hatching and no special structures associated with embryo nourishment.
- **Adrenotropic viviparity:** The egg contains enough yolk to nourish the embryo till hatching and special structures associated with embryo nourishment.
- **Haemocoelous viviparity:** This term means development of the embryo occurs in the haemocoel, not in genital ducts, and embryonic nourishment is derived from maternal tissue.
- **Pseudoplacental viviparity:** This term means the embryo obtains at least part of its nourishment by means of a pseudoplacenta in the course of reproduction.

Adenoparous: This strategy occurs when eggs have adequate yolk, and young offspring are fed from milk glands after their release, also pupating instantly without feeding. A typical example is the (*Glossina pupipara*) of Diptera [47]. This process is further divided into two groups:

- **Pseudoplacental:** This process occurs when eggs with little yolk feeding and nourishment are through a pseudoplacenta. An example is psocoptera, dermapteran, and aphids.
- **Haemocoelous:** This strategy occurs when nourishment of young offspring occurs in the hemolymph of the parent mother. Young offspring are born either by the rupture in the walls of the parent or by the genital canal. A typical example is strepsipterous and larvae of cecidomyids [48].

Parthenogenesis: The third most important means of production, which is described as the ability of female insects to reproduce without fertilization. This process occurs due to genetic factors, heredity, climatic factors, unsuccessful finding of a mate, and hormonal imbalance. Parthenogenesis is subdivided into:

- **Sporadic:** Occurs occasionally. An example is the silkworm [48].
- **Constant:** Occurs regularly or frequently. An example is thrips.
- **Cyclic:** This is an alternation of generations. A typical example is aphids.

Based on the sexes of the offspring produced, parthenogenesis can be classified as:

- **Arrhenotoky:** Only males are produced. An example is Hymenoptera.
- **Thelytoky:** Only females are produced. An example is acridids.
- **Amphytoky:** Occurs when both females and males are produced. An example is hymenopterans.
- **Paedogenesis / Neoteny:** This strategy of parthenogenesis occurs when immature insects or stages give birth to young ones, usually due to hormonal changes. A typical example is cecidomyids [49-50].

Polyembryony: Polyembryony occurs when insects reproduce by giving birth to two or more offspring instead of a single one, as two or more embryos are generated from a single egg. An example is the endoparasitic Hymenoptera.

Hermaphroditism: This type of reproductive phenomenon occurs when both male and female gonads exist in the same individual, which may be functional, as in *Icerya purchasi*, or nonfunctional, as in stonefly (*Perla marginata*) [51].

Castration: Castration in individual insects occurs mainly because of the development of the reproductive organs. An example is well-developed ovaries developing into female insects, similarly, well-developed testes develop in male insects, Lastly, is insects with underdeveloped ovaries in worker honey bee insects.

Alternation of Generation: This is another strategy through parthenogenesis and bisexual reproduction. For example, aphids exhibit this phenomenon of reproduction by parthenogenesis in summer and sexual reproduction.

4. REPRODUCTIVE STRATEGIES IN INSECTS

Semelparity and Iteroparity: Insects demonstrate two reproductive systems, namely semelparity and iteroparity. Semelparity encompasses reproducing once in an organism's lifetime, resulting in a larger number of offspring. A typical example is cicadas, which endure underground for extended periods before emerging to mate, lay eggs, and die. In iteroparity, an organism reproduces several times in its lifespan, producing smaller populations of offspring at each reproductive stage. Butterflies are a typical example of iteroparity because they mate and lay eggs several times throughout their life cycle [52].

Drifting Behavior: It has been observed that certain insects, such as wasps, ants, and honeybees, use a distinct reproductive strategy called drifting behavior. These insects are classified as social insects because one or a small number of females are in charge of laying eggs while other populations of the colony search for food. To mate and procreate, some colony affiliates leave their original nest and attach to a new one. A study on the bumblebee species *Bombus terrestris* was carried out [53]. The study found that fertile workers use a unique strategy to avoid reproductive rivalry in their own nest and instead mate and reproduce in different colonies. Workers who are fertile or infertile exhibit this fluctuating behavior, even if their propensity to immigrate to other countries and procreate within their new colonies is mostly determined by their level of fertility.

5. REPRODUCTIVE AND MATING BEHAVIOR IN INSECTS

The term used to describe the appropriation of energy and resources towards reproduction in insects is known as reproductive effort or behavior. Insects manifest a wide variety of reproductive strategies, and the stage of reproductive effort can differ significantly among species. Some insects reveal a high reproductive effort, where most of their energy and resources are committed to reproduction. A typical example is the female green veined white butterflies (*Pieris napi*), which boost their reproductive effort when they acquire large male donations, another example are fruit flies *(Drosophila melanogaster*)**,** Honeybees *(Apis mellifera)* and German cockroach *(Blattella germanica),* but speckled wood butterflies (*Pararge aegeria*), Praying mantises (*Mantodea*) and Stag beetles (*Lucanidae)* do not. The green veined white butterflies produced more eggs but did not invest more resources per egg. This behavior was important because donating capacity in green veined white butterflies is heritable, which leads to greater fecundity and high-donating sons.

Egg Size: Egg size is vital in insect reproductive strategies, with remarkable involvement for offspring success. Insects manifest a different scale of egg sizes, which can be linked to different reproductive strategies. In the burying beetle (*Nicrophorus vespilloides*), the body mass of the offspring has a positive effect on egg size when care after hatching is absent, this action dissipates when there is post-hatching care. In the European earwig (*Foricula auricularia*), the quantity of pre-hatching care has consequences on egg size and offspring number, with a positive correlation only in clutches, getting high ranges of pre-hatching care.

Parent-Offspring Conflict and Sibling-Sibling Conflict (Sibling Rivalry): Another important aspect of insect reproduction is the parent-offspring conflict, guided by genetic relatedness and maximum investment approaches. This normally involves insects frequently engaging in sibling rivalry, competing for sometimes limited resources such as parental care, space, and food, which impacts heavily on their reproductive success.

Courtship Behavior: Insects go through a series of courtship behaviors to attract and mate with their partners. The obvious example occurs when the insect employs the act of calling and courtship songs; this strategy is used by fruit flies, crickets, and mosquitoes to lure and persuade their mates to mate with them. A different behavior exhibited is dancing and foreplay, observed in male flies, dung beetles, springtails, and apterygotes. Some male insects use nuptial presents, which involves giving food or indigestible tokens to females' insects during courtship, as seen in hangingflies, katydids, and balloon flies. Some insects also use aphrodisiac tactics a typical example is the dust created by male butterflies. Lastly, visual signals are also utilized by some insects to attract their mates or partners, as seen in fireflies and butterfly species. By employing these different plans and strategies, insects can discover and copulate with their partners, ensuring the continuation of their species to avoid extinction [54].

6. THE COMPLEXITY OF INSECT SEMINAL FLUID

Female insects exhibit changes in behaviors physiologically and even anatomically through mating. These mated female insects exhibit a complete variation dramatically from their virgin self. These variances are caused by proteins and other molecules transmitted in the male's ejaculate. The ejaculate is comprised of sperm and seminal fluid which contain proteins rich in lipids, nucleic acids, carbohydrates, hormones, mucus, vitamins, water, vesicles, microbes, and in some species, glandular cells [55-58]. In several insects, the protein constituent of the ejaculate, acquired mainly from the male accessory glands, is especially varied. Recently identified and analyzed in the accessory gland in the malaria vector is amounted to 121 [56,59,60], while almost 100 seminal fluid proteins (SFPs) are transferred to females in the process of mating in a different mosquito, that is the yellow fever vector *Aedes aegypti* [54]. In *Drosophila*, seminal fluid proteins, amino acid variation is added by a diversity of post-translational modifications [61]. Insect ejaculates are normally classified into two main types [62]. Firstly, in *Drosophila melanogaster*, the male ejaculate sperm may be within the seminal fluid system. On the other hand, the male ejaculate may be transmitted as a spermatophore, example is the springtails and butterflies where all the non-sperm and sperm are wrapped within a proteinaceous capsule [62].

7. GENERAL FUNCTIONS OF MALE INSECT REPRODUCTIVE GLAND PRODUCTS

Seminal fluid constituents have been involved in the induction of different post-mating phenotypes of females [63,58,64,65,55]. The seminal fluid proteins have been reported to be very important in steering these changes, a typical example is *Drosophila melanogaster*. The performance of SFPs in female insects can be grouped into those that have influence on behavior, physiology, and anatomy. Seminal fluid proteins also have a crucial role within the male insect, by processing other seminal proteins in the male's reproductive tract during mating through to the female reproductive tract [66-68]. Some other functions include the promotion of the sperm in the female reproductive tract, an example is the successful release of sperm from storage [50].

8. INSECT PEST GENOMES ON DIAMONDBACK MOTH

Agricultural pest management is an important interest in entomology, but genome sequencing of these important pests has fallen behind that of other insects. The 'i5k' ambition was launched by Robinson and colleagues in 2011, with the aim to sequence over 5000 insects and arthropods with desirable biological research significance before 2017. The aims and objectives of the 'i5k' ambition are still not realized because of two main challenges: problems in assembling genomes of insects and financial constraints. National Center for Biotechnology Information (NCBI) has registered 1,219 insect genome-sequencing programs. Currently, complete genomes of only 28 species of agricultural pests have been sequenced but part of these genomes have low scaffold N50 values, low assembly quality, and low gene integrity. These problems may be due to the high heterozygosity of most of insect pests. Diamondback moth (*Plutella xylostella*) is a dominant pest, attacking and causing severe damage to cruciferous crops, and rapidly developing unimaginable resistance to pesticides. The genome of the diamondback moth has only 343 Mb but has a high degree of heterozygosity. The diamondback moth genome was sequenced in 2013 and reported to be the first insect genome to be sequenced with a high degree of heterozygosity. Sequence the diamondback moth genome using a fosmid-to-fosmid approach to get 1,819 scaffolds. The genome annotation found 18,071 genes and 781 noncoding RNAs, and the N50 of this genome assembly is 737 kb. The insect has 1,412 specific genes, and amplification of gene families involved in detoxification metabolism and participating in protection was done.

9. GENES ASSOCIATED WITH INSECT PRODUCTION

9.1 Oviposition-Related Genes

Oviposition-related genes have consistently been a key focus in insect molecular biology. Research over time has enhanced our understanding of these genes, including those associated with oviposition glands, oogenesis, oviposition site selection, and ovulation and hatching. Female insects, especially certain pest species, have an incredibly high reproductive capacity, laying hundreds to thousands of eggs each. These females' insects and their role of oviposition-related genes are critical for sustaining insect populations [69,70].

Insect oviposition is governed by a genetic pathway consisting of various oviposition-related genes, which are mainly categorized into four groups: genes controlling oviposition glands, genes related to the egg surface, genes involved in oviposition site selection, and genes associated with ovulation and hatching. These genes can directly or indirectly influence insect oviposition [66-68]. Modern techniques such as RNA interference (RNAi) and CRISPR/Cas9 have been employed to study these genes in detail. The combination of RNAi with other methods to control plant diseases and pests has begun to see some commercial usage [71-74].

9.2 Oviposition-Related Gland Genes

The physiological and biochemical activities in female insects, including those related to oviposition, are controlled by specific genes. A typical example is the vitellogenin gene, which is highly expressed in the ovaries and salivary glands of insects [21]. Physiological and biochemical processes support the development of organs during oviposition. In insects, especially in species like *Apis mellifera*, the vitellogenin gene is crucial for regulating immunity, stress tolerance, lifespan, feeding, and oviposition behaviors. Interfering with the expression of this gene can lead to lipid loss in females and lipid accumulation in ovaries, impacting ovary maturity [75,21].

9.3 Oogenesis-Related Genes

During ovarian development, oocytes continuously acquire nutrients to form ova. Previous research has mapped the dynamic gene expression landscape during oogenesis, identifying 1,932 genes differentially expressed at various stages, particularly from late vitellogenesis to early choriogenesis. Vitellogenesis and choriogenesis are key processes in oocyte development and maturation, regulated by factors in hormonal control of oogenesis and transgenerational hormonal effects. The vitellogenin gene, for example, plays a significant role in determining the nutritional status of oocytes and their capacity for continuous division. During oogenesis, vitellogenin protein is synthesized in the fat body, released into the hemolymph, and incorporated into maturing oocytes through vitellogenin receptor-mediated endocytosis.

9.4 Oviposition-Site-Selection-Related Genes

Identifying oviposition sites with adequate food is critical for ensuring the survival of the next generation of larvae or nymphs once the female's ovaries have fully matured [64]. Females rely primarily on the sensilla on their antennae to find these places, which express a variety of olfactory genes. These genes encode proteins responsible for the sense of smell, which play a vital role in female mating and selecting suitable oviposition locations [76]. Research indicates that a female's sense of smell is essential for recognizing hosts, mating, and oviposition. Key genes linked to olfactory proteins and receptors in female insects include those for odorant-degrading enzymes, odorant receptors, ionotropic receptors, and sensory neuron membrane proteins. These genes encode the main proteins involved in chemical signaling [77-78].

9.5 Genes Related to Oviposition and Hatching

Oviposition, which encompasses egg laying and hatching, is a crucial phase in insect reproduction. Research on ovulation associated genes especially individual genes involved in oviposition is still at the beginning stage. For instance, studies have shown that the recombinant Homeobox protein gene reduces the number of eggs laid by *Dermanyssus gallinae*. Additionally, applying recombinant Degakr protein from the Akr gene to the adult *Dermanyssus gallinae* impacts egg-laying, resulting in a 42% decrease in oviposition [65]. Several genes regulate the physiological and behavioral processes of females during oviposition, ovulation and maintenance of the internal egg environment and surface humidity.

DOPA decarboxylase, vital for corneous tanning, affects molting, survival, and reproduction in *R. prolixus*. Stern et al. [74] discovered that knocking out the Aromatic amino acid decarboxylase 2 (AADC2) gene led to delayed ovulation, lower hatchability, and higher mortality in hatched nymphs. Current research focuses on genes related to environmental stability and hatching. For example, RNAi-mediated knockout of the Transformer-2 homologue gene reduced reproduction in *Diaphorina citri*, with silenced females laying fewer eggs and a 29.86% reduction in hatching rates compared to controls [60]. Another study identified that the myxoid protein is essential for oviposition in *Nilaparvata lugens*, with Mucin (Muc) genes encoding proteins necessary for normal eggshell formation and oviposition.

10. CHALLENGES IN INSECT REPRODUCTION

Predation Risk: Because predators serve as crucial regulators of prey populations, predator threat is one of the most significant processes in ecosystem operation [32]. This selective pressure can alter demographic parameters, geographic distribution, population structure, and the evolution of physical attributes, life history traits, and behavioral techniques in both prey and predators. Attack rates provide the most precise assessment of the influence of predation on prey populations; nevertheless, in natural systems, they are notoriously difficult to quantify due to the infrequent nature of predation events and predators' fast consumption or disposal of prey carcasses. Seasonality and the complexity of the habitat's structural structure are two factors that can affect the risk of predation [33].

Competition for Mates: Darwin [26] described sexual selection as the differential reproductive success resulting from competition for mate partners. Instead of mating with multiple females, males might find it more advantageous to fertilize as many eggs as possible. Parker [26] was the first person to recognize that male competition could extend within the female, a phenomenon he termed "sperm competition." Parker defined sperm competition as the rivalry between the sperm of multiple males within a single female for egg fertilization. This competition extends sexual selection beyond mating, persisting until conception. There are two types of post-mating sexual selection: male competition (sperm competition) and female choice (cryptic female choice) [79,80].

11. DISCUSSION AND CONCLUSION

Reproduction is the basic feature of all known life of organisms and the natural process by which offspring are produced from their parents. Insects reproduce both sexually and asexually, enabling their rapid population growth. Reproductive ecology is concerned with the organism's physiology, habits, and the abiotic and biotic settings in which it lives to determine how it reproduces. Recent advancements in the study of oviposition-related genes in insects have shown significant process. However, the complexities of ovarian growth, the physiological processes of oviposition, and the involvement of antennae in selecting oviposition sites during ovulation and egg hatching are more complex than previously imagined. It's obvious that no single gene can fully regulate the oviposition behavior of females; instead, a network of genes works in concert to govern this behavior comprehensively. In insect reproductive strategies, notable examples include conflicts between parents and offspring, conflicts between siblings, variations in egg size, semelparity and iteroparity, drifting behavior, courtship activities, and various reproductive strategies. These strategies provide insights into how insects achieve successful reproduction within ecosystems. Regarding the complexity of insect seminal fluid, mating induces internal modifications in female insects, altering their behavior, physiology, and anatomy. These changes result in a dramatic transformation from their virgin state, driven by proteins and other molecules in the male's ejaculate. The products of male insect reproductive glands, particularly seminal fluid constituents, play a role in inducing various post-mating phenotypes in females. The effects of seminal fluid proteins on female insects can be categorized into changes in behavior, physiology, and anatomy.

Insect reproduction can be classified into seven main types: oviparity, viviparity, parthenogenesis, polyembryony, hermaphroditism, castration, and alternation of generation. Genome sequencing of significant pests has lagged compared to other insects. To date, the complete genomes of only 28 agricultural pest species have been sequenced, with many exhibiting low scaffold N50 values, poor assembly quality, and low gene integrity, likely due to high heterozygosity in most insect pests. Research in insect molecular biology has consistently focused on genes associated with oviposition. Advances have been made in understanding the mechanisms of oviposition-related genes, including those related to the oviposition gland, oogenesis, oviposition-site selection, and genes involved in ovulation and hatching.

12. SIGNIFICANCE OF INSECT REPRODUCTIVE STUDIES

Insect reproductive studies are significant for several reasons:

a. **Understanding Life Cycles:** Insect reproductive research helps us understand the life cycles of various insect species. This information is essential for understanding their population dynamics, behavior, and ecology.
b. **Pest Management:** Insect reproductive studies provide information on pest insects' reproductive practices. This knowledge can be utilized to build efficient pest management techniques, such as controlling insects at various periods of their life cycle.
c. **Evolutionary Biology:** Insects use a variety of reproductive techniques, such as sexual and asexual reproduction, multiple mating, and intricate courtship activities. Scientists can learn more about evolutionary mechanisms by researching these strategies.
d. **Conservation:** Insect reproductive research is critical for the preservation of endangered insects. Understanding their reproductive biology contributes to the creation of conservation strategies focused at protecting breeding locations and ensuring effective reproduction.
e. **Agricultural Productivity:** Insects contribute an important role in pollination, which is required for agricultural productivity. Insect reproduction research contributes to a better knowledge of their role as pollinators and how to improve their reproductive behavior for agricultural production.

In conclusion, insect reproductive research has important implications for many domains, including ecology, pest management, evolutionary biology, conservation, and agriculture.

13. FUTURE RESEARCH DIRECTIONS

With requisite understanding of insect biology and reproductive system, newly discovered disciplines of study within entomology are emerging. A typical example is insect neurobiology, which involves understanding the neural techniques that emphasize insect behavior. This education can provide insights into basic neurological functions and can be applied to robotics and artificial intelligence. Secondly, another interesting field of study and research is insect microbiomes, which involves microbial communities that live in symbiosis with insects [15]. These microbes are very important in insect physiology, digestion, immunity, and reproduction. Understanding these links can lead to innovative pest management tactics and a better understanding of basic biological processes. Another developing area, environmental entomology, which studies the connections between insects and their habitats, is gaining traction in the face of climate change and habitat loss. The goal of this study is to predict how environmental changes would affect insect populations and to identify potential conservation strategies.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) I hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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