



Insect growth regulators for sustainable agriculture and public health: A review

Lipsa Dehal¹, Aakanksha Malhotra^{2*}

¹ Research Scholar, Department of Zoology and Environmental Sciences, Punjabi University, Patiala, Punjab, India

² Department of Biology, D.A.V. Centenary Public School, Mandi, Himachal Pradesh, India

Abstract

Insect growth regulators (IGRs) are a class of environmentally benign insecticides that disrupt the natural growth and development of insects by targeting certain hormonal and metabolic processes. Finding affordable and ecologically friendly pest control options is essential to addressing the issues brought on by the frequent and careless application of traditional pesticides. Insect Growth Regulators are among the efficient substitutes. In contrast to traditional broad-spectrum insecticides, IGRs work selectively by either disrupting with structural processes like chitin production or by imitating or suppressing hormones like juvenile hormone and ecdysone. IGRs are sophisticated, bio-rational pesticides. By causing aberrant molting, aborted metamorphosis, fertility, or mortality, these behaviors lower pest populations with little negative impact on the environment or beneficial creatures. Understanding the molecular underpinnings of biosynthetic or endocrine signaling pathways has facilitated advancements in IGR development, which are reflected in this Special Issue. Targeting arthropod-specific processes and molecular targets ideally to more specific insect taxa that serve as pest or disease vectors is the unifying principle. Moreover, a variety of agricultural and public health pests have been effectively controlled by IGRs like methoprene, pyriproxyfen, lufenuron, and diflubenzuron. The methods of action, target pathways, new advancements in dual-acting compounds, and the potential of IGRs as a key component of integrated pest management (IPM) are all highlighted in this study. IGRs offer a sustainable substitute for chemical pesticides by fusing selectivity with efficacy, supporting contemporary approaches to managing resistance and long-term insect suppression.

Keywords: IGRs, insecticides, endocrine disruption, juvenile hormone analogue, ecdysone receptors, sustainable

Introduction

Insect growth regulators (IGRs) also known as insect hormones are compounds which suppress the growth, development and metamorphosis of insects. IGRs include synthetic analogues of insect hormones such as ecdysoids and juvenoids and non-hormonal compounds such as precocenes (Anti JH) and Chitin synthesis inhibitors (Masih and Ahmad, 2019) [33]. Most of IGRs are pest specific without harming vertebrates. From insect nervous tissue about 40 insects - neuropeptides have been isolated. These neuropeptides disrupt essential physiological processes in insect required for their growth and development. Herath *et al.*, 2024 [20] observed that IGR have been introduced as potential alternatives to control dengue vector populations. Among IGRs novaluron is considered as an active agent for insect larval control worldwide. IGR affects reproductive system in males and females along with their fertility, oviposition and eggs hatching.

First account of potential uses of IGRs in insect control was in 1956, then juvenile hormone (JH) was isolated from abdominal crude extract of male cecropia moth *Hyalothor aceropia* which prevented metamorphosis in them and resulted in reduction of the insect. IGRs are effectively used in pest management like Ecdysoids which form defective cuticle and result in integuments without scales and wax layers. Juvenoids (JH mimics) results in extra moulting producing super larvae. It keeps larvae in juvenile condition. Prococenes (Anti JH) rupture corpora allata and prevent JH synthesis. Chitin synthesis inhibitor inhibits activity of chitin synthetase. Diflubenzuron and penfluron are two important compounds of this category. Studies of (Masih and Ahmad, 2019) [33] states that IGRs are widely used as a pest control in soyabean, cotton, apple, fruits, vegetables, forest trees,

mosquitoes and pest of stored grains. IGRs used to evoke transovarian activity. Adults exposed to IGR will produce non-viable eggs. Insect Growth Regulators such as methoprene and pyriproxyfen were first developed and introduced in 1970s as third generation pesticides which interfere with gene expression during metamorphosis, the juvenoid IGRs can prevent development and emergence of adult mosquitoes like *Culex pipiens*, *Aedes aegypti* and *Aedes albopictus* that are major mosquito vectors and responsible for wide spread of Zika, Chikungunya, West nill virus and dengue fever (Clifton and Lopez, 2025) [11]. Insect Growth Regulators IGRs are biochemical biopesticides naturally occurring that are nontoxic to environment and humans (Krishnamoorti, 2024) [27]. To achieve high crop yield during Green revolution was the ultimate goal. To grow healthy crop Integrated Pest Management (IPM) was encouraged for use of IGRs. Many studies showed pyriproxyfen, Novaluron, Lufenuron, Buprofezin and flubendiamide at different concentration effectively work against *B. cucurbitae* (Melon fruit fly) (Kainat *et al.*, 2025) [23]. In an experiment effective use of IGRs such as sitara (buprofezin), Viper (buprofezin), Lufenuron, Pyroxyfen, Priority (pyriproxyfen) and Track (lufenuron) were studied against maize stem borer as a significant pest of maize causing substantial yield loss. Among them Pyriproxyfen and Priority had most potential on hampering the growth and development of Maize stem borer. According to Insect Growth Regulator Market Report 2025, The, Insect Growth Regulator market size has grown strongly in recent years. It will grow from \$1 billion in 2024 to \$ 1.08 billion in 2025 at a compound annual growth rate (CAGR) of 7.5%. The growth in the historic period can be attributed to growing pest problems, environmental concerns, regulatory support, and advancement in formulations. IGRs

are good alternatives for organic farming as it is pest-specific. Due to growing needs of organic crops there will be expand in Insect Growth Regulatory market.

Insect growth regulators (IGRs) with disruptive effects on critical life physiological processes such as molting, metamorphosis, or reproduction have emerged as promising alternatives to conventional insecticides in the light of increasing concerns on pesticide resistance, environmental sustainability, as well as mandated targeted pest control. In the present review, we discuss the molecular mechanisms, sites of action, development, and practical applications of IGRs and underscore the role of IGRs as an efficacious and environmentally friendly component of modern pest management strategies.

Classification

Insect growth regulators are effective insecticides that interfere with the growth and development of insects. Their classification is primarily based on their mode of chemical composition, action and target specificity. IGRs can be broadly classified into Juvenile Hormone Analogues, Ecdysone Agonists, Chitin Synthesis Inhibitors, Ecdysone Antagonists, Ecdysteroid Synthesis Inhibitors. The comprehensive classification of IGRs is outlined in Fig. 2.

1. Juvenile Hormone Analogues

Juvenile hormone (JH) is a unique sesquiterpenoid hormone which regulates both insect metamorphosis and insect reproduction. It can be used by some insects to facilitate polyphenisms and other life history events that are environmentally regulated (Riddiford, 2020) [44]. It control metamorphosis by conserving larval stage in insects and afterwards when the larvae attain its size there is decline in expression of gene Kruppel homolog 1 (Kr-h 1) which will suppress metamorphosis. A mimic of JH was introduced in 1966 by Williams and Slama from wood pulp of balsam fir tree *Abies balsams* and named it as Juvenile Hormone Analogue (JHAs). JHA were framed as third generation insecticides due to their insect specific action. They prevent metamorphosis in insect and are a good alternative over 1st

and 2nd generation insecticides for controlling insect causing damage to crops. The World Health Organization recommends the use of methoprene treatment of water near dwellings for mosquito control. JHa, methoprene was registered as a biological pesticide by the USA EPA in 1975 but was re- classified later as biochemical pesticide (Palli, 2021). Studies showed role of Fenoxycarb (JHA) in the European lobster, *Homarus gammarus*. The European lobster was pollutant mostly in pelagic zone in shallow ocean. When they were treated with fenoxycarb their metamorphosis seized and they remain in their zoel stage. The juvenile hormone market has been experiencing steady growth due to the increasing demand in various agricultural and industrial applications. Juvenile hormones, which play a critical role in the regulation of insect development, are primarily utilized in pest control and crop protection products. Juvenile Hormone Market size stood at USD 1.2 Billion in 2024 and is forecast to achieve USD 2.5 Billion by 2033, registering a 9.2% CAGR from 2026 to 2033.

2. Ecdysone agonists (Molting Hormone Agonists)

Ecdysone is a hormone present in insect that stimulate metamorphosis and regulate molting in insect. Ecdysone agonists were classified as IGR that mimic insect molting hormone ecdysone and interrupts insect’s developmental cycle. It stimulates premature molting leading to death of insect. Ecdysone agonists bind to ecdysone receptor EcR and protein ultraspiracle USP then afterwards a sequence of events starts leading to premature and incomplete molting in insects. Studies of (Cui *et al.*, 2024) showed role of Tebufenozide as an effective IGR against Lepidopteran pests. It leads to early molting in insect by binding to EcR. Role of IGR (halofenozide = RH – 0345) was studied on larvae of *C. pipiens*. The study revealed that RH- 0345 induced precocious larval molting in them leading to their death. Methoxyfenzide showed remarkable impact as an efficient IGR by controlling growth of *Aedes aegypti* major vector of arboviral disease such as dengue, chikungunya, Zika and yellow fever. It disrupts development and chitin synthesis of them (Kumae *et al.*, 2025).

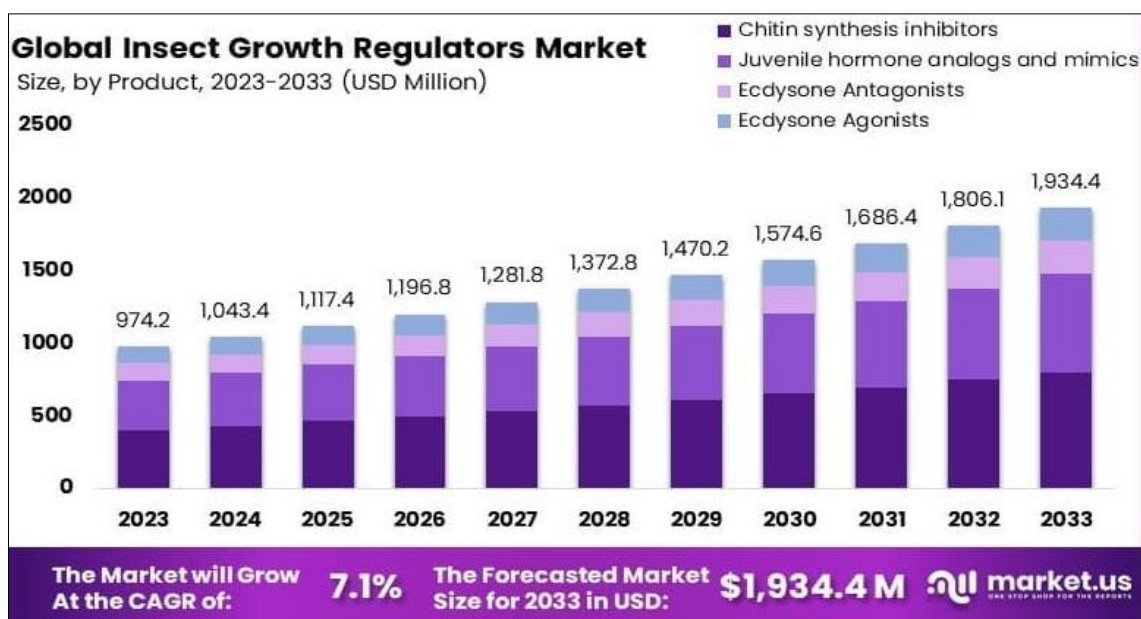


Fig 1: Report: Insect Growth Regulators Market Trends.

3. Chitin Synthesis Inhibitor

Chitin synthesis is critical for insects because chitin is important to maintain insect's shape, protecting it from predation, injury. It is the main component of exoskeleton, tracheal and internal tendon cuticles (Muthukrishnan *et al.*, 2020) [39]. Chitin synthesis inhibitors are effective against growth and development of arthropods. Arthropods shed and replace their old exoskeleton (cuticle) with a new one by the process called molting. The cuticular chitin synthetase (CHS-1) plays an important role in this. The chitin synthesis inhibitors do chemical inhibition of (CHS-1) leading to increase mortality in arthropods. The linkage between chitin

synthase 1 inhibition and mortality in arthropods was called Adverse Outcome Pathway (AOP).

Diflubenzuron affected larval-larval and larval-pupal molting of *Tribolium castaneum* (red flour beetle). The insect developed with defect in walking and died early (Kumari *et al.*, 2010) [29]. The effect of IGR was studied on Neotropical brown sting bug, *Euschistus heros* a pest that destroy soyabean in large part of central west region of Brazil. A study conducted by showed the results of novaluron, tefluzuron and lufenuron on fourth instar nymphs of *E. heros* under laboratory and greenhouse. The result was quite prominent as it hampers development and reproduction of the brown sting bug leading to its death.

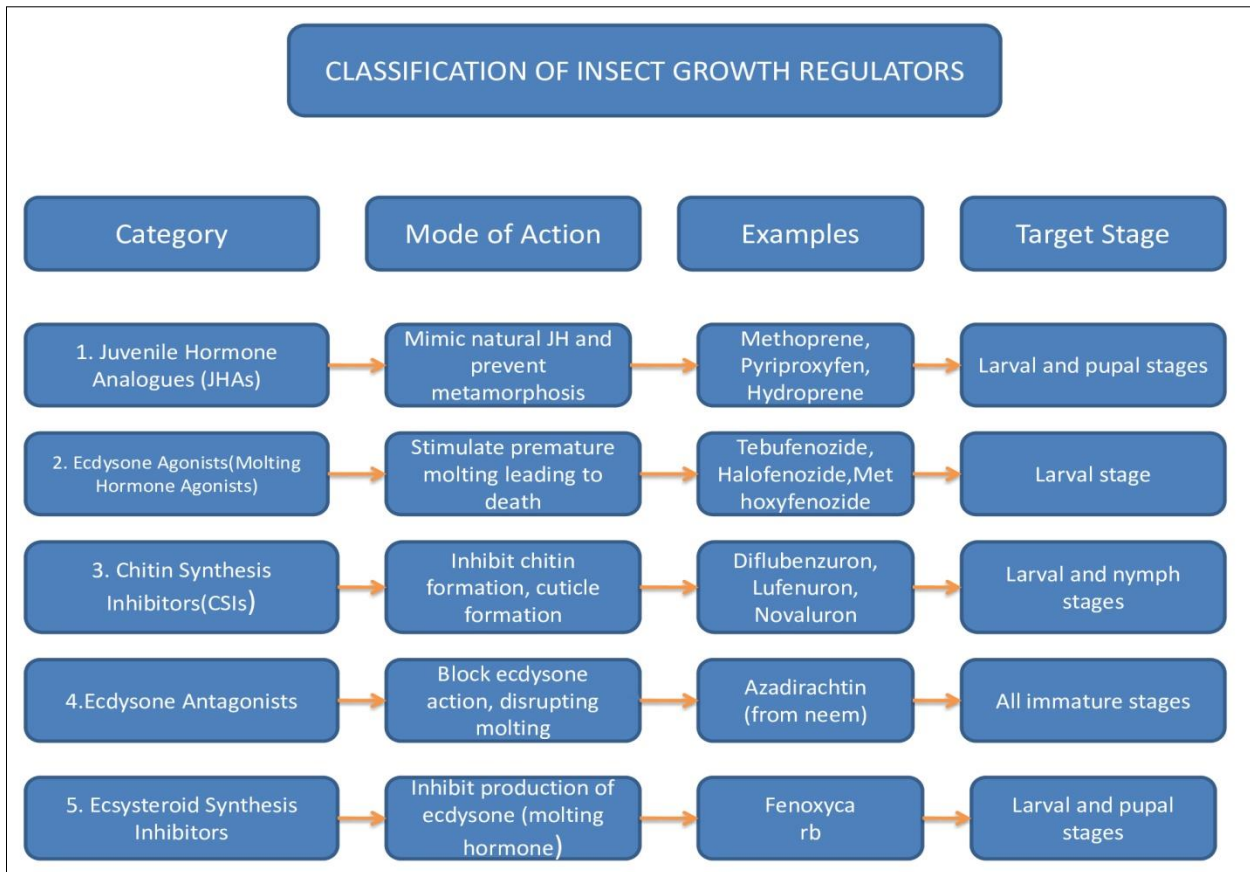


Fig 2: Different types of IGRs and their mode of action

4. Ecdysone antagonists

Azadirachtin was isolated from neem and proved to be the main bioactive metabolite responsible for various biological activities. It is used as an effective IGR as it hampers insect's growth and mortality of insect's larval stage. It leads to fecundity, wingless adult, incomplete molting. It shows its effect on species like Lepidoptera, Diptera, Orthoptera, Hemiptera, Coleoptera and Hymenoptera. It also leads to reproductive deformities like ovarian development, egg viability of insects. Azadirachtin used to control arthropod species and also controls whiteflies along with control of aphids. Azadirachtin controls locusts and caterpillars by touch chemoreception (Bartelsmaei *et al.*, 2022).

5. Ecdysteroid Synthesis Inhibitors

Fenoxycarb inhibit brassinosteroids responsible for dark induced elongation in Arabidopsis. It was also reported that brassinosteroids contain azole whereas fenoxycarb were

without heterocyclic ring. Fenoxycarb have potential to interfere with the growth and longevity of adults of rice moth, *Corcyra cephalonica staint* (Krishna, 2020) [26]. It reduces egg hatching and effect their reproductive system. Among various IGRs fenoxycarb, methoxyfenozide, pyriproxyfen and tebufenozide work effectively against *E. elaeasa* larvae. Pyriproxyfen and fenoxycarb were most toxic for the insect. It reduced insect damaging oil palm leaves by inhibiting their feeding.

Targeted Disruption by Insect Growth Regulators (IGRs)

The main way that insect growth regulators (IGRs) work is by interfering with the hormones that control insect development. These substances cause death or sterility in insects by interfering with vital functions such molting, metamorphosis, and cuticle production as discuss ahead and summarized in Table 1.

1. Hormonal Disruption

IGRs mimic or suppress endogenous insect hormones, particularly juvenile hormone (JH) and ecdysteroids (molting hormones), which are required for normal growth and metamorphosis.

1.1 Juvenile hormone analogue (JHA): JHA insecticides are endocrine disruptors that mimic juvenile hormones (JHs) to interfere with insect hormone action. Exogenous JHA insecticides may have detrimental effects on crustacean growth and reproduction that are comparable to those seen in insects since the structure and functions of methyl farnesoate in crustaceans are similar to those of insect JHs. Methoprene and fenoxycarb, two JHA insecticides, have been shown to have toxic effects on the water flea *Moina macrocopa* (Hu *et al.*, 2020) [22]. Chronic exposure to these pesticides has been shown to shorten life expectancy, suppress body growth, reduce fecundity, and disrupt gene expression related to the JH signaling pathway, cuticle development, and the metabolism of carbohydrates, amino acids, and ATP. Furthermore, even in cases where the neonates were not exposed to the chemicals, JHA exposure hampered the growth and reproduction of the progeny of *M. macrocopa* exposed to JHAs. Variations in the expression of histone methylation-related genes suggest that epigenetic modifications could encourage transgenerational impairment in *M. macrocopa* (Du *et al.*, 2023) [13].

of malformed adults are the results of JHAs such as methoprene and pyriproxyfen, which artificially maintain high JH levels to block the transition from larval to pupal or adult stages as shown in Fig. 3.

1.2 Ecdysone Agonists: Tebufenozide and methoxyfenozide are examples of ecdysone agonists that attach to ecdysteroid receptors and cause premature or aberrant molting, which can be fatal (Carlson *et al.*, 2001) [9]. Ecdysone encourages larva-to-larva molts when there is sufficient JH; when there is insufficient JH, ecdysone encourages pupation; and when there is no JH at all, the adult forms. By preventing the conversion of larval tissues into adult tissues during the pupal stage, IGRs that block ecdysone have the potential to induce pupal death (Fig. 3). The molting hormone mimics (tebufenozide), which are ecdysone agonists that seem to interfere with molting by attaching to the ecdysone receptor protein, are among the IGRs created for commercial usage (Song *et al.*, 2017) [48]. They have been effective in controlling juvenile insect pests, particularly lepidopterans.

2. Interference with Molting, Pupation, and Metamorphosis

IGRs interfere with molting, pupation, and metamorphosis by upsetting the hormonal balance (Fig. 3), which makes them particularly potent towards holometabolous insects that undergo complete metamorphosis. IGRs interfere with the normal timing of development, such as by preventing pupal molting in *Aedes aegypti*, which results in incomplete or too early molting events, nonviable pupae, or deformed adult insects (e.g. wing deformities).

IGRs were more effective in influencing the eggs, larval, and pupal stages of *A. aegypti*. Pyriproxyfen had the highest inhibition of fresh egg hatching (80%), followed by Novaluron (66%) and Larvicol (62%). Compared to fresh eggs, the hatch inhibition of embryonated eggs was lower. Pyriproxyfen inhibited the hatching of embryonated eggs 69% of the time, Novaluron 59%, and Larvicol 39%. In terms of producing 98–100% larval mortality, Pyriproxyfen and Novaluron both outperformed Larvicol (39%). Both Pyriproxyfen and Novaluron fully stopped larvae from developing to the pupal stage. Larvicol prevented pupae from emerging as adults, despite having the lowest egg hatch and larval inhibition rates. When exposed to Pyriproxyfen and Novaluron solutions, they demonstrated a 70–89% mortality rate for *A. aegypti* larvae in their third instar (Fansiri *et al.*, 2022) [14]. When applied against the egg stages, all of the IGRs shown carry-on activity of reducing growth and mortality of the subsequent stages of development, although none of them were more efficient at the pupal stage (Micocci, 2025) [35]. Consequently, it is advised to apply IGRs to mosquito habitats as early as possible in the season, when the very early stages of the mosquito life cycle are still present.

3. Specific Targets and Biochemical Pathways

Insect Growth Regulators (IGRs) work by emphasizing particular hormonal and structural pathways that are necessary for the growth and reproduction of insects. The juvenile hormone receptor (Met), ecdysone receptor (EcR), chitin synthase, and other chitinases are important biological targets. When these targets are disrupted, molting, metamorphosis, and cuticle production are hampered, which

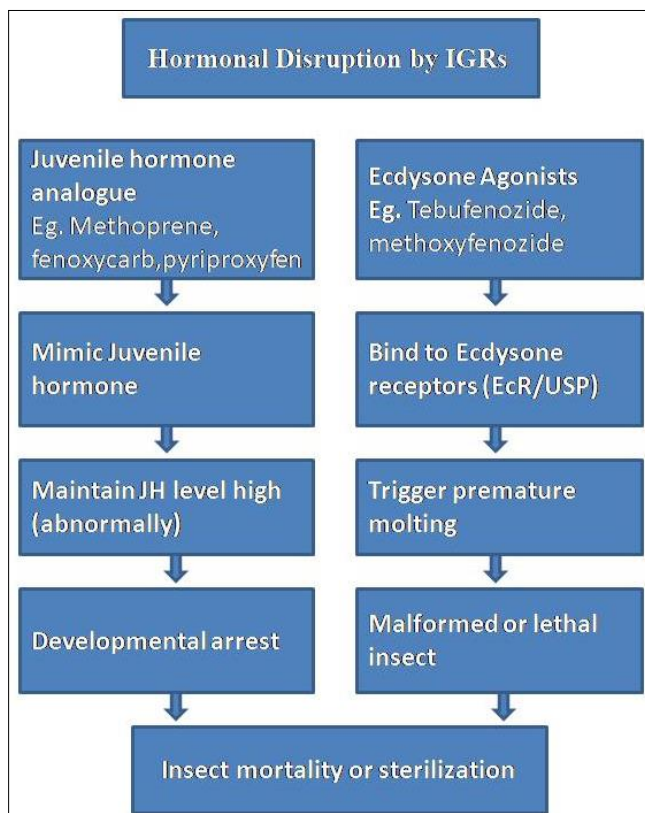


Fig 3: Hormonal Disruption by Insect Growth Regulators (IGRs)

It has been demonstrated that the strong JHA pyriproxyfen affects metabolic characteristics and reproductive processes in non-target crustaceans, such as *Moina* species, suggesting that the endocrine-mediated approach is not limited to target pests (Hu, 2019) [21]. Developmental arrest or the formation

eventually results in developmental arrest or death. Designing next-generation IGRs with enhanced selectivity and efficacy requires an understanding of these molecular mechanisms.

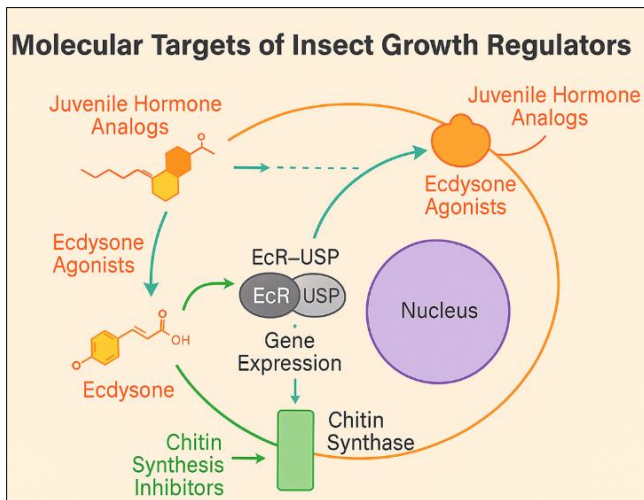


Fig 4: Molecular targets of IGRs

The Fig. 4 shows what the first orders of target are after exposure to IGRs that appear to disrupt both hormones and structure. At the heart of hormonal crosstalk are the two major receptors: ecdysone receptor (EcR) and juvenile hormone receptor (methoprene-tolerant, Met). Ecdysone agonists (e.g., tebufenozide) bind to EcR and interfere with the regular molting process, and the juvenile hormone analogs (e.g., methoprene, pyriproxyfen) bind to Met and maintain the juvenile state, as well as preventing the insect getting sexually mature. IGRs target chitin metabolism, which is necessary for the production of the exoskeleton, in parallel to endocrine disruption, as the diagram illustrates. Chitin synthase and chitinase inhibitors (ChI, OfChII, and OfChi-h) affect molting and structural integrity, which can result in death or unsuccessful ecdysis (Qu *et al.*, 2021) [42]. IGRs are effective yet selective pest control agents because of their combined activities, which eventually prevent productive growth, induce sterility, or cause mortality.

3.1 Endocrine disruption: Many insect growth regulators (IGRs) compromise with the hormonal balance necessary for insect development and their main route of action is endocrine disruption. The natural juvenile hormone is mimicked by juvenile hormone analogs including methoprene, pyriproxyfen, and hydroprene, which prolong larval stages or cause mortality by blocking metamorphosis (Parthasarathy and Palli, 2021) [41]. Tebufenozide, methoxyfenozide, and halofenozide are examples of ecdysone receptor agonists that bind to the receptor and cause aberrant or early molting (Fig. 1). Developmental psychology arrest, inability to pupate, or fatal abnormalities are the results of these disturbances. These IGRs are useful instruments for environmentally conscious pest management because they target hormone pathways unique to insects, making them extremely selective and posing little threat to non-target organisms.

3.2 Chitin synthesis inhibition: Chemicals that block chitin synthase enzymes, such as diflubenzuron, lufenuron, and novaluron, hinder the production of healthy cuticles

during molting (Morsli *et al.*, 2015) [38]. Chitin synthetase is the target site for the benzoylphenylurea analogs. By preventing the enzyme's catalyzed terminal polymerization step during the production of chitin, no chitin is formed, and insects perish from desiccation. Additionally, they prevent DNA biosynthesis and several other enzymes in larval cells (Merzendorfer and Zimoch, 2003) [34]. In addition to forming the exoskeleton and supporting the linings of the digestive tract, respiratory systems, reproductive ducts, and certain gland ducts, the cuticle of insects acts as a barrier between the living creature and its surroundings. Protein and chitin fractions make up the majority of its composition. The latter is the b-(1,4) glycoside polymer of N-acetyl-D glucosamine and is found in three different forms: a, b, and g chitin. Chitin is found in the cell walls of fungi and protozoa in addition to the cuticles of insects and crustaceans, but it is not found in vertebrates or higher plants. The extracellular chitin synthase enzyme, which is affixed to the plasma membrane, is responsible for the synthesis of chitin.

But in the endoplasmic reticulum of the epidermis, this enzyme is made as a zymogen (inactive), and in order to synthesize chitin, it must be activated by proteases. Proteases, along with other crucial regulatory stages in the biosynthesis of chitin, are prospective targets for regulation by specific chemicals since they are crucial for activating chitin production zymogens. Benzoyl phenylurea, diflubenzuron, was the first chitin synthesis inhibitor to be marketed as a new insecticide (Miyamoto *et al.*, 1993) [36]. It was thought to be a strong substance against the larvae of *Cydia pomonella* and *Spodoptera litura*, common cutworms. Some of the compound's derivatives, or structural changes, have higher levels of activity than the original (Su *et al.*, 2018). Diflubenzuron has been shown to be effective against Coleoptera and Diptera in addition to Lepidoptera (Ashouri *et al.*, 2014) [6].

Lufenuron, an oral chitin synthesis inhibitor, was also used to combat fleas. It affected the development of eggs and larvae and blocked chitin synthesis. Upon feeding on offlea dirt containing blood from the treated bug, female fleas biting animals treated with lufenuron generated sterile eggs and inhibited larval development. This observation was most likely caused by lufenuron, which is eliminated into the feces due to its lack of major metabolism. In a unique larvicidal assay, several classes of insect growth regulators were examined, including chitin synthesis inhibitors, juvenile hormone analogues, and one triazine derivative. With the exception of one strain that developed a considerable resistance to chitin synthesis inhibitors following years of intensive treatment with benzoylphenylureas, the chitin synthesis inhibitors were fairly effective against multi-resistant strains of *Musca domestica* (Ashouri *et al.*, 2014) [6].

3.3 Inhibition of reproductive maturation: Certain IGRs cause sterility or decrease egg production. By decreasing egg-laying or causing sterility, insect growth regulators (IGRs) have a major effect on insect reproduction in addition to interfering with molting and metamorphosis. Methoprene, pyriproxyfen, and hydroprene are examples of juvenile hormone analogs that disrupt vitellogenesis, the process by which yolk proteins are produced and

deposited in eggs, resulting in decreased fecundity or the creation of non-viable eggs (Glare and O'Callaghan, 1999) [16]. For example, it has been demonstrated that methoprene inhibits ovarian growth, which lowers oviposition in mosquitoes (*Aedes aegypti*) (Brabant and Dobson, 2013) [8]. Similarly, because pyriproxyfen can sterilize female mosquitoes even at low doses, it is frequently utilized in vector control operations. By interfering with the hormonal signaling required for

gamete maturation, certain ecdysone agonists, such as tebufenozide, can affect reproductive processes (Fansiri *et al.*, 2022) [14]. Furthermore, lufenuron and other chitin synthesis inhibitors can interfere with embryonic development, resulting in infertile eggs or unsuccessful hatching. IGRs are useful tools in integrated pest management (IPM) because of their reproductive effects, which reduce damage to non-target organisms while suppressing future pest populations.

Table 1: Summary for Insecticidal and Molecular Activity of IGRs

IGR	Target	Impact on insect	Compounds Examples	Risk to Non-Targets	References
Juvenile Hormone Analogs	Corpora allata, JH receptors	Larval-pupal arrest, abnormal adult development	Methoprene, Pyriproxyfen	Very low (mammals/birds)	Singh <i>et al.</i> , 2013 [47]; Hu <i>et al.</i> , 2020 [22]; Du <i>et al.</i> , 2023 [13]
Ecdysone Agonists	Binds EcR	Lethal molts, failed pupation	Tebufenozide, RH-5849	Minimal (high insect-specificity)	Carlson <i>et al.</i> , 2001 [9]; Song <i>et al.</i> , 2017 [48]
Chitin Inhibitors	Chitin synthase enzyme	Cuticle deformity, molting inhibition	Diflubenzuron, Novaluron, Lufenuron	Moderate (aquatic arthropods)	Ashouri <i>et al.</i> , 2014 [6] Morsli <i>et al.</i> , 2015 [38]; Hasnain <i>et al.</i> , 2023 [19]
Dual-function IGRs	EcR + Chitinases	Combined endocrine and exoskeletal disruption	Pyrazole carboxamides (e.g., I-17)	Not known yet	Guo <i>et al.</i> , 2024 [18]

Dual-Action compounds illustrate multi-target potential in pest species like *Plutella xylostella*, novel pyrazole carboxamide compounds have demonstrated action against the ecdysone receptor (EcR) as well as several chitinase enzymes (ChtI, ChtII, and Chi h), suggesting that hormone signaling and chitin degradation are targeted together. Successful molting is prevented by other IGR classes, particularly benzoylphenyl ureas (e.g., novaluron, lufenuron), which inhibit the enzymes that produce chitin in the cuticle (Guo *et al.*, 2024) [18].

3.4 Selectivity between Non-Target Organisms and Insects

The species uniqueness of IGRs is one of their most significant benefits. They target processes like chitin biosynthesis or hormone receptors unique to insects that are not present in vertebrates. Research has indicated that it is not harmful to fish, birds, mammals, or the majority of beneficial arthropods (Singh *et al.*, 2013) [47]. Risk evaluation in aquatic environments is necessary because certain IGRs (such as chitin synthesis inhibitors) may affect crustaceans or other arthropods in aquatic ecosystems. Numerous adverse externalities, such as pest resistance and environmental deterioration, highlight the use of traditional pesticides. Therefore, in order to achieve sustainable development goals, the use of biopesticides as substitute agrochemicals is advised. Biochemical biopesticides are known as insect growth regulators (IGRs). Biochemical biopesticides are actually natural chemicals (or precise synthetic analogs) with active components that control pests without harming the target pest, the environment, or people. Therefore, by controlling or blocking particular biochemical pathways or processes necessary for insect growth and development, pesticides with growth-regulating qualities may have a negative impact on insects.

Among the most promising IGRs are ecdysoids and juvenoids, which are JH mimics. Ecdysoids are artificial counterparts of natural ecdysone that, when administered to insects, cause faulty cuticle production, which results in death. Synthetic analogues of juvenile hormone (JH) are called juvenoids, or JH mimics. Juvenoids have an anti-

metamorphic effect on insects in their embryonic stages. In addition, anti-JH or precocenes that function as IGRs do so by killing *corpora allata* and inhibiting JH synthesis (Masih and Ahmad, 2019) [33]. In this sense, insect growth regulators have the potential to replace commercially available insecticides.

They cause little harm to mammals by taking advantage of physiological processes that are absent in vertebrates, such as chitin production or JH receptors. At environmentally relevant concentrations, JHAs have been shown to have detrimental impacts on *Moina macrocopa* reproduction, growth, and even heritable alterations, which may have an impact on non-insect arthropods, particularly aquatic crustaceans (Masih and Ahmad, 2019) [33]. Chitin-synthesis inhibitors such as lufenuron significantly decreased fecundity and egg hatchability in laboratory testing against *Bactrocera zonata*, highlighting both great target selectivity and chemosterile action in male and female adults (Hasnain *et al.*, 2023) [19].

Recent dual-action compounds illustrate multi-target potential in pest species like *Plutella xylostella*, novel pyrazole carboxamide compounds have demonstrated action against the ecdysone receptor (EcR) as well as several chitinase enzymes (ChtI, ChtII, and Chi h), suggesting that hormone signaling and chitin degradation are targeted together. Successful molting is prevented by other IGR classes, particularly benzoylphenyl ureas (e.g., novaluron, lufenuron), which inhibit the enzymes that produce chitin in the cuticle.

Applications of Insect Growth Regulators

Insect growth regulators (IGRs) are biochemical biopesticides, and in order to achieve sustainable development goals, it is advised to utilize biopesticides as substitute agrochemicals. Biochemical biopesticides are natural chemicals (or identical synthetic analogs) with active ingredients that control pests without harming humans, the environment, or the target bug. Therefore, by controlling or blocking particular biochemical pathways or processes necessary for insect growth and development, pesticides with growth-regulating qualities may have a negative impact on

insects. Commercially available pesticides may be replaced by insect growth regulators.

1. Agricultural and Stored grain Pest Management

IGRs, such as pyriproxyfen (a juvenile hormone analog) and lufenuron (a chitin-synthesis inhibitor), are used to eliminate pests like fruit flies and whiteflies from crops like cotton, vegetables, and cucurbits. A variety of insect growth regulators (IGRs) were tested against adults of *Prostephanus truncatus* in maize and adults of *Rhyzopertha dominica* in wheat (Kavallieratos *et al.*, 2012; Mahmoud *et al.*, 2022) [24, 31]. Tested IGRs include two juvenile hormone analogues (fenoxycarb and pyriproxifen), four chitin synthesis inhibitors (diflubenzuron, flufenoxuron, lufenuron, and triflumuron), one ecdysteroid agonist (methoxyfenozide), and a combination of both chitin synthesis inhibitors and juvenile hormone analogues. At doses of 5 ppm, all IGRs were highly effective (approx 88.5% suppression of progeny) against the tested species, whereas diflubenzuron at 25°C (*P. truncatus*) or lufenuron and pyriproxyfen (*R. dominica*) totally suppressed (100%) progeny production when applied at 1 ppm (Mahmoud *et al.*, 2022) [31].

Chemosterilant effectiveness against *B. cucurbitae* of five novel insect growth regulators (IGRs) at varying concentrations: Pyriproxyfen, Novaluron, Lufenuron, Buprofezin, and Flubendiamide. The most effective IGR was lufenuron, which decreased fecundity by 68.4% and adult emergence by 70.97%. Fecundity and emergence were also severely impacted by other IGRs (Ali *et al.*, 2020) [3].

Diflubenzuron has been shown to be effective against Coleoptera and Diptera in addition to Lepidoptera (Ashouri *et al.*, 2014; Ahmad and Shakeel, 2024) [2, 6]. Field crop mites and insect pests were well controlled by diflubenzuron and its derivatives, whereas beneficial insect species were largely unaffected. However, buprofezin, another inhibitor of chitin synthesis, was used to combat homopteran pests that attack fruit crops and specific species of Coleoptera and Acarina, such as nymphs of brown planthoppers, *Nilaparvata lugens* (Stal.), leafhoppers, *Nephotettix cincticeps* (Uhler), whiteflies, *Bemisia tabaci* (Gennadius), and scale insects, *Trialeurodes vaporariorum* (Westwood) (Abrol and Shankar, 2017; Zeng *et al.*, 2023) [1, 49].

2. Regulation of Urban and Structural Pests

To manage fleas, cockroaches, and ants, IGRs such as methoprene and pyriproxyfen are used in household sprays, dusts, pet products, and bait stations. Our knowledge of effective cat flea pest management has grown significantly as a result of the use of IGRs, such as methoprene and pyriproxyfen, to prevent egg hatching and larval development in the environment, as well as oral applications of lufenuron to disrupt egg viability. In order to control fleas inside homes, combination treatments using adulticides and IGRs disrupted the flea life cycle (Cermolacce *et al.*, 2023) [10].

Dicyclanil and chlorfluazuron, which have lethal concentrations of 0.78 and 0.3 ppm [LC95] in larval rearing media, are two more IGRs that are equally effective against cat fleas as methoprene and pyriproxyfen. Remarkably, pyriproxyfen and methoprene worked together to increase the effectiveness of the former against larval cat fleas. The pyriproxyfen: methoprene (10:1) combination was twice as

effective (LC₅₀ 0.20 ppfvmethoprene or pyriproxyfen by itself (Clifton and Lopez, 2025) [11]. Because of the synergism, each IGR could be used at lower concentrations and still be effective.

3. Veterinary Application

A JH analog and an IGR that affects insects' embryonic, larval, and reproductive stages is pyriprofen. It stops larvae from maturing into adults, which makes them incapable of procreating. Pyriproxyfen is frequently used in veterinary medicine to eradicate both indoor and outdoor ants and roaches as well as fleas from household pets (Anadón *et al.*, 2025) [4].

An active component in flea management, lufenuron is also used as an anthelmintic and in conjunction with milbemycin oxime to treat ringworm and heartworm (Lynn, 2008) [30]. Adult fleas receive lufenuron through the blood of their host after it has been deposited in the animal's body fat. It is spread by adult fleas through their blood to their eggs and to born larvae that consume their waste. One type of insect development inhibitor (IDI) is lufenuron. Adult fleas are not killed by lufenuron. It prevents insects from producing chitin, which is necessary for the development of a strong exoskeleton in larval fleas. Consequently, the flea's internal organs are exposed to air, causing it to succumb to dehydration shortly after hatching or molting. For cats to benefit from lufenuron, it must be administered orally once a month or by injection every six months (Nwonuma *et al.*, 2025) [40].

4. Vector Control

Aedes, *Culex*, and *Anopheles* eggs, larvae, and pupae were more effectively affected by IGRs such as pyriproxyfen, S methoprene, and novaluron (Rahman *et al.*, 2024) [43]. For up to 90 days, pyriprofen granules reliably produced 90–100% suppression of emergence (Deshpande, 1994) [12].

5. Integrated Pest Management (IPM)

Because of their ability to target juvenile stages, show species specificity, have relatively little damage to non-targets, and aid in delaying the development of resistance, IGRs are essential to IPM. Because of this, they work in tandem with biological toxins and other methods of control. The target pest, California red scale (*Aonidiella aurantii*), was reduced to undetectable levels on leaves by pyriprofen (Khozimy *et al.*, 2022) [25]. Compared to the parasitoid *Comperiella bifasciata* gathered on sticky cards, the California red scale parasitoid *Aphytis melinus* was more severely reduced by pyriproxyfen treatments. Lemon treatments only 33% of citrus limon infested with *A. melinus*-parasitic scales directly died, indicating that low host density was the cause of the population decline seen on sticky cards (Mohammed, 2020) [37]. California red scale was brought down to a very low but noticeable level with buprofezin.

Similar amounts of the parasitoids *A. melinus* and *C. bifasciata* gathered on sticky cards were reduced as a result of buprofezin treatments. Only 7% of the parasitoids died after treatments of lemons infested with *A. melinus*-parasitic scale, indicating that low host density was the cause of the population decline shown on sticky cards (Grafton-Cardwell *et al.*, 2006) [17].

Table 2: Applications of Insect Growth Regulators

Application	Target	IGRs	Outcome	References
Agricultural Pest Management	Whiteflies, fruit flies, aphids	Fenoxycarb, Pyriproxifen, Diflubenzuron	Impaired emergence and fertility	Kavallieratos <i>et al.</i> , 2012 ^[24] ; Mahmoud <i>et al.</i> , 2022 ^[31]
Stored grain Pest Management	Grain pests like <i>R. dominica</i>	Lufenuron, Fenoxycarb	Suppressed progeny	Ali <i>et al.</i> , 2020 ^[3] ; Zeng <i>et al.</i> , 2023 ^[49]
Urban and Structural Pest Management	Fleas, cockroaches, ants	Methoprene, Pyriproxifen	Intrupt egg hatching, Breaking pest life cycles	Cermolacce <i>et al.</i> , 2023 ^[10] ; Clifton and Lopez, 2025 ^[11]
Veterinary Ectoparasite Control	Fleas on pets, heartworm, ringworm	Pyriproxifen, Lufenuron	Long-term suppression of reproduction	Nwonuma <i>et al.</i> , 2025 ^[40] ; Anadón <i>et al.</i> , 2025 ^[4]
Vector Control	Aedes, Culex and Anopheles	pyriproxifen, S-methoprene, novaluron	Suppression of emergence	Deshpande, 1994 ^[12] ; Rahman <i>et al.</i> , 2024 ^[43]
Integrated Pest Management (IPM)	<i>Aonidiella aurantii</i> , <i>A. melinus</i> , <i>Comperiella bifasciata</i>	Pyriproxifen, Buprofezin	Sustainability and resistance delay	Mohammed, 2020 ^[37] ; Khozimy <i>et al.</i> , 2022 ^[25]
Mechanistic Benefits and Synergy	Flea control	Imidacloprid and pyriproxifen, Imidacloprid and methoprene	Prevent metamorphosis	Rust and Hemsarth, 2019 ^[45] ; Sarwar and Shad, 2021 ^[46]

6. Mechanistic Benefits and Synergy

Chitin synthesis inhibitors (diflubenzuron, lufenuron) interfere with the production of cuticles during molts, while juvenile hormone analogs (pyriproxifen, methoprene) imitate insect endocrine signals to stop metamorphosis (Sarwar and Shad, 2021) ^[46]. Methoprene and pyriproxifen combinations exhibit synergism, reducing LC₅₀ values and improving residual efficacy in flea control. Imidacloprid and methoprene were synergistic against larval fleas, as were imidacloprid and pyriproxifen (Rust and Hemsarth, 2019) ^[45].

Conclusion

Most synthetic insecticides are toxic to all animals including human beings. Although many insecticides can be used safely, a few are persistent in the environment and a small number have multigenic, carcinogenic and teratogenic effects on human beings and domestic animals. Furthermore, their magnification in the food chain sometimes threatens non-target organisms. These facts have become of deep concern to agricultural and health scientists, producers and consumers alike. Based on this discussion, IGRs represent the newest of all approaches to operational and commercial insect control. Their species or stage-specificities that were higher than those of conventional insecticides offer a good alternative for a selective insect pest control that is in harmony with existing IPM programs. IGRs generally have a good margin of safety for most non-target biota including invertebrates, fish, birds, and other wildlife. They are relatively safe for human beings and domestic animals. Although CSIs are broad-spectrum compounds, the mode of action between the targets and non-target organisms (e.g., crustaceans) should be considered. Similarly, JHAs are generally selective, but the last stage of some Non-Target Organisms will potentially suffer morphogenetic effects or anomalies, while crustaceans will probably have defective reproductive systems.

References

1. Abrol D, Shankar U. Biorationals in integrated pest management. Technological Innovations in Integrated Pest Management Biorational and Ecological Perspective, 2017, 97-171.
2. Ahmad A, Shakeel M. Assessing the efficacy of eco-friendly insecticides against the Spodoptera. A new binding mode for ecdysteroid analog tebufenozide as a

multitargeted IGR with chitinase, Advanced Agrochem,2024;3(3):229-236.

3. Ali Q, Rasul A, Akhtar MF, Aslam A, Shakir HU, Rehman MA. *et al.* Effect of insect growth regulators on fecundity, fertility and adult emergence of *Tribolium castaneum* (herbst) and *Trogoderma granarium* (everts). Pak. J. Agri. Sci,2020;57(3):799-805.
4. Anadón A, Ares I, Martínez-Larrañaga MR, Martínez M, Martínez MA. Pyrethrins and Pyrethroids: Ectoparasiticide Use in Veterinary Medicine. In Natural Products: Phytochemistry, Botany, Metabolism of Alkaloids, Phenolics and Terpenes. Berlin, Heidelberg: Springer Berlin Heidelberg, 2025, 1-34.
5. Ascher KS, Nemny NE. Contact activity of diflubenzuron against *Spodoptera littoralis* larvae. Pesticide Science,1976;7(5):447-452.
6. Ashouri S, Pourabad RF, Ebadollahi A. The effect of diflubenzuron and hexaflumuron on the last larval instars of the Mediterranean flour moth *Anagasta kuehniella* (Zeller) (Lepidoptera: Pyralidae) under laboratory conditions. Archives of Phytopathology and Plant Protection,2014;47(1):75-81.
7. Bartelsmeier I, Kilian M, ten Broeke CJM. *et al.* Local and systemic effect of azadirachtin on host choice and feeding activity of *Macrosiphum rosae* on rose plants. Arthropod-Plant Interactions,2022;16:191-204.
8. Brabant PJ, Dobson SL. Methoprene effects on survival and reproductive performance of adult female and male *Aedes aegypti*. Journal of the American Mosquito Control Association,2013;29(4):369-375.
9. Carlson GR, Dhadialla TS, Hunter R, Jansson RK, Jany CS, Lidert Z. *et al.* The chemical and biological properties of methoxyfenozide, a new insecticidal ecdysteroid agonist. Pest Management Science: formerly Pesticide Science,2001;57(2):115-119.
10. Cermolacce A, Lacoste R, Moulin V, Briand A, Bakker J. Successful Treatment of Captive Common Marmosets (*Callithrix jacchus*) Infested with Common Cat Fleas (*Ctenocephalides felis*) by Using Topical Imidacloprid and Environmental Control Measures. Veterinary Sciences,2023;10(9):580.
11. Clifton ME, Lopez K. Assessing Insect Growth Regulator Resistance Using Bioassays: A Systematic Review and Meta-Analysis of Methoprene and Pyriproxifen Inhibition of Emergence in Three Vector

- Mosquito Species. Tropical Medicine and Infectious Disease,2025:10(4):87.
12. Deshpande SG. Action of some insect growth regulators on behaviour, development, metamorphosis and biochemistry of the yellow fever mosquito *Aedes aegypti* (L)(Diptera: Culicidae), 1994.
 13. Du YQ, Cai JY, Deng XQ, Liang WW, Hu XL. Growth, Reproduction, and Transgenerational Effects of Kinoprene on *Moina macrocopa*. Bulletin of Environmental Contamination and Toxicology,2023:110(6):113.
 14. Fansiri T, Pongsiri A, Khongtak P, Nitatsukprasert C, Chittham W, Jaichapor B. *et al.* The impact of insect growth regulators on adult emergence inhibition and the fitness of *Aedes aegypti* field populations in Thailand. Acta Tropica,2022:236:106695.
 15. G Silva, S Vieira, S Vieira, da Silva, J Ávila. Effect of Insect Growth Regulator Insecticides Novaluron, Teflubenzuron and Lufenuron on the Morphology and Physiology of Euschiistus heros. Journal of Agricultural Science,2023:15:44-44.
 16. Glare TR, O'Callaghan M. Environmental and health impacts of the insect juvenile hormone analogue, S-methoprene. Report for the Ministry of Health New Zealand, 1999.
 17. Grafton-Cardwell EE, Lee JE, Stewart JR, Olsen KD. Role of two insect growth regulators in integrated pest management of citrus scales. Journal of Economic Entomology,2006:99(3):733-744.
 18. Guo B, Chen L, Luo S, Wang C, Feng Y, Li X. *et al.* A potential multitarget insect growth regulator candidate: design, synthesis, and biological activity of novel acetamido derivatives containing hexacyclic pyrazole carboxamides. Journal of Agricultural and Food Chemistry,2024:72(18):10271-10281.
 19. Hasnain M, Saeed S, Naeem-Ullah U, Ullah S. Evaluation of chemosterility effect of different insect growth regulators on *Bactrocera zonata* population. Science Progress,2023:106(1):00368504231155388.
 20. Herath, JMMK, De Silva, WAPP, Weeraratne TC. *et al.* Efficacy of the insect growth regulator novaluron in the control of dengue vector mosquitoes *Aedes aegypti* and *Ae. albopictus*. Sci Rep,2024:14:1988.
 21. Hu X. Effects of Juvenile Hormone Analogue Insecticides, Fenoxycarb and Methoprene, on *Neocaridina davidi* and *Moina macrocopa*. The Chinese University of Hong Kong (Hong Kong), 2019.
 22. Hu XL, Tang YY, Kwok ML, Chan KM, Chu KH. Impact of juvenile hormone analogue insecticides on the water flea *Moina macrocopa*: Growth, reproduction and transgenerational effect. Aquatic Toxicology,2020:220:105402.
 23. Kainat I, Saeed S, Farooq MA, Alkherb WAH, Abbasi A, Baig F. *et al.* Chemosterilant Potential of Insect Growth Regulators for Management of *Bactrocera cucurbitae* (Diptera: Tephritidae). Insects,2025:16(2):137.
 24. Kavallieratos NG, Athanassiou CG, Vayias BJ, Tomanović Ž. Efficacy of insect growth regulators as grain protectants against two stored-product pests in wheat and maize. Journal of food protection,2012:75(5):942-950.
 25. Khozimy A, Abuzeid MA, Darwish AA. Effect of some insecticides and their side effects in controlling the California red scale, *Aonidiella aurantii* (Maskell). Journal of the Advances in Agricultural Researches,2022:27(1):113-124.
 26. Krishna Tiwari. Potential of Fenoxycarb (a Juvenile Hormone Analogue) on the Growth Duration and Longevity of Adults of Rice Moth, *Corcyra cephalonica* Staint. (Lepidoptera: Pyralidae) Exposed as Second Instar Larvae. International Journal of Zoological Investigations,2020:6:187-195.
 27. Krishnamoorti Dr. Application of Insect Growth Regulators (IGRs) as Biopesticides for Sustainable Agriculture. International Journal of Scientific Research in Science and Technology,2024:11:936-939. 10.32628/IJSRST24112156.
 28. Kumar Sanjay, Samal Roopa, Sankar Manu, Kumar Sarita, Kumar Arvind. Methoxyfenozide as a potent insect growth regulator: Disruption of growth, development and chitin synthesis in *Aedes aegypti* for sustainable vector control. Journal of Natural and Applied Sciences,2025:17:951-960.
 29. Kumari Meera, Merzendorfer Hans, Kim Hee Shin, Specht Charles, Beeman Richard, Kramer Karl. *et al.* Mode of action of the insect growth regulator diflubenzuron: A comprehensive study in *Tribolium castaneum* utilizing genomic tiling array and immunolocalization approaches, 2010.
 30. Lynn RC. Antiparasitic drugs. Georgis' parasitology for veterinarians,2008:9:254-294.
 31. Mahmoud MA, Abdelrahman IE, Zedan OAA, Abdel-Rahman YA, Saba RM, Laban GA. *et al.* Effect of three insect growth regulators on certain biological aspects of the lesser grain borer, *Rhyzopertha dominica* (Coleoptera: Bostrichidae). Brazilian Journal of Biology,2022:82:e267629.
 32. Martínez LC, Plata-Rueda A, Serrão JE. Effects of Insect Growth Regulators on Mortality, Survival, and Feeding of *Euprosterina elaeasa* (Lepidoptera: Limacodidae) Larvae. Agronomy,2021:11(10):2002.
 33. Masih SC, Ahmad BR. Insect growth regulators for insect pest control. Int. J. Curr. Microbiol. App. Sci,2019:8(12):208-218.
 34. Merzendorfer H, Zimoch L. Chitin metabolism in insects: structure, function and regulation of chitin synthases and chitinases. Journal of Experimental Biology,2003:206(24):4393-4412.
 35. Micocci M. Advancements in knowledge and approaches towards pyrethroid-free control of mosquitoes, vectors of arboviruses, 2025.
 36. Miyamoto J, Hirano M, Takimoto Y, Hatakoshi M. Insect growth regulators for pest control, with emphasis on juvenile hormone analogs: Present status and future prospects. ACS Symp. Ser, ACS, Washington, DC,1993:524:144-68.
 37. Mohammed KO. Biological responses and control of California red scale *Aonidiella aurantii* (Maskell) (Hemiptera: Diaspididae) (Doctoral dissertation, Murdoch University), 2020.
 38. Morsli SM, Merad I, Khebbeb MEH, Soltani N. Potential hazards of a chitin synthesis inhibitor diflubenzuron in the shrimp *Penaeus kerathurus*: biochemical composition of the hemolymph and muscle during the

- molt cycle. *Advances in Environmental Biology*,2015;9(3):518-525.
39. Muthukrishnan S, Mun S, Noh MY, Geisbrecht ER, Arakane Y. Insect Cuticular Chitin Contributes to Form and Function. *Current pharmaceutical design*,2020;26(29):3530–3545.
 40. Nwonuma CO, Omoniwa BP, Elleke TE, Aladele P, Ogundipe OE. The modes of action of biopesticidal compounds in insect control. *International Journal of Tropical Insect Science*, 2025, 1-11.
 41. Parthasarathy R, Palli SR. Stage-specific action of juvenile hormone analogs. *Journal of Pesticide Science*,2021;46(1):16-22.
 42. Qu MB, Sun SP, Liu YS, Deng XR, Yang J, Yang Q. *et al.* Insect group II chitinase OfChtII promotes chitin degradation during larva–pupa molting. *Insect Science*,2021;28(3):692-704.
 43. Rahman AU, Khan I, Usman A, Khan H. Evaluation of Insect Growth Regulators (IGRs) as biological pesticides for control of *Aedes aegypti* mosquitoes. *Journal of Vector Borne Diseases*,2024;61(1):129-135.
 44. Riddiford LM. *Rhodnius*, Golden Oil, and Met: A History of Juvenile Hormone Research. *Frontiers in cell and developmental biology*,2020;8:679.
 45. Rust MK, Hemsarth WLH. Synergism of adulticides and insect growth regulators against larval cat fleas (Siphonaptera: Pulicidae). *Journal of Medical Entomology*,2019;56(3):790-795.
 46. Sarwar MF, Shad NA. Management of Insect Pests through Hormones. In *Biopesticides in Organic Farming*. CRC Press, 2021, 191-196.
 47. Singh S, Pandher S, Sharma RK, Kuma R. Insect growth regulators: practical use, limitations and future. *Journal of Eco-friendly Agriculture*,2013;8(1):1-14.
 48. Song Y, Villeneuve DL, Toyota K, Iguchi T, Tollefsen KE. Ecdysone receptor agonism leading to lethal molting disruption in arthropods: review and adverse outcome pathway development. *Environmental science and technology*,2017;51(8):4142-4157.
 49. Zeng B, Chen FR, Liu YT, Guo D, Zhang YJ, Feng ZR. *et al.* A chitin synthase mutation confers widespread resistance to buprofezin, a chitin synthesis inhibitor, in the brown planthopper, *Nilaparvata lugens*. *Journal of Pest Science*,2023;96(2):819-832.