Juvenile hormone: Production, regulation, current application in vector control and its future applications

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INTRODUCTION

In 1936, an insect “inhibitory hormone” or currently known as juvenile hormones (JHs) was first discovered by Sir V. B. Wigglesworth in Rhodius prolixus (Hemiptera: Triatominae). In this early discovery, JH is classified as a sesquiterpenoid hormones found in insect. It is secreted and synthesis by a pair of endocrine glands located near the tritocerebrum area of an insect brains, known as corpora allata (CA). Secretion and biosynthesis of JHs by the CA regulate various physiological roles in insects such as reproduction, development, behaviour, and caste determination. Nevertheless, JHs are well known in their roles in metamorphosis and reproduction where inhibition of adult moulting and yolk deposition in eggs are regulated according to the level of JHs in the haemolymph (Gullan & Cranston, 2010).}

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ABSTRACT

Juvenile hormone is an exclusive hormone found in insects which involves regulating various insect physiology. A total of eight juvenile hormones have been identified in insects which include JH 0, JH I, JH II, JH III, 4-methyl JH I (Iso-JH 0), JHB III, JHSB III, and MF. Corpora allata are the glands responsible for the production and synthesis of these hormones. They are involved in moulting, reproduction, polyethism, and behavioural regulations in different orders of insects. Factors such as diet temperatures, photoperiods, and plant compounds affect the biosynthesis and regulation of juvenile hormones. Juvenile hormones analogue is usually used to disrupt normal regulation of JH and this analogue is categorized as insect-growth regulators (IGRs) and is widely used in pest control as an alternative to chemical insecticides. Other applications of biosynthesis activities of this hormone have not been explored in the area of JHs. In this review, current applications of JHs with an addition of their future application will be discussed.

Keywords: Juvenile hormones; corpora allata; insect brain; insect physiology; pest control.
structure instead of one epoxy group like other JH homologs. A higher rate of JHB III biosynthesis compared to JH III was found in Diptera, indicating that JH III is not the sole JH in this Order (Bylemans et al., 1998). Nevertheless, the specific roles of this JH homolog are still unknown.

JHs are classified as a true hormone in insects, but the discovery of methyl farnesoate (MF), which is a hormone found in crustaceans, is believed to be grouped together with JHs because of their function. However, some believed that MF is not related to JHs. In crustaceans, MF serve as hormones in development and reproduction regulation similar to JH in insects. In a recent study by Di-Wen et al. (2015), MF is reported to act as an immediate precursor and hormone in the regulation of metamorphosis in *D. melanogaster*. In terms of the structure, MF is also classified as sesquiterpenoid compounds, but lacking the epoxy group. In order to prove the identity of MF, further structural and functional studies need to be conducted for a definite classification.

This review will briefly discuss about JH production, regulation, and their applications of JH is pest and vector control, developmental studies as well as future applications.

**Juvenile hormone regulation by corpora allata and accessory glands**

JH is known to be produced and synthesised by a pair of glands named CA. This gland can be categorized into five difference morphological types according to their positions which are: (1) lateralized; (2) distally lateralized; (3) semi-centralized; (4) centralized; and (5) annular types (Goodman & Cusson, 2012).

However, the role of CA as the only organ to regulate the secretion and synthesis of JH is proven to be inaccurate by various researchers (Tobe et al., 1985; Bylemans et al., 1998). A concise review on the regulation of CA in JH synthesis and regulation has been done by K. Hartfelder (2000). Based on a study by Wu et al. (1987), decapitation of *D. melanogaster* brain has resulted in the activation of CA to secrete JH. The absence of the brain significantly affect JH production in this species. Also, the absence of the brain affect the hormonal control in the reproduction of *D. melanogaster* where yolk peptides failed to be synthesized. This finding is further supported by the radiochemical assay (RCA) performed on CA attached to the brain (Bylemans et al., 1998). Attachment of the brain to the CA, known as Br-CA complex, was observed to be more productive in synthesizing JH than the one without the brain.

In the absence of the brain, allatotropin will be produced by accessory glands, fat body, ovaries, and the gut. Allatotropin is a peptide that stimulates the secretion of JH to regulate the hormonal control. The effect of allatotropin on CA has been demonstrated by the application of synthetic allatotropin of *M. sexta* to the CA of *Lacanobia oleracea* (Lepidoptera: Noctuidae) where a stimulation by 255% was observed in the CA of *L. oleracea* (Audsley et al., 1999). In the same study, a peptide that inhibit CA activity known as allatostatin was also applied on the same insect and a maximum inhibition by 54% was recorded. However, applications of synthetic allatostatin and allatotropin did not show the same affect among insect orders, for example, cockroach's allatostatin, Dip- allatostatin-2, had no significant affect on JH synthesis on *L. oleracea* when compared to *M. sexta*. These findings suggested that a diversity of allatostatin and allatotropin may be present among the orders of insect. Nonetheless, the effect of allatostatin in JH synthesis remains inconclusive because of the constant low quantity of JHs being detected in insects (Audsley et al., 1999). In normal JH regulation, degradation of JHs is mediated by three enzymes: – juvenile hormone esterase (JHE), juvenile hormone epoxide hydrolase (JHEH), and juvenile hormone diol kinase (JHDK) (Yang et al., 2016). Yang et al. (2016) reported gene expressions of BdJHE2 and BdJHDK in *Bacterocera dorsalis* (Diptera: Tephritidae) during larval-pupal transition and the genes suggested that JH was degraded in the preparation to pupate because low JH was required for successful larval-pupal development (Yang et al., 2016). Requirement of low JH during larval-larval moult from early to late third instar larva followed by high demand JH degradation, which high expression of BdJHE3 will be needed for this moulting to be successfully occurred. Adults of 7-days-old and 10- days-old *B. dorsalis* exhibited high expression of these three genes indicating that JH degradation was required for sexual maturation (Yang et al., 2016). In summary, the abundance of these genes found in the fat body and Malpighian tubules of *B. dorsalis* suggested that excretion of degraded JH was part of JH regulation.

**Juvenile hormone biosynthetic pathway**

Juvenile hormones are identified based on their chain length of 16-19 carbon atoms (Gullan & Cranston, 2010). JH is synthesized in CA through the mevalonate pathway (MVAP) in the early stage and undergo JH branching in the later stage of biosynthetic pathway. This pathway was reviewed by Noriega (2014) where the synthesis of JH in CA comprises of 13 enzymatic reactions which involves eight enzymes in early MVAP and five enzymes in the JH branch (Noriega, 2014; Huang et al., 2015). The early step of MVAP includes the conversion of Acetyl-CoA to farnesyl pyrophosphate (FPP). Next, oxidation of FPP to farnesoic acid (FA) occurred and later transformed into a final product namely JH. The last step in the JH branching was mediated by two enzymes genes, juvenile hormone acid O-methyltransferase (JHAMT) and methyl farnesoate epoxidase (CYP 15A1) (Marchal et al., 2011). JHAMT catalysed the FA and JH acid to the methyl ester forms which are JH and MF. Epoxidation of MF and JH is encoded by P450 enzyme with the expression of CYP 15A1. However, the late stage of MVAP is dependent on the order of an insects (Marchal et al., 2011). The late stage can precede with epoxidation followed by methylation in Lepidoptera or vice versa in Diptera, Coleoptera, Orthoptera, or Dictyoptera (Huang et al., 2015). Details on the pathway of JH biosynthesis (Figure 1) was reviewed by Noriega (2014) and includes the complete JH pathway and branching. However, Di Wen (2015) reported that the JH synthesis pathway of *Drosophila* is more complicated compared to other insects because of the presence of JHB III. The common precursor of JH present in *Drosophila* is believed to be farnesonic acid rather than methyl farnesoate. Methyl farnesoate is also reported to have a dual role as a hormone and precursor of JHBIII in *Drosophila*. The juvenile hormone acid methyltransferase (JHAMT) is known to be involved in JHB III biosynthesis only but not in JH III (Di-Wen et al., 2015). However, the complete pathway of JH biosynthesis is still unknown. Previous studies (Richards et al., 1989; Bylemans et al., 1998; Shiga et al., 2003) revealed a possibility of different biosynthesis in the type of JH and among different orders of insect. In other words, JH 0, JH I, and JH II may have different biosynthesis pathways that have yet to be explored.

**Juvenile hormone control and regulation in insects**

JH has been identified to control and regulate various functions in insects from all order of insects. In this section, the control and regulation will be discussed among the different insect orders. The control of reproduction and development seem to be the most important one, as it the
**Table 1.** Types of Juvenile Hormone (JH) identified in various insects

| Order: Family | Species of insects | JH homologs          |
|---------------|--------------------|----------------------|
| Hymenoptera: Apidae | *Apis mellifera* | JH I, 4-methyl JH I, JH II, JHB III, Methyl farnesoate (MF) |
| Lepidoptera: Sphingidae | *Manduca sexta* | JH I, (eggs)(Bergot et al., 1980) |
| Lepidoptera: Noctuidae | *Lacanobia oleacea* | (Audsley et al., 1999) |
| Blattodea: Termesidae | *Hodotermopsis sjostedti* | (Cornette et al., 2008) |
| Diptera: Culicidae | *Aedes aegypti* | (Shapiro et al., 1986) |
| Diptera: Sarcophagidae | *Sarcophaga (Neobellieria) bullata* | (Bylemans et al., 1998) |
| Diptera: Calliphoridae | *Lucilia cuprina* | (Lefevere et al., 1993) |
| Diptera: Calliphoridae | *Protophormia terraenovae* | (Lefevere et al., 1993) |
| Diptera: Calliphoridae | *Phormia regina* | (Lefevere et al., 1993) |
| Diptera: Calliphoridae | *Calliphora vombatoria* | (Very low; Duve et al., 1992) |
| Diptera: Drosophilidae | *Drosophila melanogaster* | (Bowes & Rambold, 1987) |
| Diptera: Tephritidae | *Anastrepha suspensa* | (Teal et al., 2000) |
| Orthoptera: Acrididae | *Locusta migratoria* | (Minderhoud et al., 1980) |
actively being studied in the past few years involving various insect species.

Despite the various forms of JH homologs, they shared the same control and regulations. In Diptera, three homologs were present in the extract of Musca domestica (Muscidae) and Sarcophaga bullata (Sarcophagidae) namely JH I, JH II, and JH III (Lefevere et al., 1993). However, further studies disputed the presence of JH II in M. domestica and S. bullata (Trumann, 1974; Girard et al., 1976; Schooley et al., 1976). Following this, a confirmation was made that JH III is the only principal JH found in cyclorrhapha Diptera. This JH is found in Drosophila hydei, D. melanogaster, Calliphora vomitoria (Calliphoridae), and Phormia regina (Calliphoridae) (Bownes & Rembold, 1987; Duve et al., 1992).

In reproduction, not only JHS control the vitellogenesis and oogenesis but also regulate the reproductive behaviour and pheromone production in adult insects (Raushenbach et al., 2004). JH titre is reported to rise immediately after the emergence of both male and female D. melanogaster: − 6.9 pmol/g of wet weight in females and 5.3 pmol/g wet weight in males (Nijhout & Williams, 1974). The increased concentration of JH in haemolymph immediately after emergence involves an initiation of the transcription and translation machinery in female’s fat body for the induction of the first oogenesis cycle (reviewed by Wyatt & Davey, 1996). This result is consistent with other studies where there was high titre of JH in the females of A. aegypti (Diptera: Culicidae) and both females and males of Neobellieria (Sarcophaga) bullata (Diptera: Sarcophagidae) immediately after eclosion but rapidly declined thereafter. Teal et al. (2000) proposed that the increase of JH titre five days after eclosion in males N. bullata and D. melanogaster were associated with reproductive maturity and sexual signalling. However, females have lower titres compared to the males of the same age and these differences were related to the presence of an allostatic-like compound found in the ovaries of both D. melanogaster and N. bullata females (Bownes & Rembold, 1987; Bylemans et al., 1998). This allostatic-like compound may inhibit the biosynthesis of JH III and JHB III present in both insects which explained the rapid decline of these hormone titres in females. In males, the titre increases with mating behaviour as reported in Anastrepha suspensa (Diptera: Tephritidae), where a 3-fold increase of JH concentration were observed in mated young males compared to the virgin males (Teal et al., 2000).

JH also plays a part in the production of eggs, where a high concentration of JH is correlated with high productions of eggs and a low concentration of JH is accompanied by low egg production (Yamamoto et al., 2013). Low JH production is due to the knockout of CA (CAKO) in females of D. melanogaster, which is the site of JH production and synthesis. Even though the correlation existed between JH and egg production, Yamamoto et al. found that some CAKO females produced a similar quantity of eggs in comparison to wild strain flies. This situation may be due to sufficient amounts of JH being produced before the knockout and hence the egg production is similar to the wild strains. As mentioned previously, the brain may play a part in sending the signal to the other accessory gland to increase JH synthesis before the CA is shutting down. In addition, JH was observed to be involved in oogenesis when a sharp decline of JH titres in A. aegypti were observed immediately after the blood meal and the rise of JH took place between 36 to 48 hours post-feeding (Shapiro et al., 1986). The decline of JH in early blood meals after eclosion create an opportunity for 20-hydroecdysone (20E) to release a neurosecretory hormone for egg development (Shapiro et al., 1986). A decline of JH level may be due to the action of juvenile hormone esterase, excretion, or the activities of its CA (Shapiro et al., 1986). The second blood meal in mosquitoes trigger the development of second follicles which will cause the rise of JH and a new cycle of egg development. In flesh fly, N. bullata, the increase of JH titres was more rapid when compared to A. aegypti which took an additional one day in both males and females following a liver and blood meal (Bylemans et al., 1998). However, the decline of JH in N. bullata females a few days

Figure 1. Morphological position of the retrocerebral glands in insects. (a) Lateralized types, (b) distal lateralized type, (c) ventral type, (d) semicentralized type, (e) centralized type, and (f) annular type. Red area represented corpora allata and yellow area represent corpora cardiaca. Adapted from Cassier (1979).
after the liver meal showed a similar trend with *A. aegypti*, demonstrating the involvement of JH in vitellogenesis (Bylemans et al., 1998).

In *D. melanogaster*, fluctuating patterns of JH titres were demonstrated throughout larval development until the prepupal stage (Bownes & Rembold, 1987). First and second instar of *D. melanogaster* larvae showed high titres of JH (1.3 pmol/g fresh weight) (Bownes & Rembold, 1987). However, third instar and prepupa showed low titre and pupae did not show any detectable titre of JH. Reappearance of JH in the prepupal stage is required to prevent precocious metamorphosis in some tissues such as the eyes, the optic lobe, and the ventral diaphragm (Riddiford, 2012). Larval-pupal development was interrupted when the secretion of prothoracicotropic hormone (PTTH) was inhibited by the low gene expression which subsequently led to larval-pupal moulting (Riddiford, 2012). Suppression of Kr-h1 is regulated by histone deacetylace 1 (HDAC 1) (George et al., 2019) with maximum mRNA expression of HDAC 1 was detected after 24 hours of entering the pupal stage. George et al. (2019) suggested that expression of Kr-h1 was related to JH concentration. In burying beetles, *Nicrophorus orbicollis* (Coleoptera: Silphidae), JH did not seem to be involved in ovarian maturation but involved in behavioural regulation instead (Trumbo, 1994). The spiking of JH titres was detected in *N. orbicollis* upon the discovery of rat carcasses. The peak value of JH upon the discovery of carcasses were accompanied by four behaviour changes including palpating, lifting, walking around carcasses, and making forays into surrounding soils (Trumbo et al., 1994). However, the action of JH in the behavioural regulation is still not fully understood.

In social insects, JH has a different role compared to non-social insects. JH has been known to be involved in the polyethism (i.e., age polyethism and caste polyethism) and also behavioural changes. Polyethism is defined as functional specialization in different members of a colony of social insects, which lead to a division of labour (i.e., organisation on insect society that consists of different activities performed simultaneously by a specialized group of individuals). Polyethism can be categorized into age polyethism and caste polyethism. For example, honey bees, *Apis mellifera* (Hymenoptera: Apidae) are one of the social insects that undergo age polyethism, which is related to changes of division of labour as they age (Huang & Robinson, 1995). For instance, the foragers have high JH titre compared to young *A. mellifera*. Huang and Robison (1995) also reported that the titres of JH are directly proportional with the age of honey bees, although low titre of JH was reported in inactive foragers and young *A. mellifera*. However, foraging activity was not totally dependent on the high titre of JH as active foragers in cold weather had a low titre than the active forager in warm weather. When compared with the young bees (which are non-foragers), the foraging bees in the cold weather exhibited a higher JH. This showed that JH titre increases directly with the age of honey bees and also environmental temperature. Note that JH response towards temperature alone will not affect honey bees division of labour (Huang & Robinson, 1995).

In addition, JH is playing a part in the pre-vitellogenetic events of termites, *Hadotermopsis sjostedti* (Blattodea: Termosidae), *Reticulitermes speratus* (Blattodea: Rhinotermitidae), and *Cryptotermes secundus* (Blattodea: Kalotermitidae). High titre of JH during pre-vitellogenetic events activates the vitellogenin synthesis (Cornette et al., 2008; Santos et al., 2018). The relationship between JH and polyethism was demonstrated in caste determination of damp wood termites, *H. sjostedti*. During moulting, high JH titre was associated with pre-soldier moulting while the moulting of nymph to the alate form showed low JH titres (Cornette et al., 2008). However, the titres started to fluctuate when soldiers reach maturity, in spite of these changes, titres in soldier termites were still higher than pseudergates termites (worker caste termites that unable to become a winged imago termite) (Cornette et al., 2008). This high titre may be linked at an increased volume of corpora allata in the soldiers. Yet, moulting of nymphs into pseudergates instead of alates due to the increase of JH titres may be due to:

| Acetyl-CoA | Thr |  
| Acetoacetyl-CoA | HMGs |  
| HMG-CoA | HMGCoR |  
| Mevalonic acid | PhMK |  
| Phosphomevalonate | PPMK |  
| Diphospho mevalonate | IPPMD |  
| Isopentyl mevalonate | IPP |  
| Dihydroneopteron | Dimethylallyl diphosphate |  
| Geranyl diphosphate | FPPS |  
| Farnesyl diphosphate | FPPS |  
| Methyl farnesolate | IPPMT |  
| Farnesolate | FOLDS |  
| Farnesal | FALD |  
| Methyl farnesolate | JHAMT |  
| Farnesonic acid | CYP15A |  

**Figure 2.** JH III biosynthesis pathway adapted from Noriega (2014). JH branch in the biosynthesis is in the red box. The enzymes involved are in blue. Abbreviations: Thiol= Acetoacetyl-CoA thiolase; HMGs= HMG-CoA synthase; HMGCoR= HMG-CoA reductase; MK= Mevalonate kinase; PhMK= Phosphomevalonate kinase; IPPMD= Diphosphomevalonate kinase; IPP= Isopentyl diphosphate isomerase synthase; FPPS= Farnesyl diphosphate isomerase synthase; FPP= Farnesyl diphosphate synthase; FOLD= Farnesol dehydrogenase; FALD= Farnesal dehydrogenase; JHAMT= Juvenile hormone acid methyl transferase; CYP15A= Methyl farnesolate epoxidase.
to the aggressive conspecific interaction in termites (Cornette et al., 2008). In a recent study by Oguchi et al. (2020), the differentiation of pseudergates to neotenics forms was depending on the presence of neotenics in the colony and this was regulated by the concentration of JH. Juvenile hormone was the key player in controlling the caste differentiation during the inter-molt of termites which will later determine the fates of the caste. Based on the experiment, the presence of neotenics in the colony will accelerate the differentiation of the opposite sex pseudergates to neotenics. However, the presence of male neotenics were able to maintain a low level of JH that led to the moulting of pseudergates to neotenics. In contrast, the presence of female neotenics, have showed high level of JH in the first three days, and then a gradual decrease, eventually reached the lowest level of JH on day seven. This differentiation may be caused by the urgency of a male to copulate due to the intraspecific competition (Oguchi et al., 2020).

In a recent study, behavioural roles of JH in honey bee larvae were studied by exposure to juvenile hormone analogue (JHA), pyriproxyfen, which subsequently showed an effect on behavioural change in the resulting adults (Fourrier, 2015). The pyriproxyfen-exposed adults did not perform many social tasks (i.e., brood care and ventilation) but rather performed more non-social tasks (i.e., self-grooming, inactive, and walking instead of flying). Exposure of high JHA concentration may affect brain development and cognitive abilities of the honey bee and subsequently alter social performance that eventually led to its rejection by nestmates (Fourrier, 2015).

**Factors affecting JH activities**

As previously mentioned, JHs regulate many physiological activities in insects such as development, reproduction, polyethism, and behaviour. JHs are known to be declining in older larvae until reaching adulthood under normal regulation (Bownes & Rembold, 1987). However, some factors may cause interruptions in the regulation and lead to the changes in physiological activities. Common effects such as prolong phagoperiod in larvae and delayed puation occur due to rising JH titles in the haemolymph (Slama & Williams, 1965; Saunders et al., 1990). Albeit low titles of JHs can also be a consequence due to environmental stress faced by insects.

One of the factors that affect JH activities is plant extracts, specifically balsam fir (Abies balsamea) that can be found in most American newspapers and some paper towels. This discovery was reported by Slama and Williams in 1965, when linden bug (Pyrrhocoris apterus) showed high title of JH after being exposed to the plant extract. Following the high title of JH, larvae failed to moult into adults and most of the larvae died without reaching adulthood. Slama and Williams (1965) also reported that CA was not involved in the sensitivity of P. apterus towards the plant extract. Involvement of CA was not observed because the plant extract was applied directly to the larvae rather than injecting it into the haemolymph. Application of the extract to the other species of Hemiptera such as Oncopeltus fasciatus and Rhodnius prolixus did not show the same effect as in P. apterus. This indicates that the balsam fir extract cause changes of JH concentration in certain insect species only. This suggests that the plant extract acts as JH agonists (JHAs) to stimulate JH receptors.

Nevertheless, plant compounds can also act as JH antagonists (JHANs) that inhibit the binding of JH to its receptor, known as Methoprene-tolerant (Met). Diterpene from two plant extracts, the fruits of Lindera erythrocarpa and the roots of Solidago serotina, showed relatively strong and mild activity in the regulation of JH in A. aegypti, respectively. Both diterpene LE3B (Kanakugiol) and SS5A (Kingidiol) caused mortality in third instars, disrupted ovarian follicles development, and also cause ovarian retardation in females of A. aegypti. Retardation of A. aegypti female ovaries may be caused by precocious development by LE3B applied on the second instar during metamorphosis (Lee et al., 2015). Another factor that affect the titre of JH is seasonal changes. Photoperiod and temperature changes in each season effect the titre of JH in many insects. Saunders et al. (1990) reported that short-day photoperiod affected JH biosynthesis in D. melanogaster. Ovarian diapause was induced in short-day photoperiod that was regulated by JH titles in the haemolymph. The relation of JH titles in the haemolymph and photoperiod was measured by using the uptake of yolk proteins (YPs) by the ovaries of female D. melanogaster. The uptakes of YPs were low in a short-day photoperiod. This is because the synthesis of JH may not occur after a certain period of diapause (Saunders et al., 1990). The YPs tend to accumulate in the haemolymph and cannot be taken up by the ovaries (Saunders et al., 1990). Vitellogenesis is not complete in this situation. Vitellogenin synthesis is resumed in D. melanogaster by transferring the colony into a higher temperature (25°C) and 12:12 light:dark photoperiod in order to break the ovarian diapause. However, the colony that were reared in short-day photoperiod for a long period (i.e., a month) did not recover from ovarian diapause following the method stated above. Another method that was applied to break the diapause was the topical application of JH (Saunders et al., 1990). Increasing JH in the haemolymph will increase the uptake of YPs by the ovaries. The correlation of JH and ovarian diapause was observed in non-diapausing flies that produced four times more JH than the diapausing flies (Saunders et al., 1990). The flies that produced more JH in the haemolymph were likely to undergo vitellogenesis (Saunders et al., 1990). Diapause-induced Pr. terraenovae also showed a low JH synthesis similar to diapause-induced D. melanogaster (Shiga et al., 2003).

It is known that JH titles are correlated with temperature. To further understand the effect of temperature on JH titles, foraging bees with high JH titles were placed into a cold room during summer (Huang et al., 1995). Eight days after the placement, A. mellifera showed a decline in the JH titles. Damp wood termites, Hodotermpopsis sjostedti, also displayed temperature effects on JH but it is only affecting a certain caste which is the pseudergates termites (Cornette et al., 2008). Pseudergates termites experienced a dropped of JH titles during winter but the JH titles in soldier termites were similar to the warm weather despite the drop in temperature (Cornette et al., 2008).

Diet may also affect the production of JH. Duve et al. (1992) reported that unrestricted diet in blow flies, C. vomitoria showed high production of JH and oocytes development in the first gonadotrophic cycle. In the laboratory, colonies where a restricted diet (i.e., sugar, water, meat) was given, the JH produced was less than 50%. Bylemans et al. (1998) reported that the diet only affects biosynthesis of JH in female flesh flies, N. bullata, and not the males. This is based on an immediate increase of JH after a liver meal compared to males that showed a slower increase (Bylemans et al., 2015). Starvation of fruit flies, B. dorsalis, demonstrated that the low expression of BdJHEH gene was responsible for the degradation of JH. Starvation can cause low degradation of JH in their haemolymph which contradicted with previous studies by Duve et al. (1992). Thus, high JH in the haemolymph causes slower larval-larval moult. However, BdJHKD gene
was highly expressed during insect starvation and caused precocious metamorphosis. In the adult females of *Drosophila virilis* (Diptera: Drosophilidae), starvation caused low production of eggs and a delay in oviposition (Rauschenbach et al., 2004). This is caused by the low degeneration of JH which affect the production of 20-hydroxyecdysone (20E) that is important for the late stages of oogenesis.

**Detection and quantification of juvenile hormone**

Identification and quantification of JH had been performed in various method, ranging from classical method, bioassay, or physicochemical assay. In the early research, parabiosis and CA implantation was employed to study the JH synthesis (Villalobos-Sambucaro et al., 2020). Radiochemical assays, radioimmunoassay, and physicochemical methods which include gas chromatography (GC), liquid chromatography (LC), and spectrophotometry are the methods that being applied in JH studies to identify and quantify the hormone.

Radiochemical assay (RCA) is one of the common methods to analyse the rate of biosynthesis of JH in corpora allata. This assay is performed by tagging the compound with a radioactive isotope and incubation of the tissue (Bylemans et al., 1998). Observations were made in RCA by the incubation of brain-corpora cardiaca-corpora allata (Br-CC-CA) and corpora cardiaca-copora allata (CC-CA). The rate of biosynthesis between these two complexes was then compared and the result showed higher biosynthesis in Br-CC-CA than the CC-CA incubated without the brain. The synthesis is proven by the implantation of an active CA from young larvae into older larvae of *M. sexta* with less active CA. This implantation resulted in an increase of JH level in the haemolymph (Huibregtse-Minderhoud et al., 1980). In vitro incubation of CA in radiochemical assay (RCA) also showed JH synthesis by the CA. A study on locusts, *Locusta migratoria* by Huibregtse-Minderhoud et al. (1980) used capillary GC to detect three JH homologs; JH I, JH II, and JH III. A concentration of 2.3 ng/g haemolymph of JH III was detected in 0-24 hours fifth instar larvae compared to 24-48 hours larvae at minimum of 0.9 ng/g haemolymph which is much lower compared to the young larvae. After 18 days, upon reaching adult stage, the reading of JH III concentration is higher with 36.0-74 ng/g haemolymph. Whereas, JH I and JH II have low concentrations, less than 0.3-2.5 ng/g haemolymph, and cannot be detected in some samples.

In 1981, Bergot et al. developed a rapid, specific, and sensitive method for the extraction, purification, and quantitative determination of four known JHs which are JH 0, JH I, JH II, and JH III. This method involved the application of Gas Chromatography Mass Spectrometry (GC-MS) to two lepidopteran species; *M. sexta* and *H. virescens*. The method developed by Bergot et al. has simplified and shortened the purification process of the sample and only a small sample size is required for the analysis. Furthermore, higher sensitivities can be achieved using this method. Adapting the method, Tobe et al. (1985) detected 46-740 ng/g of JH III in the whole-body extract of *Dipteropa punctata* for each developmental stage (n = 12-15 individuals).

In the recent advancement of technology, simultaneous identification and quantification of JH can be performed in a single run in LC Ramirez et al. (2020). This method allowed the identification and quantification of JH I, JH II, JH III, and Juvenile Hormone Skipped-Bispexode (JHSSB). Employment of LC coupled to electrospray tandem mass spectrometry (LC-MS/MS) permitted the simultaneous identification and quantification based on JH structural features. This developed protocol could detect a femtomole range of the JH concentrations, allowing analysis of an individual insect. Previous methods developed by Rivera-Perez et al. (2012) are also able to detect a femtomole range of JH titres but this result is obtained by tagging the JH to the fluorescent tag prior to the High-Performance Liquid Chromatography (HPLC). This procedure can be applied to three type of samples which are the haemolymph, whole tissue, and CA-CC samples.

**Application of JH in vector control and its future applications**

The application of JH is mainly centred on the agricultural and vector control industries especially on the development of insecticides or insect growth regulators (IGRs). The use of pesticides renders significant negative impacts to human and environmental health. IGRs do not deliver a rapid termination on the insect lives but it affects the biology of insects with long term effects. In general, JH manipulation in insect pest and vector control was executed in the form of JH mimicry or JH analogues. These analogues include methoprene, pyriproxyfen, and hydropropane. The detailed management and potential use of IGRs was reviewed by Mondal and Parween (2001).

Despite of its effectiveness, tolerance and resistance towards IGRs by some insects such as mosquitoes, house flies, and flour beetles were reported (Cornel et al., 2002). Resistance towards methoprene maybe caused by (i) reduced penetration of the substance into the system; (ii) increased excretions, and (iii) insensitivity of the target site. While, in *D. melanogaster*, the resistance was caused by mutation of the Met genes which is the receptor for JH (Minkoff & Wilson, 1992). In a review by Parthasarathy and Palli (2021), the tolerance of the JHA is simply depended on the specific gene in the targeted insects. A study on *Tribolium castaneum* (Coleoptera: Tenebrionidae) showed three different outcomes from the same treatment: – (i) failure of *T. castaneum* to emerge as adult; (ii) successfully emerged as adult but produced no offspring, and (iii) emerged as adult and produced normal offspring (Wijayaratne et al., 2012). Following these outcomes, males *T. castaneum* were more susceptible to the treatment compared to females. Treatment applied to females *T. castaneum* did not show significant differences in the production of normal offspring compared to untreated females. In contrast, untreated females mated with treated males showed differences in the production of eggs (e.g., failure to hatch). This indicated that males were more susceptible than females against treatment. Susceptibility of males may be caused by the disruption in the process of spermatogenesis by methoprene during the developmental cycle (Wijayaratne et al., 2012). Thus, disruption in reproductive development in insects reduces the progeny of insect population to achieve the purpose of pest control (Shapiro et al., 1986; Wijayaratne et al., 2012).

One of the most potent JH analogues used in insect population control is pyriproxyfen or 2-[1-methyl-2-(4-phenoxyphenoxy) ethoxy] pyridine (Ishaaya & Horowitz, 1992). They reported the effect of pyriproxyfen on the development of sweet potato white flies, *Bemisia tabaci* (Hemiptera: Aleyrididae) which is known to infest cotton, vegetables, and ornamental plants. Pyriproxyfen did show a positive response in the suppression of the development of *B. tabaci* in every developmental stage. Inviable eggs were produced from adult females treated with the substance. The direct effect of pyriproxyfen to eggs was only seen in the 0-1 day-old eggs and not on the older eggs. The same was observed in the larval stages. However, the effects were only seen in the later stages when the pupae of the treated larvae failed to emerge as adults. Pyriproxyfen also showed localized effect on the area of interest, where eggs laid on specific
targeted area of the leaves failed to hatch (Ishaaya & Horowitz, 1992).

Juvenile hormone analogues (JHAs) has been investigated in insect vectors such as mosquitoes and triatomid bugs. Mosquito is a known vector of various tropical diseases such as dengue fever, malaria, and Zika. While triatomides are vectors of Chagas disease and both of these insects required a blood meal for oocytes productions (Ramos et al., 2020). Associations of these insects with human is concerning as they will spread diseases among human populations and therefore vector control programs are paramount important in this context. Methoprene, also known as isopropyl (2E, 4E)-11-methoxy-3,7,11-trimethyl-2-4-dodecadienoate, is the most common JH analogue used to control mosquitoes in this context. Methoprene, also known as isopropyl (2E, 4E)-11-methoxy-3,7,11-trimethyl-2-4-dodecadienoate, is the most common JH analogue used to control mosquitoes and fruit flies (Wilson & Turner, 1992). Shapiro et al. (1986) reported a five time increase in the amount of JH in unfed A. aegypti females when methoprene was applied topically (100 pg). The application of JHA causes vitellogenesis to occur in female A. aegypti and most of the females successfully oviposited. However, most of the eggs produced were not viable, which suggested that high levels of JH caused failure in embryogenesis (Shapiro et al., 1986).

JHA is also known to cause defect and death in mosquito larvae (Parthasarathy & Palli, 2021). It may produce a larva-pupal intermediate during the larval-pupal critical period. Continuous exposure to JH after the larval-pupal critical period will cause mortality during the prepupal stage (Braga et al., 2005). Methoprene has been reported to control A. aegypti successfully (Braga et al., 2005a, 2005b). While pyriproxyfen is able to inhibit adult emergence of A. aegypti and A. japonicus (Webb et al., 2012; Tuten et al., 2016). Furthermore, methoprene is able to control horn flies and house flies (Beadles et al., 1975; Miller et al., 1977; Breeden et al., 1980). However, it is interesting to note that no JH homologs was found in ticks (Acari). The JHA that has been studied thus far in insect vector is summarised in Table 2.

In a recent study, Chang et al. (2021) shows that the increase of JH in an adult A. aegypti reduces their immunity and that they are more susceptible to an infection. This study revealed that the disruption of JH signalling not only affect reproduction but also the insect immunity. In triatomid bugs, there is no reports on the JHA used to control this insect vector as the JH that is specific to this organism was just discovered recently (Villalobos-Sambucaro et al., 2020). The JH discovered is thoroughly studies for a development of specific targeted JHA (Villalobos-Sambucaro et al., 2020). Some JHAs do showed high specificity to a specific insect order, one of the JHAs acting this way is methyl ester of 3,7,11-trimethyl-7,11-dichloro-2-dodeceniol and “dihydrochloride” of methyl farnesoate (Masner et al., 1968). This substance showed potency in sterilization of the linden bug, Pyrrhocoris apterus. Female P. apterus showed high sensitivity to this substance as low as 0.1 μg which is sufficient to cause partial viability of the eggs produced (Masner et al., 1968). However, no effect was observed in the developmental of first and fourth instars of P. apterus. This indicated that the effect was taking place during the embryogenesis. Yet, in some other species such as Lepidoptera, Coleoptera, Diptera, and some Heteroptera, it did not show any effect, suggesting high specificity of this substance (Masner et al., 1968).

Juvenile hormone chemistry, biosynthesis, and pathway have been extensively study for better understanding on its regulations in insects for a few decades. However, most of the studies were centred on JH application in the insect pest and vector control industry in the form of IGRs. JH analog are the most commonly used to regulate the JH titres in pest insects. High JH during embryogenesis caused non-viable egg production (Shapiro et al., 1986) which is efficient in controlling the insect pest and vector population. Altering the JH titre in larval stages is a useful strategy in vector population control because inducing JH titre in the old larvae stops adult transformation and resulted in the discontinuation of its life cycle (Bowes & Rembold, 1987).

Declining trends of JHs during fly larval development may be useful in the determination of the age of the larvae. Larval age is used for the determination of minimum post-mortem interval (mPMI) in forensic investigations (Goff, 1993), especially to differentiate the age of third instar and post feeding stages. It is known that the larvae of blow flies are common insect evidence found on decomposing remains (Lee et al., 2004). Furthermore, beetle larvae can also be used in the estimation of PMI at a later stage of body decomposition. We hypothesized that the levels of JH determined from fly larvae or beetle larvae during the discovery of a body can be used to determine PMI. Furthermore, the peak concentration of JH in carrion beetles during the discovery of the carcasses could potentially be useful in determining the time of the beetle arrival. Yet, to apply this knowledge in forensic entomology, extensive studies are required to fully understand the relationship of JH titres changes and the time of beetle arrival to the decomposing remains. Analysis of biological changes in each insect found at the crime scene can improve mPMI estimations. Although, a study focusing on the trends of JH in the development of a blowfly need to be performed to explore their application in forensic because of their value in mPMI estimation compared to beetles. Nevertheless, a baseline data on the JH changes in each insect species involved in crime scene investigation need to be constructed for its application in the real setting.

The other potential application of JH is in the recovery of an important social insects by studying evolution of JH in the regulation of insect behaviour. This may be advantageous in the recovery of a social insect colony. Instability of JH within the colony of a social insect may cause aggressiveness.

**Table 2. Application of JHA in controlling vector of diseases**

| JHA                       | Vector                  | Life stages | Authors          |
|---------------------------|-------------------------|-------------|------------------|
| Methoprene                | *Ochlerotatus nigromaculis* (Diptera: Culicidae) | Larvae | Cornel et al., 2002 |
|                          | *Aedes aegypti* (Diptera: Culicidae) | Larvae | Braga et al., 2005a, 2005b; Wu et al., 2006 |
| Pyriproxyfen              | *Aedes vigilax* (Diptera: Culicidae) | Larvae | Webb et al., 2012 |
| Methoprene (added to the chicken feed) | *Musca domestica* (Diptera: Muscidae) | Adults | Breeden et al., 1980 |
| Methoprene (added to water system) | *Haematobia irritans* (Diptera: Muscidae) | Adults | Beadles et al., 1975; Miller et al., 1977 |
and rejection behaviours by their nest mates which can lead to the collapse of a colony. These aggressive behaviours may be corrected by the application of JH. Acceptance rates by nestmates may be increased by manipulating the level of JH to induce social or non-social behaviour in social insects.

**CONCLUSION**

JH clearly have a complex and unique biosynthesis in each order of insects. Eight different JH homologs have been identified thus far and presented in a different combination for each insect order. These hormones are synthesized by the gland namely corpora allata (CA) which is situated near the brain.

JHs are known to regulate various physiological changes such as moulting, reproduction, polyethism, and behavioural changes. Due to the complexity of JH pathways and regulation, this has opened new research interests among researchers to fully understand the impact of JHs on every insect species. The relationship of JH titre which change with various abiotic factors such as temperature, photoperiod, and also diet is an interesting area to be explored.

In addition, synthetic JH compounds have been widely applied in insect population control such as IGRs in the pest control industry. Due to its potency and environmental benefits compared to chemical pesticides, synthetic JH products have been widely used in the industry worldwide. Yet, a continuous effort should be conducted to understand the nature of each JH of every insect in molecular level for the production of effective vectors control compound. Nevertheless, the dynamics of JH titres in fly larval development on decomposing bodies might potentially be useful in the field of forensic entomology. As discussed in this review, extensive entomo-biochemistry studies are needed before the data can be applied in real forensic settings.

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**Conflict of Interest**

The author declares that there is no conflict of interest.

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