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The puzzle of pheromones in nature and their mysterious influence: a comprehensive review

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ABSTRACT

Pheromones are chemical signals that are given off by creatures to communicate with other conspecifics. Because of their influence on animal behavior and relationships throughout the animal world, pheromones have fascinated scientists for decades. The newest findings and new perspectives on the intriguing field of pheromones are synthesized in this thorough review article. We investigate the many roles played by pheromones, from mating attraction and territorial marking to alarm signaling and social organization. The chemical diversity of pheromones is explored in depth in this paper, highlighting the variety of substances used by different animals as messengers. We go over the processes involved in pheromone detection and processing to help understand how chemosensory receptors and brain circuits interact in complex ways. Additionally, we discuss the role that pheromones play in ecology and evolution by promoting speciation and adaptation. This review emphasizes both the new research on pheromones in humans as well as their function in the animal world. We investigate the data supporting human pheromones and their possible impact on social and reproductive behaviors. The review aims to offer a detailed exploration and insight into the role and effects of pheromones in the natural world. This includes examining the chemical essence of pheromones and their functionality as communication signals across different species, investigating the specificity of these chemicals to certain species and how non-specific pheromones come about, and delving into the evolution of pheromones with a focus on the physiological and evolutionary mechanisms that drive communication. Additionally, the review seeks to understand the role pheromones play in pest management, specifically how species-specific pheromones can be utilized in eco-friendly pest control strategies. It will also explore the enigmatic impact pheromones have on the behavior and interactions within and among species. Drawing from a variety of sources, such as scientific research articles, studies on pheromone evolution, and articles on pheromone application in pest management, the review aspires to synthesize existing knowledge to provide a comprehensive overview of pheromones and their intriguing influence in nature. This study intends to not only summarize existing information but also encourage further research, shedding light on these cryptic chemical signals and their tremendous influence on the biology and behavior of species. It does this by offering a comprehensive perspective on the complex world of pheromones.

1. INTRODUCTION TO PHEROMONES

Chemical cues, called pheromones, are exchanged by individuals of the same species. By attracting one or more adult individuals to the pheromone-producing individual, several of the known insect pheromones function as long-range attractants. In order to attract members of the opposing sex for the express goal of mating, individuals of one sex produce sex pheromones. In general, one sex releases aggregation pheromones that attract conspecific male and female individuals to areas where mating takes place and where females choose sites for oviposition on suitable substrates for larval feeding. Pheromones thus function in unique biological situations and are very species-specific. Pheromones are distinct from other, less specialized insect attractants, such as the aromas of food or host plants, which may be all-purpose attractants for several species. Improvements in the collection, isolation, and chemical identification of extremely minute amounts of pheromones generated by live insects have sparked a boom in research on insect pheromones during the last 30 years. For the majority of the main stored-product insect pests, i.e., a variety of insects that infest and damage stored food, books, documents, fabrics, leather, carpets, and any other dried or preserved items, at the current time, attractant pheromones have been discovered and synthesized. Large populations of certain pest species may be attracted to traps using artificial pheromones. Pheromones have been used to manipulate and suppress populations in the study. However, pheromones are not commonly utilized to control insect pest populations at the moment. Synthetic pheromones are often utilized in traps as monitoring and detection techniques in pest control programs. Additionally, traps baited with non-pheromone food attractants, as well as unbaited traps that collect insects passively, are employed to

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monitor insect populations in settings where stored goods are present. In addition to discussing the use of pheromones and associated trapping and enticing techniques as Integrated Pest Management (IPM) tools, this chapter will also consider the possibility of creating pheromone-based strategies for pest population control. In 1966, the black carpet beetle, Attagenus unicolor (Brahm) (megatoma), chemically produced the first stored-product insect pheromone. Since then, pheromones from more than 40 species of insects that feed on stored goods have been found. Numerous review publications have thoroughly examined the biology, chemistry, and use of insect pheromones found in stored products [1].

Pheromones are classified according to their chemical makeup, purpose, and the environment in which they are employed by a species. The classification is given in the table below [Table 1].

2. TYPES OF PHEROMONES

2.1. Sex Pheromones

Sex pheromones are chemical signals that one member of a species emits, and another member of the same species detects. They provide a number of functions, including mating attraction, territorial marking, and communication. The ability of creatures to recognize potential mates of the other gender is the primary purpose of sex pheromones. It goes without saying that sex-specific chemical signals indicating gender are often created, whether they are male- or female-specific or a mix of the two. Many of the most well-known insect sex pheromones are female-specific, long-range male attractants, as a result of the finding of bombykol. Studies of several Hemiptera (true bugs) have mostly identified male-specific sex pheromones, which may represent historical prejudice rather than taxonomic class bias [Figure 1] [2]. Pheromones come in two different varieties: releasers and primers. While primer pheromones generate physiological changes in an animal that eventually lead to a behavioral response, releaser pheromones elicit rapid behavioral reactions in insects upon receiving them.

There are three main categories of chemically recognized releaser pheromones: those that promote recruitment, alarm behavior, and sexual attraction. Recruiting pheromones are mostly used to indicate routes to food supplies. Bees and other flying insects apply the compounds at irregular intervals, while terrestrial insects leave continuous odor trails. For warning pheromones, insects exhibit far reduced sensitivity and chemo specificity. Alarm selectivity is more influenced by volatility than by distinctive structural characteristics. The full sexual toolkit is released by sex pheromones. So, an inanimate item with a sex pheromone on it may attract and seek to mate with a male insect. It seems that the majority of insects are very choosy and sensitive to their species' sex pheromone.

The queen bee uses a sophisticated pheromone system to regulate worker behavior. The fatty acid 9-ketodecenoic acid, which is generated by the queen and transferred to the workers, is one well-known part of this system. This substance hinders the workers' ability to raise queens and stops the development of ovaries in the workers. Additionally, virgin queen bees employ the same substance as a sex attractant. [3]. Insect pheromones, which are volatile in nature, make up the bulk of pheromones that have been discovered so far. It has been exceedingly uncommon to identify nonvolatile pheromones, particularly in vertebrates. The sexual behavior of male and female garter snakes is mediated by pheromones. The male sex identification pheromone includes squalene, but the female sex attractiveness pheromone of the Canadian red-sided garter snake, *Thamnophis sirtalis parietalis*, has a unique sequence of nonvolatile saturated and monounsaturated long-chain methyl ketones. Field testing has shown that these isolated, recognized, and partly synthesized chemicals are physiologically active [4].Even among closely related species, the Lepidoptera use a wide variety of pheromone structures. The puzzle is how signal divergence happens. It is unlikely that transitions to pheromones with various structures occur via adaptive modifications in modest increments because of the significant normalizing selection pressure on blend composition and response preferences. Here, we show evidence in favor of the theory that activation of a desaturase gene transcript found in the pheromone gland led to a significant change in the pheromone of an *Ostrinia* species. We also show that there are uncommon men who react to the novel pheromone mixture. They would make it possible to follow male reactions asymmetrically to the new mix, leading to the emergence of an *Ostrinia* species with structurally distinct sex pheromone components [5].

In regards to the presence of pheromonal communication, data on humans has caused the most debate. The likelihood of pheromonal communication in humans is evaluated in this review with a discussion of chemical substances produced by the axilla that may serve as pheromones, the likelihood that the vomeronasal organ (VNO), a putative pheromone receptor organ in many other mammals, is functional in humans, and the potential functions of pheromones in humans. The human axilla resembles other primates' smell glands

Table 1: Types of pheromones and functions.

Types of pheromones	Functions	References
Releasers	These cause a prompt, precise response. They are short-acting and are often linked to sexual attraction.	[65]
Signalers	These release information about the animal.	[7]
Modulators	These are found in sweat and impact emotions. They influence emotions and moods.	[66]
Primers	These impact endocrine or neuroendocrine responses connected to development and reproduction.	[24]

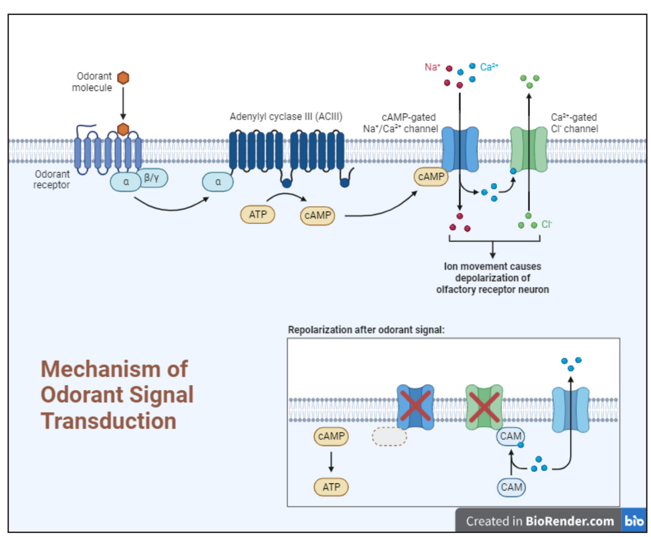

Figure 1: Molecular mechanism of odorant signal transduction.

due to interactions between the axillary secretions and cutaneous microorganisms. Axillary secretions in humans have a chemistry that is similar to other mammalian pheromone systems, and they also have similar effects on conspecifics. The receptor is another unidentified element of whatever chemical molecules have pheromonal effects on people. There is abundant evidence to support the idea that the olfactory epithelium may react to pheromones, despite the fact that the VNO has been linked to the receipt of pheromones in many vertebrates. The VNO is only one avenue by which this information might reach the central nervous system. Additionally, a chemical need not be a pheromone just because it causes the VNO's receptors to light up. The fact that crucial elements usually present in the functional VNO of other nonprimate animals are absent in humans is a significant caveat, indicating that the human VNO may not work as other mammals' VNOs have been reported to. Pheromones are categorized as releasers, modulators, signalers, and primers from a larger viewpoint. The first three can definitely be found in humans, according to strong evidence. Examples include influences on the menstrual cycle (primer effects), the mother's ability to recognize her infant by scent (signaler), and the possibility that people may emanate distinct odors depending on their emotions (suggestive of modulator effects). In mature humans, releaser effects are not supported by solid data. It is noteworthy that no bioassay-guided research project has succeeded in isolating genuine human pheromones, a step that would clarify the precise roles of human chemical signals [6].

2.2. Alarm Pheromones

Different creatures release alarm pheromones as a chemical warning in the presence of danger or threat. Conspecifics are forewarned by these signals, prompting an immediate and well-coordinated defensive reaction. Alarm pheromones have been well explored in several species and are important in a variety of ecological and evolutionary circumstances. Alarm pheromones cause a variety of behaviors to be triggered in reaction to a perceived threat. They may trigger defensive responses in social insects, such as the mobilization of the colony to fight or repel predators. Alarm pheromones in fish may cause predator-avoidance actions like running away or looking for cover. These reactions are often well-coordinated and crucial to the group's survival [7].Alarm pheromones aren't only used by prey species. Alarm cues may also be used to a predator's advantage. For instance, certain predatory insects, such as ladybirds, are known to find their prey by making use of the alarm signals of aphids. Due to these complex ecological interactions, it is now possible for different species to respond differently to the same chemical stimuli. Academic research on alarm pheromones is one of many fields of study. Understanding these chemical signals may help with pest control and agriculture in real-world situations. Researchers and farmers may create ways to interfere with the communication of nuisance insects by understanding their alarm pheromones, possibly minimizing crop damage.

In other situations, specific pheromones may also be traded. The release of a biological substance by a member of any species to warn conspecifics of potential danger is one example of such an occurrence. Alarm pheromones (APs) are the biochemical signals that are emitted during this activity, which often occurs when an organism is in danger or under attack from a predator or its environment [8]. Many animals employ alarm signals to warn conspecifics, although their methods vary. Some animals utilize auditory warning calls, others visual or chemosensory cues, or a mix of both [9].

2.3. Aggregation Pheromones

Various species use aggregation pheromones to recruit conspecifics and establish groups. Insects, animals, and certain plants use these chemicals to coordinate social behavior and interactions. Insect aggregation pheromones are well studied. Bark beetles use aggregation pheromones to settle on host trees to mate and deposit eggs. VOCs in these pheromones are sensed by conspecifics from afar. Bark beetle aggregation pheromones are complex chemical mixtures that attract and govern behavior. These pheromones frequently include numerous components that attract and coordinate insects, according to studies.

Aggregation pheromones are perceived via several sensory modalities. Olfaction is the main way insects perceive chemical stimuli. Insect antennae and appendages have specialized sensors to detect pheromone trails. In rats, the vomeronasal organ in the nasal cavity detects aggregation pheromones. Neural responses from these pheromone receptors affect behavior, such as mating or foraging [10]. Not just animals use aggregation pheromones. Certain plants produce volatile chemicals to attract herbivores that eat their tissues. When attacked by herbivorous insects, maize plants release volatile chemical substances. Herbivore enemy parasitic wasps use these chemicals as aggregation pheromones. Chemical signals attract wasps, which hunt on herbivorous insects and defend maize. The ecological and evolutionary effects of aggregation pheromones must be understood. Aggregation pheromones impact species distribution and density in ecosystems. Social insects like ants emit aggregation pheromones to create forage and defense colonies. This aggregation may cause ecological processes to cascade.

The evolution and use of aggregation pheromones may affect species' fitness and survival. Complex social systems evolve as those who can react to aggregation pheromones profit from group life and collaboration. Plants may evolve aggregation pheromones to guard against herbivores, which can affect herbivore evolution and drive chemical cue and response mechanism development [11]. Aggregation is much harder. It shows the aggregation and even permanence of people at a given position at the endpoint level. Although aggregation may be the result of attraction and arrestment or, in certain situations, inadvertent arrival and arrestment, it does not immediately suggest a navigational system. Thus, odor-induced aggregation may be characterized by an endpoint distribution. The phrase "aggregation pheromone" refers to a variety of behaviors with different orienting mechanisms, behavioral and ecological purposes, and evolutionary factors. One way to distinguish aggregation pheromones from typical sex-attractants is to limit them to circumstances when both sexes react, or when the responder's sex is the emitter's.

Some bark beetles (*Scolytinae*) use aggregation pheromones to attack the victim in bulk. One sex generates a pheromone that attracts the other for mating and attracts both sexes of beetles. The collective onslaught weakens the tree, increasing the beetle's chances of survival. Finding a partner precedes host colonization and drives orientation selection [12]. Certain creatures, especially social insects like ants and termites, employ trail pheromones as chemical signals to communicate and coordinate movement within a group. These pheromones act as a trail for other animals to follow, facilitating effective resource exploitation, navigation, and foraging. These pheromones may arise from a single gland or, in some rare situations, from a mixture of two glands. They can be made up of a single compound or, in one extraordinary example, a blend of as many as 14 compounds. They could be unique to a particular species or might be shared by many species. They are found by workers at trace levels on a trail and are present in glandular secretions in nanogram to picogram concentrations [13]. According to definitions, trail-laying is a field activity in which an insect marks a path with smell or odor traces so that other insects in the same group may follow it [14].

Scout ants locate food to start trails. When it returns to the nest after feeding, it leaves chemicals. It attracts additional workers in unknown ways within or outside the nest. It may include antennal touch, regurgitation, jerking, or another odor that gets workers to leave the nest. Recruitment is now recognized as part of the chemical process of trail-following. Recruitment is communication that brings nestmates to work. The hired laborers follow the food trail. Returning food-laden workers strengthens the path. When the food runs out, and the workers return empty, they stop applying trail stuff, and the odor disappears. Thus, the route survives only as long as needed [15]. Social insect societies utilize a variety of tactics for adaptation and optimization, but one prominent one is the application of trail pheromones. Foraging and navigation efficiency are vital to the colony's survival and reproduction. Many ant and termite species have thrived due to improved trail pheromones and higher sensitivity. Some species use social insect trail pheromones, which is intriguing. Parasitic ants or kleptoparasites may follow host ants to food sources without foraging. These ecosystems have intricated evolutionary interactions and adaptations among species.

2.4. Territorial Pheromones

Territorial pheromones are chemical signals used by a variety of species to create and defend territories. They are an essential component of chemical communication in the animal world. These pheromones have been the focus of in-depth ethological investigation because they play a crucial function in a variety of ecological and evolutionary circumstances [16]. The complex chemical molecules that make up territorial pheromones provide unique information about the identity, sex, and health of the territorial owner. Specialized glands, which are found in varied forms throughout animals, may manufacture these substances. For example, it is known that the sebaceous or urine glands of animals are providers of territorial pheromones. Urine markings are often used by rats to define territorial boundaries. These distinctive smell signals in the markings provide information about the identity of the bearer and its propensity to protect the area [17]. Territorial pheromones have a crucial role in ecology. They control who has access to resources, lessen the likelihood of direct disputes, and support ecological equilibrium. For instance, territorial marking with urine and scent markings helps large cats, who are territorial carnivores, designate their hunting territory and minimize interactions with possible rivals. This reduces potentially fatal confrontations and frees up energy for essential tasks like hunting.

Intraspecific territoriality may affect population dynamics, dispersion patterns, and resource use. Territorial pheromones are often the mediators of intraspecific territoriality. Chemical signals have a crucial role in controlling foraging and resource exploitation in social insects like ants because territories are not only about space but also about resources. Understanding the spatial organization of populations and their interactions in natural environments requires an understanding of territoriality and territorial pheromones [18]. There are several practical uses for knowing territorial pheromones. Researchers have looked at the possible use of artificial territorial pheromones in agriculture to control insect populations or prevent animals from entering certain regions [67-69]. Understanding territorial behavior in animals may help conserve biodiversity by designing protected areas and habitat corridors.

3. CHEMISTRY AND MOLECULAR MECHANISM OF PHEROMONES

3.1. The Chemical Structure of Pheromones

Pheromones have a wide range of chemistry. Simple molecules like fatty acids or more complicated ones like proteins may make up these compounds. Pheromones often have high volatility, which makes them readily dissipate. Thanks to this, they may then be transferred to other animals via the wind or water.

Bombykol: Bombykol, the sex pheromone of the silkworm moth, has the molecular formula $C_{16}H_{32}O$ and is a straightforward alcohol. It has an indistinct flowery smell and is an oily liquid without color [19]. (Z)-9-Tricosene: (Z)-9-tricosene, the honey bee alarm pheromone, has the molecular formula $C_{23}H_{46}O_2$. It is a waxy, colorless material that smells faintly like grass [20]. Castoreum is a pheromone that is mostly contained in beavers' anal glands. Fatty acids, ketones, and alcohols are among the many different substances that make up this combination. Phenylacetaldehyde, which has a powerful, sweet scent, is the main ingredient in castoreum [21]. Androstenone: Both male and female humans manufacture androstenone, a steroid hormone. The liquid has no color or smell. However, some individuals can smell androstenone at extremely low levels, and they often describe it as having a sweaty or musky smell [22]. Male conspecifics are released or attracted by chemical signals sent by the female gametes of marine brown algae. Most of these substances are unfunctionalized, acyclic, or alicyclic C_{11} hydrocarbons. The mixes may include a variety of enantiomer combinations as well as configurational isomers of the real pheromones. Dodeca-3,6,9-trienoic acid is used to make C_{11} hydrocarbons in higher plants; brown algae use the icosanoids family to make the same chemicals. The biosynthetic pathways include a number of spontaneous pericyclic processes, including [3.3]-sigmatropic rearrangements, [1.7]-hydrogen shifts, and electrocyclic ring closures. All pheromones are (a)biotically destroyed by common oxidative processes involving singlet oxygen or hydroxyl radicals, which may be generated by the action of heavy metals, humic acids, or light [23]. The cuticular hydrocarbons pentacosane and heptacosane, the fatty acids palmitic acid and trans-vaccenic acid, cholesterol, and the aromatic molecule 2-phenyl undecane make up the pheromone [24].

3.2. The Process of Pheromones Being Detected by Receptors

The sensilla-specific macromolecules that bind and break down pheromone molecules must be well understood in order to comprehend the molecular basis of pheromone sensing. The four types of enzymes that break down pheromones are (a) tissue- and substrate-specific, (b) tissue-specific but nonspecific for pheromone components, (c) broadly dispersed but pheromone-specific, and (d) broadly distributed and nonspecific enzymes. Only enzymes that are localized in pheromone-receiving tissues and those that are selective for pheromone molecules (independent of tissue location) are allowed to be used. Presence of at least two different kinds of proteins that may reversibly bind pheromones: a plentiful, soluble sensillum lymph protein with low molecular weight and weak binding affinity and a small number of membrane-associated macromolecules with stronger binding affinity [25].Superior analytical chemists are insects. Semiochemicals provide them with heightened perception. Signal translators are antennas. Mostly on the antennae, the sensilla transforms chemical cues into brain language (nerve impulses or spikes). The brain receives this information for processing. The insect olfactory system efficiently distinguishes natural pheromones from compounds with slight structural alterations. Some stereoisomers are attractant sex pheromones, and their antipodes may restrict behavior.

Two filters provide the olfactory system specialization. Odorant binding proteins (OBPs) let hydrophobic pheromones penetrate an aqueous barrier and reach their receptors, determining the first round of discrimination. OBP and OR contribute to cell response specificity and provide the insect olfactory system's exceptional selectivity. There are several olfactory and non-olfactory proteins in the OBP-gene family that encode encapsulins. While many family members' duties are unknown, OBPs' way of acting is well established. Upon encapsulation by odorant-binding proteins, pheromones and other semiochemicals enter the sensilla lymph via cuticle pore tubules and are delivered to olfactory receptors. Pheromone-bound molecules are safe. A conformational shift in the OBP-ligand complex causes pheromone ejection from negatively charged dendritic membrane locations. As odorant molecules directly activate odorant receptors, spikes are generated. A new idea of reverse chemical ecology screens attractants using OBPs' binding capacity to evaluate compounds [26].

The molecular foundation of pheromone response and behavior. The molecular mechanics of pheromone reception are modeled using changing equilibrium states in chemical reactions. This kinetic equilibrium model postulated a multifunctional binding protein, a unifunctional esterase, and potential receptor proteins. Pheromone molecules with these qualities, according to this model PBP solubilize pheromone molecules into the lymph after they enter the sensory hair via pore tubules and enter the internal lymph space. Once solubilized, the pheromone moves through the proteinaceous phase of the sensory hair lymph until it encounters a receptor molecule, enzyme, or other binding site. (4) The pheromone molecule has a finite lifetime within a sensory hair, allowing it to activate receptor molecules repeatedly until it is degraded by an enzyme molecule; (5) The relative concentrations of the protein species involved and their kinetic properties determine this lifetime and the sensory hair's dynamic response to pheromone stimulus; and (6) The multifocal proteins are involved [27].

3.3. Pheromone Synthesis and Release

In the current molecular model of insect olfaction, some receptor proteins in a dendritic membrane detect pheromones in a minimum-energy configuration after their passage through the extracellular sensory fluid, which is mediated by binding proteins. The second messenger, inositol 1,4,5-trisphosphate (IP3), is released in a brief pulse after binding to the receptor protein and activating a G-protein-linked phospholipase C. IP3 may mobilize Ca^{++} ions via its receptor, which finally results in a transmembrane ion current. Alternatively, IP3 may directly gate the ion channel [28]. The production and release of pheromones is a difficult process that currently needs to be better understood. However, in recent years, researchers have made considerable strides and created a number of techniques for generating and releasing pheromones in insects and animals.

3.4. Pheromone Synthesis in Insects

The sex pheromone gland, the Dufour's gland, and the mandibular gland are only a few of the glands in insects that produce pheromones. Depending on the kind of insect, different glands generate different pheromones. Hormones often control the production of pheromones in insects. The juvenile hormone and the pheromone biosynthesis activating neuropeptide, for instance, control the generation of sex pheromones in female moths. A multitude of methods are used to release pheromones into the environment once they have been created. Pheromones may be released by certain insects directly from their glands, while others do so use specialized structures like pheromone brushes or pouches [Figure 2] [29].

The olfactory receptor neurons, which are essential to the olfactory system, have odorant signal transduction mechanisms that are shown in detail in the figure that is given. One of the most important first steps in detecting scents is the binding of an odorant molecule to a particular odorant receptor located on the cell membrane. The process by which ATP (adenosine triphosphate) is transformed into cAMP (cyclic adenosine monophosphate) is catalyzed by this binding event, which activates Adenylyl cyclase III (ACIII). The opening of cAMP-gated Na+/Ca2+ channels are the outcome of the subsequent rise in cAMP levels. This means that while chloride (Cl–) ions are facilitated in their escape from the cell, the channel opening permits the entry of sodium (Na+) and calcium (Ca2+) ions. These channels' ion movements are essential because they depolarize the olfactory receptor neuron, which is the first stage in the production of a nerve impulse. The messages from the olfactory receptors must go through this electrical activity in order to reach the brain and be processed as different smells. The process guarantees that the neuron returns to its resting state by lowering cAMP levels after detecting an odorant. This reduction causes the Na+/Ca2+ channels to close and the C1−channels to open, which encourages the cell to repolarize.

4. PHEROMONE RELEASE IN INSECTS

4.1. The Following are a Few Instances of Pheromone Emission in Insects

Sexual pheromones found in moths Sex pheromones are released by female moths to entice males. The sex pheromone gland of the female moth produces the pheromones, which are then dispersed via a pheromone brush. The pheromones emitted by female moths may be detected by male moths thanks to unique pheromone receptors on their antennae. Alarm pheromones produced by honey bees When attacked, honey bees emit alarm pheromones. The pheromones are created in the Dufour's gland of the honey bee and released when the bee stings or stings itself. Other bees are alerted to the threat by the alarm pheromones, which also set off a protective reaction. Ants produce trail pheromones that they emit to mark their paths. The pheromones are created in the Dufour's gland of the ant and released as it moves. The pheromone trail may be followed by other ants to locate food or their nest [30].

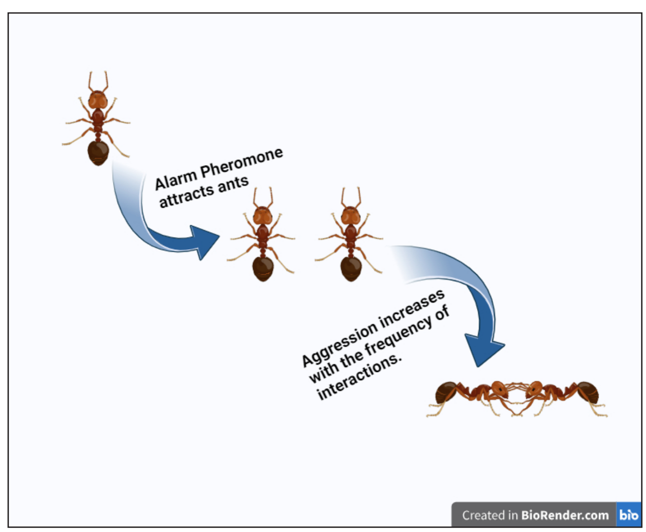

Figure 2: Pheromones and their activation process in insects.

Table 2: Comparison between animal, human, and plant pheromones.

Category	Animal pheromones	Human pheromones	Plant pheromones	References
Definition	Chemical signals are produced by animals to communicate	Chemical signals are produced by humans, though debated	Chemical signals are produced by plants to interact with their environment	[63]
Chemical nature	Typically, volatile organic compounds (VOCs) or proteins	Controversial, not fully established	Aromatic compounds, terpenes, and volatile organic compounds (VOCs)	[23]
Functions	Mating attraction and readiness, Territory marking, Alarm and defensive signals, Aggregation and coordination, social organization	Potential role in sexual attraction (controversial, Emotional communication (pheromonal impact on mood, etc.)	Defense against herbivores, Attracting pollinators and seed dispersers, Signaling environmental stress or damage.	[1]
Perception	Detected through specialized chemoreceptors, often in olfactory organs or antennae	Controversial, debated among scientists; some claims of detection through the vomeronasal organ.	Detected by neighboring plants, as well as by herbivores and pollinators through olfaction	[27]
Examples	Sex pheromones in insects, Territorial markings in mammals, Alarm pheromones in ants, trail pheromones in social insects |	Controversial, potential role in social bonding and mate attraction	Release of volatile organic compounds (VOCs) in response to herbivore attacks, Floral scents to attract pollinators, Release of allelopathic compounds to inhibit neighboring plant growth	[12]
Role in Ecology	Crucial for species survival, communication, and ecological interactions	Subject to ongoing research, there is limited evidence of direct effects	Essential for plant-pollinator interactions, herbivore deterrence, and environmental adaptation	[52]
Production	Produced by various glands or secretory structures in animals	Proposed production in specialized glands and skin secretions	Produced by different plant tissues, including leaves, flowers, and roots	[29]
Scientific study	Well-documented and extensively studied in animal behavior	Controversial and less established in human biology	Growing areas of research in plant biology and chemical ecology	[16]

4.2. Pheromone Synthesis in Mammals

Pheromones are produced by a number of glands in animals, including the apocrine, sebaceous, and mammary glands. The particular pheromone-producing glands depend on the type of animal. Hormones also control the creation of pheromones in animals. For instance, the sex hormones estrogen and progesterone control the synthesis of sex pheromones in female animals [31].

An intriguing feature of ant behavior—more particularly, how they react to alarm pheromones—is depicted in the image. An alarm pheromone is first released by a single ant, and it functions as a chemical signal to draw additional ants to its position. Ants become more aggressive as a result of increased interaction during the collection of additional ants. An important aspect of any communication and group behavior is this increase in aggression, which allows the ants to quickly gather and respond angrily to any perceived threats. This technique guarantees a prompt and coordinated response to threats, which greatly increases the colony's chances of survival.

4.3. Pheromone Release in Mammals

A multitude of methods are used to release pheromones into the environment once they have been created. Some animals produce pheromones directly from their glands, whereas others do so from more specialized sources, such as urine or scent marks [Table 2].

4.3.1. Here are some instances of mammal pheromone release

Canine scent-marking: Dogs communicate with one another via scent-marking. Their feces and pee both emit pheromones. The sex, age, and social standing of the dog may be revealed by these pheromones. Other canines are able to recognize these pheromones and utilize them to learn more about their surroundings [32]. Human moms emit pheromones from their nipples and breasts, which is known as the "maternal pheromone" in humans. These pheromones encourage nursing and strengthen the attachment between the mother and child. These pheromones may be picked up by babies, who then utilize them to locate their mother's breast. Research on the production and release of pheromones in insects and animals has advanced significantly in recent years.

4.3.2. Here are some instances of recent scientific advancements

Novel pheromones discovered: In insects and animals, researchers have discovered a variety of novel pheromones. New pheromone-based products for pest control and other uses have developed as a result of this.

Development of new pheromone synthesis techniques: Modern pheromone synthesis techniques have been improved upon by scientists to be more effective and affordable. As a result, pheromones may now be produced in enormous numbers for use in industry [33]. Creating new pheromone release techniques: New pheromone release techniques have been created by scientists that are more precise and efficient than earlier techniques. The effectiveness of pheromone-based pest control solutions and other uses has increased as a result.

5. PHEROMONES IN HUMANS

5.1. Human Pheromones and Their Existence

Axillary steroids, vaginal aliphatic acids, and stimulators of the vomeronasal organ are the three kinds of potential human pheromones that have received the majority of attention in the search for evidence of these substances. Examples from each of these groups have been patented for use in commerce and, in some instances, actively promoted, although there is insufficient proof to back up any specific claim that a drug behaves as a human pheromone. Although the enormous axillary scent glands in humans are ideally suited for pheromone generation, they may also be employed for non-pheromonal odor communication, such as the exchange of immune system-related information. The presence of human pheromone systems may be suggested by hypothesized menstrual synchronization among social groups of women and hypothesized acceleration of the menstrual cycle brought on by the scents of males, although the evidence in both situations is still ambiguous [34].

Pheromones may be released from the skin into the environment via two different methods. According to one theory, putative pheromones are very volatile. If there are any odorous molecules on the skin, they will volatilize and be inhaled by someone nearby. The idea that relatively non-volatile pheromones found on or connected to the skin surface may naturally be delivered by the skin itself is a more intriguing prospect [35].

5.2. Pheromones and Sexual Attraction

Increasing data suggests that pheromones have a significant impact on human sexual attraction. For instance, research revealed that women exposed to the perspiration of males in optimal physical shape assessed them as more appealing compared to women exposed to the perspiration of men who were not in optimal physical shape. A further study revealed that males who were exposed to the fragrance of an artificial pheromone known as androstenone had an increased inclination to approach and engage in flirtatious behavior with females. The detection of pheromones occurs via the vomeronasal organ, situated in the palatal region behind the incisors. The vomeronasal organ transmits messages to the brain, which then interprets these signals and subsequently affects behavior. Pheromones are believed to have various effects on sexual desire. Initially, they may effectively heighten individuals' awareness of one another's existence. Additionally, they have the potential to stimulate the secretion of hormones that enhance sexual pleasure. Furthermore, they have the potential to shape individuals' evaluations of one another's physical appeal.

5.3. Below are Many Study Publications That Have Examined the Influence of Pheromones on Human Sexual Attraction

This study examines the research supporting the influence of pheromones on human sexual attraction. The authors' conclusion asserts the presence of compelling data demonstrating the capacity of pheromones to have an impact on human behavior, including the realm of sexual desire [36]. This study presents a thorough and extensive examination of the existing research on pheromones and their impact on human behavior. The author's conclusion is that the data on the influence of pheromones on human sexual attraction remains inconclusive; however, there is an increasing body of evidence indicating their involvement [37].

According to this meta-analysis of 28 studies, pheromones do indeed have a modest but noteworthy influence on human sexual desire. Women had a more pronounced impact compared to men. According to this comprehensive study and synthesis of 44 investigations, it was shown that pheromones may have a modest but noteworthy impact on human sexual desire. The impact was more pronounced in males than in females. This study presents a thorough examination of the existing body of research on pheromones and their role in human mating. The author's conclusion is that the data on the influence of pheromones on human sexual attraction remains inconclusive. However, there is an increasing body of evidence indicating their involvement [38].

In general, the study of pheromones and sexual attraction is now in its preliminary phase, although there is increasing evidence to indicate that pheromones do indeed have an impact on human sexual attraction. Further investigation is required to have a deeper comprehension of the mechanisms by which pheromones operate and their potential for augmenting sexual allure. Aside from the aforementioned study publications, many further studies have examined the influence of pheromones on human sexual desire. Several of these studies have had favorable outcomes, while others have yielded unfavorable outcomes. The collective assessment remains inconclusive; nevertheless, the available research strongly indicates that pheromones do really have an influence on human sexual desire.

5.4. Pheromones and Social Behavior

This research examined the impact of artificially produced human male pheromones on the sociosexual behavior of males. Thirty-eight heterosexual males, aged 26 to 42, participated in a 2-week initial period followed by a 6-week trial. The experiment was placebo-controlled and double-masked, evaluating a pheromone specifically created to enhance the romantic aspects of their lives. Each participant maintained a daily log documenting their engagement in six sociosexual behaviors: stroking, affection, kissing, formal dates, informal dates, sleeping next to a romantic partner, sexual intercourse, and self-stimulation leading to ejaculation (masturbation). These logs were faxed on a weekly basis. A much higher number of individuals using pheromones saw an increase in sexual intercourse and sleeping with a romantic partner compared to those using a placebo. There was a higher inclination for those using pheromones compared to those using a placebo to have an increase in petting, affection, kissing, and informal dating, but not in self-stimulation leading to ejaculation or in formal dates. A considerably greater percentage of those using pheromones, compared to those using a placebo, exhibited a rise in at least two, three or more of the five sociosexual activities with a female partner. Consequently, there was a notable rise in male sociosexual activities influenced by a woman's sexual desire and collaboration but no increase in male masturbation, which only involves the guy. The preliminary studies need replication but indicate that human male pheromones influence the sexual appeal of males to women [39].

5.5. Pheromones in Plants

Plant pheromones include a wide range of chemicals, and their precise function is only sometimes fully known. Nevertheless, ongoing

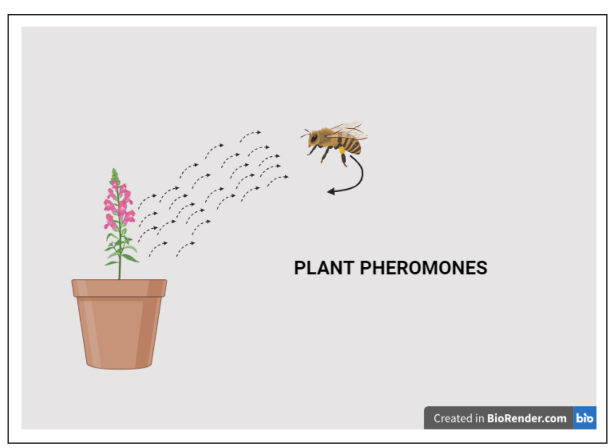

Figure 3. Plant pheromones and their behavior.

research in this field is progressing swiftly, revealing the significant involvement of plant pheromones in several plant functions, such as:

Pollination: Plant pheromones have the ability to allure pollinators towards flowers, thereby facilitating effective pollination and reproduction. Defense against herbivores and pests: Plant pheromones serve as a means to alert neighboring plants of potential threats, deter herbivores and pests, or entice predators that prey on herbivores and pests.

Interplant competition: Plant pheromones may be used to hinder the growth or prevent the germination of rival plants. Interactions with other creatures: Plant pheromones facilitate communication with other organisms, including beneficial bacteria and fungi, to foster mutually advantageous relationships.

The symbiotic relationship between a bee and a blooming plant, which is made possible by the release of plant pheromones, is shown in full in the image. This process is started by a blossoming plant with pink blooms, which release plant pheromones, which are shown in the illustration as dotted lines. Pheromones are chemical signals that travel through the atmosphere and allow plants and possible pollinators to communicate with one another. A bee is lured to the plant when it detects these pheromones because of the chemical signals. A key component of plant-pollinator dynamics is this interaction, in which the plant uses these chemical cues to draw in bees and other pollinators. These pollinators are then essential to the plant's pollination process and subsequent reproduction.

5.6. Several Instances of Plant Pheromones Include

Methyl jasmonate is a pheromone emitted by plants when they are harmed by herbivores or pests. It serves as an attractant for predators that prey on herbivores and pests while simultaneously functioning as a warning signal to neighboring plants [40]. The compound is (Z)-3-hexene. The compound is named (Z)-3-hexen-1-ol. -1-ol is a pheromone secreted by some plants' roots to attract advantageous microbes and fungi. These bacteria facilitate the absorption of nutrients by plants from the soil and provide protection against illnesses [41]. (E)-2-hexenal is a pheromone emitted by some plants to signal the presence of rival plants. This may elicit the secretion of defensive chemicals from the rival plants [42].

5.7. Utilization of Plant Pheromones

The use of plant pheromones has significant promise for many applications in the fields of agriculture and horticulture. Plant pheromones may serve several purposes, such as enhancing pollination in crops; pheromone lures may be used to attract pollinators, specifically targeting fruit trees and vegetable crops. Implementing this technique may enhance agricultural productivity and the quality of crops.

Prevent infestations and infections: Pheromone traps may be used to ensnare pests, while pheromone repellents can be utilized to discourage pests and illnesses from assaulting crops. Enhance plant growth and development: Plant pheromones have the potential to enhance plant growth and development, as well as enhance plants' ability to withstand stress. Volatile Organic Compounds (VOCs): The process by which plants emit chemical compounds that have the ability to attract pollinators, deter herbivores, and facilitate communication between plants [43].

Plants emit chemical substances via many mechanisms, such as: Plants exude chemicals into the soil via their roots. These substances possess the ability to allure advantageous microorganisms, deter pests, or impede the sprouting of rival plants. Plants emit chemical substances into the atmosphere via their foliage. These chemicals possess the ability to allure pollinators, deter herbivores, or transmit signals to neighboring plants. Flowers emit a diverse array of chemical substances in order to allure pollinators. The compounds include nectar, fragrances, and pigments. Plants synthesize a diverse array of chemical compounds to lure pollinators. The compounds include nectar, fragrances, and pigments. Nectar is a viscous solution containing sugars that is secreted by flowers. It serves as nourishment for pollinators, including bees, butterflies, and bats. Aromas: Flowers emit a diverse range of aromas in order to allure pollinators. These fragrances might possess a sweet, flowery, or even fruity aroma. Flowers use color to allure pollinators. Certain flowers exhibit vibrant hues to lure pollinators from a distance, but others possess more subdued tones that captivate bees at close range.

5.8. Deterrence of Plant-Eating Animals

Plants also synthesize a diverse array of chemical substances to deter herbivores. These chemicals possess toxicity, an unpleasant taste, or the ability to cause irritation in the digestive tract of herbivores. Phytotoxins: Certain plants synthesize phytotoxins that are toxic to herbivorous organisms. As an example, the foxglove plant synthesizes a chemical known as digitalin, which is toxic to cardiac muscle [44]. Unpalatable chemicals: Some plants generate substances that have an unpleasant taste for herbivores. As an example, the milkweed plant generates a chemical known as cardenolide, which has a distinctly bitter flavor. Aggravating substances: Certain plants generate chemicals that provoke irritation in the digestive tract of herbivores. As an example, the chili pepper plant generates a chemical known as capsaicin, which causes irritation to the mucous membranes of the mouth and stomach [45].Plants use chemical molecules to engage in communication with other plants. When a plant is subjected to herbivore assault, it has the ability to emit chemical compounds that serve as a warning to other plants about the imminent threat. Subsequently, other plants have the capability to synthesize defensive chemicals as a means of safeguarding themselves from herbivorous organisms. Plants use chemical molecules to compete with each other. For instance, several plants emit chemical substances that impede the development of other plants that are in competition with them. Allelopathy: exploring how some plants release chemicals to inhibit the growth of nearby competing plants. Plants have the ability to generate and emit allelochemicals, which may disrupt the establishment and development of both similar and different plant species. Allelopathy has a crucial role in facilitating interactions between different plant species in both natural and controlled settings. The primary emphasis of this study is to examine the phenomenon of allelopathy and the role of allelochemicals in grasslands and forests. Allelopathy is the main factor behind plant invasion, worsens the deterioration of grasslands, and plays a role in the natural regeneration of forests. Moreover, pastures and tree plantations often experience autotoxicity, which refers to intraspecific allelopathy. Phenolics, terpenoids, and nitrogen-containing chemicals found in herbaceous and woody species have a role in allelopathy in grasslands and forests. Terpenoids, which have a wide range of metabolites, are qualitative allelochemicals found in annual grasslands. On the other hand, phenolics, which have a limited number of specialized metabolites, are quantitative allelochemicals found in permanent forests. Crucially, allelochemicals have a role in underground ecological interactions and plant-soil feedback, which in turn have an impact on the biodiversity, productivity, and sustainability of grasslands and forests. Allelopathic plants have the ability to distinguish the identity of neighboring plants

Table 3: Comparison of pheromone products and their claims.

Product	Manufacturer	Claims	Reference
Athena Pheromone Oils	Athena Pheromone	Contains human pheromones to attract mates, boost confidence, and reduce stress.	[64]
Evo-Science Pheromone Sprays	Evo-Science	Contains human pheromones to attract mates, increase social status, and improve mood.	[54]
Pheromone XS	Pheromone XS	Contains human pheromones to attract mates, increase sexual attraction, and boost self-esteem.	[22]
True Pheromones	True Pheromones	Contains human pheromones to attract mates, increase social intelligence, and reduce anxiety.	[1]
Alpha Male Pheromones	Alpha Male Pheromones	Contains human pheromones to attract women, increase dominance, and boost confidence	[55]

by means of signaling molecules, which allows them to regulate the production of allelochemicals. Hence, allelochemicals and signaling chemicals work together in a synergistic manner to control both interactions between different species and interactions within the same species in grasslands and forests. The study of allelopathy and allelochemicals in grasslands and forests has yielded valuable knowledge on the interactions between plants and their impact on biodiversity, productivity, and sustainability. This research has significantly enhanced our understanding of terrestrial ecosystems and global environmental changes. Allelochemicals include a wide range of plant secondary metabolites, mostly categorized into three groups: phenolics, terpenoids, and nitrogen-containing substances [Table 3]. Phenolics are found in many different parts of plants and consist of a varied collection of molecules that have an aromatic ring with at least one hydroxyl group and maybe other additional groups, such as simple phenolic acids, coumarins, flavonoids, and quinones. Within forest ecosystems, a significant quantity of lignin derived from decaying organic matter undergoes decomposition, resulting in the formation of diverse phenolic acids. The lignin-derived phenolic acids are the primary allelochemicals found in forest soil, which result in a decrease in the quantity and richness of forest species [46].

Terpenoids, such as monoterpenes, sesquiterpenes, diterpenes, triterpenes, and steroids, are a group of molecules that originate from the 5-carbon isoprene. Monoterpenes and their derivatives exhibit high volatility and may interact with nearby plants in their gaseous form. The release of volatile allelochemicals by donor plants primarily affects neighboring plants via two primary mechanisms: the formation of "terpene clouds" that directly influence certain target plants [16] or the leaching of these chemicals into the soil, indirectly affecting other target plants. The volatile compounds produced by *A. frigida* include a large amount of terpenoids, namely the monoterpene camphor, which plays a significant role as an allelochemical in influencing nearby species [47]. Nitrogenous substances mostly include alkaloids, nonprotein amino acids, benzoxazinoids, and cyanogenic glycosides. Nitrogen-containing allelochemicals are less familiar compared to phenolics and terpenoids. Nevertheless, a number of distinct nitrogen-containing metabolites have been recognized as allelochemicals, that possess noteworthy ecological ramifications for grasslands and forests. Hexadecahydro-1-azachrysen-8-yl ester [Figure 3], which has been discovered as a possible alkaloid allelochemical in *Imperata cylindrica*, has the ability to inhibit root development and diminish mycorrhizal colonization [48]. There are various nonprotein amino acids involving allelopathic interferences with co-occurring species in grasslands. The presence of meta-Tyrosine in fine fescue grasses (*Festuca rubra*) might hinder the growth of other plants by inhibiting root formation [49].

6. PHEROMONES IN PEST CONTROL:

Pesticides have been shown to be an inadequate remedy for managing insect infestations. Pheromones have potential as a component of integrated pest control. The principal insect pests acquired resistance as a result of repeated and excessive applications of the pesticide. Pheromones and other behavioral compounds were crucial in the implementation of integrated pest control. The first need is to comprehend the behavior of a certain insect pest. Regrettably, the examination of insect behavior remained neglected for a considerable period, as most entomologists focused on practical applications such as spraying and quantifying. Subsequently, the chemist is required to precisely delineate the chemical message to a sufficient extent for practical applications. Furthermore, it is necessary to provide the chemical components and an efficient delivery mechanism, as well as conduct comprehensive field investigations. Additionally, the Environmental Protection Agency must get approval for the distribution system to be registered. Furthermore, it is essential to provide the industry with compelling motivation to actively participate. Furthermore, it is essential that experts get a comprehensive education in the field of chemical ecology, while technicians should undergo rigorous training. Competently educated county agricultural extension agents might fulfill a significant function in the United States [50]. An encouraging development is that the Environmental Protection Agency (EPA) has recently acknowledged that there is a significant difference in the way pesticides are applied. Specifically, there is a distinction between spraying large amounts of a harmful pesticide to kill insects and releasing small amounts of a biodegradable substance in the form of vapor to attract insects to a trap or disrupt their mating process. The EPA suggests classifying pheromones as "biorational pesticides" and has implemented more practical registration criteria. Some individuals who adhere strictly to a certain viewpoint may contend that pheromones are substances that affect behavior and should not be classified as pesticides or toxicants, despite the word "biorational" being used to describe them in a more positive light. Employing pheromones is an exceptionally secure method, even when administered by severely misled individuals [51]. The field of chemical ecology, specifically focusing on pheromones and other semiochemicals that impact insect behavior, offers potential techniques for pest management as substitutes for the exclusive reliance on wide-ranging poisonous substances. Nevertheless, in order to fully harness the potential of semiochemicals in crop protection, it is imperative to develop a deeper understanding of insect/insect and insect/plant interactions, as well as the broader field of insect chemical ecology. When used in isolation, semiochemicals frequently provide inadequate or inadequately strong pest control. Therefore, the use of semiochemicals should be linked with other methods to enhance management techniques. The key elements of these tactics are pest surveillance for precise scheduling of pesticide applications, the use of semiochemicals, host plant resistance, trap crops to alter pest behavior, and the use of selective insecticides or biological control agents to diminish pest populations. The goal is to integrate these tactics into a push-pull or stimulo-deterrent diversionary strategy (SDDS). Within an SDDS (Sustainable Disease and Pest Management System), the crop that may be gathered is safeguarded by the application of host-masking agents, repellents, antifeedants, or oviposition deterrents. Simultaneously, aggregative semiochemicals, such as host plant attractants and sex pheromones, promote the colonization of pests on trap crops or their admission into traps, where diseases may be discharged. Due to the relatively low efficiency of the individual components of the SDDS, they do not greatly favor the development of resistance compared to traditional toxicant pesticides. This inherent characteristic of the SDDS contributes to its higher sustainability [52].

The study involves the presentation of twelve models to assess the viability of using pheromone-baited traps with chemosterilant for pest management. It aims to compare the effectiveness of this approach with (i) pheromone-baited traps containing insecticide and (ii) sterile releases. Research revealed that the quantity of matting per person has little impact on the effectiveness of population management. However, the introduction of even a small number of pest species via immigration significantly hampers the capacity of this strategy to regulate the population. The presence of density-dependent regulation significantly boosts the efficacy of this control approach. If the birth rate significantly surpasses one offspring per adult each day, then the use of chemosterilants is almost twice as effective as either insecticide in the pheromone traps or the introduction of sterile males. However, if the birth rate is far lower than one per day, as shown in tsetse, chemosterilants are considerably more effective than either strategy. The variations in relative efficiency seem to be contingent upon the frequency of mating in relation to the rates of birth and death [53].

7. HUMAN PHEROMONE PRODUCTS

During a double-blind and placebo-controlled investigation, some individuals had the artificially created potential pheromone incorporated into their scent. The primary findings of the research indicate that a considerably larger percentage of individuals in the experimental group exhibited an increase in the frequency of the dependent variables, namely sexual intercourse, sleeping close to a partner, formal dates, and petting/affection/kissing, compared to their initial baseline measurements. The scientists found that the chemical functioned as a pheromone, enhancing the appeal of women to males [54]. Pheromones derived from non-human mammals are often included as components in perfumes. The primary function of these compounds is to serve as a fixative or carrier for the olfactory properties of the other components while also contributing to the overall fragrance of the perfume. Perfumes are mostly used for their fixative and olfactory properties rather than their pheromonal impacts. However, they are often advertised as having the capacity to augment sexual allure. Although the act of delivering a smell might trigger a good and enjoyable reaction, it is important to note that this should not be mistaken for a pheromone response. The allure of fragrances is mostly attributed to the impact of their delightful fragrance. A more rational strategy would include using human pheromones, which are both more inherent and more efficient as genuine sensory stimulants for people. The use of this technique is expected to become a significant paradigm in the perfume business as perfumery transitions from being an art to a science.The most prominent constituents among these substances are muscone, which is synthesized by the musk deer (*Moschus moschiferus*), civetone and skatole, which are created by the civet cat (*Viverra civetta*), and castoreum, which is made by the Canadian beaver (*Castor fiber*). These chemicals were first derived from the anal sacs of these animals. Chemical synthetics have replaced this process and are now widely used in the perfume business. The compounds are used in perfumes primarily as fixatives or carriers for the aroma of other components, and they also contribute, to some extent, to the overall smell of the perfume.A genuine pheromone will stimulate an increase in sexual desire, although a fragrant perfume may provide some degree of sensory pleasure. One would anticipate that the impact of pheromones would be more significant and seductive. Differentiating between the effects of pheromones and scents may be achieved by evaluating variations in receptor binding or activation, provided that the receptors for these substances are distinct [55].

8. SYNTHETIC PHEROMONES

The production of pheromones is a difficult endeavor due to the intricate nature of pheromone molecules. Scientists have devised many techniques for producing pheromones, including chemical synthesis, which is the predominant approach used for synthesizing pheromones. The process involves using chemical processes to synthesize the targeted pheromone molecule. This technique is applicable for the production of a diverse range of pheromones; however, it may be intricate and costly. Enzymatic synthesis refers to a more recent approach used in the synthesis of pheromones. The process entails using enzymes as catalysts to facilitate the chemical processes responsible for synthesizing the targeted pheromone molecule. This approach has superior efficiency and reduced cost compared to chemical synthesis, while its use remains relatively limited. Biological synthesis is the least prevalent approach for synthesizing pheromones. The process involves using live organisms, such as bacteria or yeast, to synthesize the specific pheromone compound. This technology is now in the process of being developed; nevertheless, it has the potential to become the most efficient and economical approach for producing pheromones on a large scale.The primary objectives of synthesis in pheromone science are twofold: (1) to confirm the hypothesized structure, including the exact configuration, and (2) to provide an adequate quantity of samples for biological research and effective pest management [56]. The availability of synthetic pheromones allows for conducting extensive field experiments to create eco-friendly pest control methods. Due to their possible uses in pest management, insect pheromones are highly sought after for the creation of synthetic methods. The synthesis of these chemical messengers, which are distinct to each species, has been a central focus of extensive study in the area of pheromone chemistry. This review provides a comprehensive list of the synthesized compounds and focuses on the latest techniques in organic synthesis, including carbon-carbon coupling reactions, organo-transition metal chemistry (such as ring-closing olefin metathesis), asymmetric epoxidations and dihydroxylations, and enzymatic reactions [57].

9. ORGANIC SYNTHESIS

It is crucial in pheromone chemistry because it supplies the necessary materials to accurately determine the (absolute) configuration of molecules and conduct comprehensive biological experiments [58]. The insect pheromones now recognized are relatively simple compounds consisting of fewer than four asymmetric centers and four functional groups. Thus, the most suitable substrate (whether chiral or achiral) for most of these structures is a somewhat functionalized molecule, namely hydroxy- and amino-acids, along with monoterpenoids. The last category of compounds is the most readily available for this series and is particularly advantageous for creating molecules with a branching carbon structure, namely isoprenoid pheromones. Oxidative techniques for converting monoterpenoids are the most practical and extensively used ways for conducting diverse transformations of initial molecules and including a broad range of functional groups. The stated synthetic processes include allylic oxidation using selenium dioxide, functionalization of monoterpenoids using epoxidation, and ozonolysis [59].

The fast synthesis of a limited selection of lepidopteran sex pheromones, such as 8E,10Z-tetradeca-8,10-dienal 5c, from the horse chestnut leaf miner (*Cameraria ohridella),* is achieved by the shuffling of two basic building blocks and a regioselective transfer hydrogenation. The dialdehydes 1a-e9 underwent a twofold Wittig reaction with the commercially available phosphonium salt 2, resulting in the formation of the R-unsaturated diene dials 3a-e10 with high yields. It is important to mention that the process of converting to more stable E-enols by acidic hydrolysis of the R- unsaturated acetals is known as isomerization. The needed trials were obtained with acceptable selectivity (Z/E > 9:1) but in poor yield by performing a second Wittig reaction using 0.8 equivalents of the necessary alkyl phosphonium salt. The procedures included in this study included the synthesis of R,α-dialdehydes three from the corresponding dialdehydes, the synthesis of trienals four from the corresponding R- unsaturated dialdehydes 3, and the synthesis of pheromones five by conjugate reduction from the corresponding trienals [60]. Commercial Applications: Discuss how synthetic pheromones are used in products like perfumes, colognes, and air fresheners.

In the context of commercial pig production, it is common practice to mix piglets together after they have been weaned. However, this may lead to intense conflict among the piglets, causing physical harm, disturbances in their eating patterns, and hindered development. Utilizing a synthetic mother pheromone may be regarded as a valuable tool in the array of measures aimed at mitigating aggressiveness and ensuring the well-being of groups of weaned pigs, particularly in situations where mixing is inevitable [61]. Invasive ants, such as the Argentine ant, are often shown to support honeydew-producing hemipteran pests like mealybugs, which may transmit plant infections. The use of synthetic pheromones might provide a precise approach to managing these ants, thereby reducing the prevalence of honeydew-producing pests. The findings indicate that the strategic placement of pheromone dispensers might effectively decrease the foraging activity of Argentine ants in grapevines. This technology has the ability to decrease the population of mealybugs and the spread of viruses they carry over a vast region [62-64].

10. CONCLUSION

In conclusion, this study has offered a thorough summary of the function of pheromones in many biological situations. As chemical messengers, pheromones are essential for inter-organism communication because they have an impact on behavior, physiology, and ecology. The latest research demonstrates the intricate function that biochemical signals like pheromones play in both immune response induction in other species and interspecies communication. It emphasizes how important it is to comprehend these chemical signals, their origins, and their wider effects on ecosystems and human health [70]. The findings included in this review have brought attention to the diversity and complexity of pheromone communication in many species and have clarified the processes behind pheromone synthesis, reception, and the ensuing behavioral reactions. With continued study into the chemical identification, synthesis, and useful uses of pheromones, the subject of pheromone research is also constantly evolving. As a result, the potential for pheromone-based pest management and agricultural techniques is growing, providing sustainable solutions for a variety of sectors. Future research will uncover new complexity levels in the intriguing realm of chemical transmission among living beings. Pheromones continue to be a fascinating topic of study with significant ramifications.

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12. AUTHOR CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agreed to be accountable for all aspects of the work. All the authors are eligible to be an author as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

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The authors report no financial or any other conflicts of interest in this work.

15. ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

16. DATA AVAILABILITY

All the data is available with the authors and shall be provided upon request.

17. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

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