**Role of retinoic acid as a functional hormone in crustaceans**

**Abstract**

The synthesis, metabolism, physiological, and patho-physiological functions of vitamin A and its active metabolite retinoic acid are well studied in vertebrates. In parallel, there is an increasing recognition of vitamin A and retinoic acid in invertebrates and especially in crustaceans. The discovery of vitamin A and different vitamin A metabolites including 9 *cis*-retinoic acid and all-*trans* retinoic acid is now well documented in crustaceans. Most notably some functional attributes of vitamin A and retinoic acid in the biological framework of crustaceans have been demonstrated. This review aims at giving a comprehensive overview of the retinoid system and the role of retinoids in the regulation of physiological events in crustaceans. To accomplish this task, this review deals with three aspects. The first aspect deals with the discovery of retinoids and its metabolic repertoire in crustaceans and to gain insights into crustacean retinoid system, vertebrate retinoid system was used as background. Second aspect details about the regulatory effects of retinoic acid in the regulation of glucose homeostasis, reproduction, lipid metabolism and limb regeneration. The third aspect deals with genomic and non-genomic mechanisms that underlie retinoic acid mediated regulation of crustacean physiological events. Finally, perspectives on current and possible research are offered.

**Key Words**: Crustaceans, hyperglycemia, lipid metabolism, reproduction, retinoic acid and vitamin A

**Introduction**

Vitamin A also known as retinol (ROL) is one of the important nutrient factors associated with proper development of an organism starting from embryonic period (Menezes and Almeido, 2024). In animals, vitamin A is not synthesized *de novo* and relies exclusively upon ROL, retinyl esters (REs) and pro-vitamin A (mainly beta-carotene) dietary sources (Theodosiou et al., 2010). A wealth of studies till date focused on the retrospective, perspective and prospective facets of retinoid system in biological framework of vertebrates and we cite a few of the major ones here, just as an entry point (Theodosiou et al., 2010; Al Tanoury et al., 2013; Andre et al., 2014; Hammerling et al., 2016; Canete et al., 2017; Das et al., 2019; Wołoszynowska-Fraser et al., 2020; Yee et al., 2021; Niranjana and Supriya, 2023). The role of retinoid signalling in the regulation of biological processes, such as differentiation, embryogenesis, cellular proliferation, apoptosis, normal vision, induction of neural differentiation, motor axon outgrowth and neural patterning, immune based functions, regulation of carbohydrate and lipid metabolism, reproduction and fertility is well appreciated in vertebrates (Maden and Hind, 2003; Md Noh et al., 2019; Carazo et al., 2021; Kim et al., 2021; Chen et al., 2023; Menezes and Almeido, 2024). Though, retinoid system and their physiological significance is well characterized in vertebrates including fishes, while such information is not well established in invertebrates. Here we review, the retinoid system of crustaceans (ecdysozoan group and phylum arthropoda) as these occupy a strategic position as one of the key elements of food sectors like fisheries. Based on the literature available on retinoids in crustaceans, this review presents three major aspects. First aspect deals with biochemistry of retinoid signalling in crustaceans based on the vertebrate background. Second, appreciating the significance of retinoid signalling in crustaceans can be greatly enhanced by integrating our work on crustaceans with other invertebrates and vertebrates. Finally, perspectives on current and possible future research are offered.

**Crustacean retinoid system based on vertebrate retinoid system as background**

The retinoid system can be broadly viewed by considering three components in general (**Fig. 1**): synthesis, storage and signalling aspects of retinoids. Following ingestion, intestinal mucosal enzymes hydrolyse retinyl esters (REs) to ROL, whereas carotenoids are cleaved into retinal (RAL) and then reduced to ROL or oxidised to retinoic acid (RA). Depending on the homeostatic requirements, ROL can undergo either esterification in the form of REs to promote retinoid storage and/or converted into retinal (RAL) and retinoic acid (RA), a biologically active metabolite. With regards to storage of retinoids, liver acts as the storage organ for retinoids. Retinol homeostasis is tightly regulated and as a result, much of the ROL synthesised is converted back into REs for storage in hepatocytes and stellate cells in the liver.

****

**Figure 1**: Schematic representation of key players involved in synthesis, transport, catabolism and signaling of retinoids

**Synthesis:** β,β-carotene1058 15,15’-monooxygenase (BCO-I), β,β-carotene 9-10’-dioxygenase (BCO-II), alcohol dehydrogenases (ADHs), short-chain dehydrogenases/reductases (SDRs), retinaldehyde dehydrogenase (ALDH). **Storage and mobilization:** lecithin:retinol acyltransferase (LRAT), acyl-CoA:retinol acyltransferase (ARAT), acetyl-CoA-retinol acyltransferase (DGAT1), retinyl ester hydrolases (REHs). **Catabolism:** cytochrome P450 family 26 (CYP26). **Transport:** Stimulated retinoic acid protein 6 receptor (STRA6), transthyretin (TTR), retinol binding protein (RBP), cellular retinoic acid binding protein (CRABP), and cellular retinol binding protein (CRBP). **Genomic actions:** Retinoic acid receptors; Retinoic acid receptor (RAR) and retinoic acid X receptor (RXR).

These esters are cleaved and released into the bloodstream as ROL when needed (Marill et al., 2003; Ambrosio et al., 2011). Two enzymes viz., retinol ester hydroxylases (REHs) and ß-carotene 15,15-oxygenase 1 (BCO1) play a key role in the hydroxylation of REs to ROL and symmetrical cleavage of beta carotene to RAL and its subsequent conversion to ROL, respectively (Lampert et al., 2003). During storage of retinoids, transport proteins viz., cellular retinol binding proteins I and II (CRBP1 and II) plays a key role in the transport of ROL to target tissues such as liver. ROL in the enterocytes binds with CRBPII and re-esterified to REs by lecithin:retinol acyltransferase (LRAT) before its secretion into the lymph and circulating REs are transported to the liver for storage. In the hepatocytes, hydroxylation of REs to ROL occurs and binds to CRBPI which in turn transported to hepatic stellate cells and esterified by LRAT thereby its storage in liver. On the other hand, to sustain retinoid levels during inadequate levels of vitamin A, REs stored in the liver are mobilized and converted into ROL by REHs and binds retinol-binding protein 4 (RBP4) before its release into the circulation. Transthyretin, an evolutionary conserved protein is strategic to prevent the excretion of ROL-RBP4 complex. At the peripheral tissues, a transmembrane receptor known as stimulated by retinoic acid 6 receptor (STRA6) facilitates the ROL cellular uptake followed by its conversion into RAL. This step is mediated by two enzyme family members *viz*., the cytosolic alcohol dehydrogenases belonging to the medium-chain dehydrogenase/reductases family and the microsomal retinol dehydrogenases included in the short-chain dehydrogenases/reductases family (Pares et al., 2008), while RAL oxidation occurs via retinaldehyde dehydrogenases (Niederreither and Dolle, 2008; Theodosiou et al., 2010). Alternatively, ROL and RA can also result from symmetrical and asymmetrical cleavage of β-carotene by β,β carotene 15̍-15̍ monooxygenase and β,β carotene 9̍-10̍ monooxygenase, respectively. Accordingly, different isoforms of RA have been discovered such as all-*trans*, 9-*cis* and 13-*cis* RA and their biological significance in vertebrates are also well documented (Andre et al., 2014). Furthermore, studies of Wang (1996) demonstrated that the biotransformation of ß-carotene to RA occurs without the involvement of ALDHs in rabbits. Cell culture studies have shown that cytochrome P450 subunit CYP1B1 catalyses the conversion of retinol to retinaldehyde and RA (Andre et al., 2014). The RA binds with cellular RA binding proteins (CRABPs) and transported to the cell nucleus where RA exerts its genomic actions via retinoid receptors viz., retinoic acid receptors (RAR) and retinoic acid X receptor (RXR). RA mediated non-genomic actions via cell surface receptors have also been demonstrated in vertebrates. It is well known that the homeostasis between synthesis and catabolism of RA are equally important. The later step is mediated by cytochrome P450 family 26 (CYP26), wherein oxidation of RA leads to metabolites such as 4-hydroxy retinoic acid, 4-oxo retinoic acid, 18-hydroxy retinoic acid that are polar, and less potent in nature (Blomhoff and Blomhoff, 2006; Theodosiou et al., 2010).

With regards to crustaceans, researchers focused on the discovery followed by gene repertoire and metabolic aspects of retinoids. Thanks to advanced molecular and analytical techniques that paved a way to the discovery of retinoid system counterparts in basal metazoans also. Studies of Hopkins (2001) measured the levels of retinoid isomers such as all trans retinoic acid (ATRA) and 9-cis retinoic acid (9CRA) in the regenerating limb of *Uca pugilator* and also demonstrated the occurrence of enzymes that convert retinaldehyde to RA in the extracts of *U. pugilator* blastemas. Studies of Hopkins et al. (2008) quantified all-*trans* RA, retinal (RAL), 13-*cis*-RAL, ATRA and 9CRA in blastema’s of regenerating limbs in the fiddler crab, *Uca pugilator* by using HPLC and GC/MS. Studies of Paniagua-Michel and Linan-Cabello (2000) and Linan-Cabello et al. (2003) using diode array spectrophotometer and HPLC quantified the ROL, RAL and β-carotene (provitamin A) in the ovary of the shrimp, *Litopenaeus vannamei*. Studies of Venne et al. (2016) reported the occurrence of endogenous retinoic acid isomers (9CRA and ATRA) in daphnia by using liquid chromatography-triple quadrupole mass spectrometry. We also demonstrated the occurrence of two vitamin A metabolites such as 9CRA and ATRA in the ovaries of mud crabs, *Scylla serrata* using HPLC analysis (Venkaiah et al., 2019). Studies of Durica et al. (2006) demonstrated that the β,β carotene 15̍-15̍ monooxygenase cDNAs have been identified in an EST library of crab blastema tissues. Studies of Huang et al. (2022b) showed that vitamin A in the hemolymph of chinese mitten crab, *E. sinensis* supplemented with vegetable oil, palm oil that is rich in beta carotene. These results tempted us to suggest that the crustaceans can able to convert beta carotene to vitamin A catalyzed by β carotene 15̍-15̍ monooxygenase. This notion needs further authentication. Studies of Gauthier et al. (2023) demonstrated the identification of RA metabolites (all-*trans* 4-oxo and 13-*cis* 4-oxo RA), RA isomers (all-*trans* and 13-*cis* RA) as well as retinaldehyde (RALD) isomers (all-*trans*, 11-*cis,* and 13-*cis* RALD) using liquid chromatography-tandem mass spectrometry in an amphipod crustacean, *Gammarus fossarum*. Studies of Gu et al. (2002) reported that a member of retinoid/fatty acid binding-like protein family, that displayed characteristics of both CRABP and CRBP that can able to bind RA and RAL with similar affinity was isolated from the crustacean *Metapenaeus ensis*. Based on the homology modelling, studies of Ma et al. (2020) have shown that the lipocalin 1 and lipocalin 3 exhibit similarity to retinoic acid binding protein in the ridgetail white prawn, *Exopalaemon carinicauda*. It is noteworthy to mention that the retinoid receptors such as retinoic acid X receptor has been cloned from several crustaceans (Andre et al., 2014). The genome of *Daphnia pulex* also demonstrated the occurrence of RXR ortholog, yet machinery required for retinoid storage, transport and mobilization are missing (Theodosiou et al., 2010). Further, genes related to vertebrate type ALDH1a (an enzyme responsible for RA synthesis) were predicted, while CYP26 homologues, which mediate RA oxidative clearance are also missing from the genome of *D. pulex* (Andre et al., 2014).

To conclude, the complete picture of retinoid system is not yet fully characterized in crustaceans. However, occurrence of retinoids (RAL, RA isomers and RA metabolites), signaling cascade (RXR), transport proteins such as retinoid/fatty acid binding-like protein and biotransformation enzymes such as beta carotene 15̍-15̍ monooxygenase in crustaceans at least in part indicate the occurrence of retinoid metabolism.

**Physiological significance of retinoids in crustaceans**

This section encompasses a possible crosstalk between the involvement of retinoids and endocrine mediated processes such as glucose metabolism, limb regeneration and reproduction in crustaceans (Mantiri et al., 1995; Hopkins and Durica, 1995; Durica et al., 2002; Linan et al., 2004; Zou and Bonvillian, 2003; Reddy and Sainath, 2008; Reddy and Srilatha, 2015; Venkaiah et al., 2019; 2023). To understand the effect of retinoids in the biological framework of crustaceans, it is appropriate to understand the endocrine regulation of carbohydrate metabolism, molting/limb regeneration and reproduction in crustaceans (**Fig. 2**) (Sainath et al., 2013; Reddy and Kishori, 2017; Jayasankar et al., 2020).

 **Figure 2**: Schematic representation of hormonal regulation of glucose metabolism, growth (molting) and reproduction in crustaceans

CHH-Crustacean hyperglycemic hormone; GSH-Gonad stimulating hormone; MOIH - Mandibular inhibiting hormone; MIH -Molt inhibiting hormone; MF - Methyl farnesoate; E – Ecdysteroids; RA-Retinoic acid; VIH/GIH – Vitellogenesis/Gonad inhibiting hormone; XO-SG: X-organ sinus gland complex

- inhibition; + stimulation; ?- not established

 The X-organ-sinus gland (XO-SG) complex located in the eyestalk is the major neuroendocrine center of crustaceans, which secretes a set of multifunctional regulatory peptide molecules, collectively called as CHH family peptides which includes crustacean hyperglycemic hormone, CHH, molt inhibiting hormone, MIH, mandibular organ inhibiting hormone, MOIH, and VIH (also called gonad-inhibiting hormone, GIH). CHH plays an important role in the regulation of glucose metabolism via activation of glycogen phosphorylase system in the CHH-target tissues such as hepatopancreas and muscle tissue. MIH and MOIH are key regulators of ecdysis or molting and reproduction in crustaceans which antagonistically control and coordinate the synthesis of ecdysteroids from the Y-organs and methyl farnesoate, a sesquiterpenoid from mandibular organs, respectively (Nagaraju et al., 2011; Pamuru, 2019). Further, factors like gonad stimulating factor, opoids, biogenic amines, vertebrate type steroids also significantly impact crustacean reproduction (Sainath et al., 2013; Pamuru, 2019).

***Glucose metabolism***

Glucose homeostasis in crustaceans is well known process controlled and coordinated eyestalk peptide hormone crustacean hyperglycemic hormone (CHH) released from the X-organ sinus gland complex (Böcking et al., 2002; Katayama et al., 2002; Fanjul Moles, 2006). Few researchers studied the effect of vitamin A and its metabolites on glucose metabolism in crustaceans. Studies of Zou and Bonvilliain, (2003) and Reddy and Sainath, (2008) have shown that the administration of 9-CRA into the crabs, *U. pugilator* and *O. senex senex,* respectivelyinduced hyperglycemia. Further, Reddy and Srilatha (2015) also demonstrated that 13-CRA injection significantly increased hemolymph glucose levels in *O. senex* in intact crabs in a dose-dependent manner and also an increase in the CHH mRNA.Studies of Venkaiah et al. (2023) demonstrated that the injection of 9-cis-retinoic acid elevated glucose levels accompanied by increased expression levels of CHH mRNA in the freshwater edible prawn, *M. malcolmsonii*. The possible mechanism of retinoic acid induced hyperglycemia in intact but not in eyestalk-less crabs and/or prawns could be as follows: retinoic acid target the cells producing CHH followed by which the CHH from the eyestalks target hepatopancreas and muscle tissue thereby through G protein coupled receptors activate cAMP (Sainath et al., 2013). This step subsequently activates the phosphorylase kinase through protein kinase A which in turn activates glycogen phosphorylase, thereby induces glycogenolysis (Davidson and Sittman, 1999). The glucose resulted from glycogenolysis leaks into hemolymph resulting in hyperglycemia (Sainath and Reddy, 2010; Venkaiah et al., 2023).

To conclude, the findings suggest that exogenous supplementation of retinoic acid at least in part trigger eyestalk hormone, CHH. The chemical nature, mode of action and the target sites of CHH have been extensively studied in several crustaceans (Böcking et al., 2002; Katayama et al., 2002). However, the mechanism of release of CHH into circulation in coordination with other endogenous signals is not clearly understood. The crosstalk between eyestalk peptide and retinoic acid (Reddy and Sainath, 2008; Venkaiah et al., 2023) might be an indication that retinoic acid could promote synthesis of CHH from XO-SG complex thereby hyperglycemia.

***Limb regeneration***

In order to grow in size, crustaceans must shed their old exoskeleton and then expand a new soft, paliant exoskeleton which has been formed beneath the old one and this process is known as molting or ecdysis (Sainath et al., 2013). Many factors affect molting process including nutritional status and whether or not the animal is generating a limb (Hopkins, 2001). In crustaceans, autotomy is a response against injury or predation which ensures that the limb is cast off at a predetermined point at the base of all walking legs and the lost appendages are regenerated before the next molt. Thus, both limb bud regeneration and molting are obligatory linked to each other. Few researchers studied the effect of vitamin A and its metabolites on limb regeneration in crustaceans. Now evidences indicated that the role of retinoid signaling in the regulation of metamorphosis, regenerative growth and limb regeneration in cnidarians, arthropods (lower insects: Eg: *Locusta migratoria* and crustaceans) and non-chordate deuterostome, echinoderms (Hopkins et al., 2008; Nowickyj et al., 2008; Andre et al., 2014; Fuchs et al., 2014; Yamakawa et al., 2018). In decapods, tt has been shown that the precise regulation of hormones such as MIH, MOIH, MF and ecdysteroids during limb regeneration and molting are key factors (Jayasankar et al., 2020). Exogenous studies have shown that the exogenous admisnitration of retinoids may induce precocious limb regeneration in crustaceans, suggesting a crosstalk between endogenous hormones. For example, Blastema of *Uca pugilator* contains retinoids such as 13cis-retinaldehyde and all-trans-retinaldehyde, which can serve as precursors for 9CRA and ATRA and relatively, aldehyde forms were found to be abundant over RA isomers in *Uca* blastemas (Hopkins, 2001; Hopkins et al., 2008). Recent findings of Xing et al. (2024) showed that innexin genes play a vital role in the morphological and molecular changes during limb regeneration of shrimp, *Exopalaemon carinicauda* (Xing et al., 2024). Innexin are cell to cell gap junction proteins that are required for tissue polarity, electrical signalling, directional movement and germ cell maintenance and development (Yue et al., 2023). Studies of Wang et al. (2022) found upregulation of six *Innexin* genes in *E. sinensis*, eight *Innexin* genes in *L. vannamei*, six *Innexin* genes in *M. rosenbergii*, and four *Innexin* genes in *M. nipponensis* after autotomy at 1 day post autotomy. Intriguingly, the effect of retinoic acid on innexin genes during modulation of electrical signals between the cell junctions has been demonstrated in invertebrate, *Lymnaea stagnalis* (Rothwell et al., 2017).

To conclude, the findings suggest that exogenous supplementation of retinoic acid induced limb regeneration might indicate: a) promote ecdysteroidogenesis from Y-organ; b) inhibit MIH from XO-SG and c) both a and b. These conclusions needs further authentication by designing experiments using retinoid blockers and *in vitro* studies targeting Y organs and XO-SG complex.

***Reproduction***

Though mechanisms are poorly understood, studies have shown that exogenous supplementation of vitamin A and its metabolite retinoic acid have significant role in crustacean reproduction. The role of vitamin A in spermatogenesis, oogenesis, and embryonic growth of crustaceans has been demonstrated (Mantiri et al., 1995). This section only deals with ovarian maturation in crustaceans. Linan et al. 2004 observed that the ovarian maturation in *L. vannamei* is due to the trigger of retinol palmitate. Injection of vitamin A metabolites i.e 9-cis retinoic acid and 13-cis retinoic acid in the regulation of ovarian maturation of crustaceans has been demonstrated (Nemec et al., 1993; Girish et al., 2018). Our findings also revealed that the exogenous supplementation of 9-cis retinoic acid resulted in ovarian maturation in mud crabs, *Scylla serrata* as evidenced by significant increase in ovarian index, oocyte diameter, and circulatory ecdysteroid levels (Venkaiah et al., 2023).

To conclude, the findings suggest that exogenous supplementation of retinoic acid induced reproduction might indicate: a) promote ecdysteroidogenesis from Y-organ, methyl farnesoate synthesis from mandibular organ and GSH from thoracic ganglia and brian; b) inhibit MIH, MOIH, G/VIH from XO-SG and c) both a and b. Moreover, retinoids may directly trigger ovarian maturation via vitellogenesis thereby promote crustacean ovarian maturation. These conclusions needs further authentication by designing experiments using retinoid blockers and *in vitro* studies targeting Y organs, thoracic ganglia, and ovaries.

***Lipid metabolism***

There is no question about the importance of lipids to the life of the organism as they serve as structural constituents of biological membranes, acts as insulators of cells, acts as coenzyme factors, precursors of hormones and vitamins thereby sustain structural and physiological integrity of cellular and sub-cellular membranes (Perona et al., 2017). Regulation of lipid metabolism is tightly linked to vitamin A in mammals and fishes (Bonet, et al., 2012; Chen and Chen, 2014; Howell and Chen, 2012). Few researchers studied the effect of vitamin A and its metabolites on lipid metabolism in crustaceans. Studies have shown that the lipids contribute to normal growth, stress resistance and reproduction in crustaceans (Cahu et al., 1994; Jannathulla et al., 2019; Ouraji et al., 2010). Further, a possible link between lipid metabolism and vitamin A supplementation (Shiau and Chen, 2000; Huang et al., 2022a, b and c) was also reported in crustaceans. Studies of Huang et al. (2022a) suggested that vitamin A (6000 IU/kg) exhibited lipid lowering effects in juvenile crabs *E. sinensis* fed with lipid diet (either at 7 or 13% of lipids). Vitamin A supplementation elevated the levels of *aco,cpt1a* and *cpt2* mRNA in high lipid diet fed crabs over its respective controls suggesting enhanced lipid catabolism (Huang et al., 2022a). Studies of Huang et al. (2022a) indicated that elevated *mttp* mRNA levels and VLDL levels associated with a reduction in the levels of TG in the hepatopancreas of crabs subjected to both vitamin A and high fat diet over high fat diet alone group supports the notion that vitamin A supplementation promote VLDL secretion to overcome lipid accumulation under high fat diet. Interestingly, supplementation of vitamin A at 30444 IU/kg in diet revealed down regulation of genes (*ATP-citrate synthase, fatty acid synthase, long-chain-fatty-acid--CoA ligase ACSBG2, sterol regulatory element-binding protein-1, long-chain fatty acid elongase protein 6, acetyl-CoA carboxylase and acyl-CoA delta-9 desaturase*) related to lipid synthesis and upregulation of genes related to lipolysis (*gastric triacylglycerol lipase, intracellular triacylglycerol lipase, inactive pancreatic lipase related protein 1, pancreatic lipase-related protein 2, pancreatic lipase*), β oxidation (*carnitine O-acetyltransferase, carnitine O-palmitoyltransferase 1a, very long-chain specific acyl-CoA dehydrogenase, mitochondrial*), genes related to immunity and antioxidant capacity (*crustin-1, crustin-2, lysozyme, glutathione S-transferase, heme oxygenase 1-like*, and *catalase isozyme 1-like*) (Huang et al., 2022b) in treated crabs over controls. Further, these authors showed a positive effect on growth performance and most notably elevated total antioxidants, superoxide dismutase and catalase associated with decreased lipid peroxidation levels in Vitamin A supplemented juvenile crabs treated with high lipid diet (Huang et al., 2022a and b).

**Possible mechanism(s) of action of retinoids in crustaceans**

It is well known that the retinoids mediated functions in vertebrates can be broadly categorized into genomic (Andre et al., 2014) and non-genomic actions (Piskunov and Rochette-Egly, 2012; Al Tanoury et al., 2013).

Genomic actions of retinoids are mediated by nuclear receptors-type II including the retinoic acid receptor (RAR) family, which includes three isotypes, RARα, RARβ, and RARγ, and the retinoid X receptor (RXR) family, which also includes three isotypes, RXRα, RXRβ, and RXRγ. The members of this family can able to bind ligands such as steroids, thyroid hormones, ecdysteroids, and retinoic acid. RARs are activated by all-*trans* retinoic acid and its stereoisomers, 9-cis-retinoic acid and 13-cis-retinoic acid, whereas RXRs are activated by 9-*cis*-RA. RARs function as RAR/RXR heterodimers. In addition, RXR also heterodimerizes with other nuclear receptors such as thyroid receptors, peroxisome proliferator-activated receptor, and vitamin D receptors and interfere with the transactivation processes of its heterodimeric partner (Matsuda and Kitagishi, 2013; Evans and Mangelsdorf, 2014).

Interestingly, RXR orthologs have been demonstrated in several crustaceans *Celuca pugilator* (Durica et al., 2002), *Gecarcinus lateralis* (Kim et al., 2005), *Marsupenaeus japonicas* (Asazuma et al., 2007), *Daphnia magna* (wang et al., 2007), *Fraxinus chinensis* (Priya et al., 2009), *Carcinus maenas* (Nagaraju et al., 2011), *Homarus americanus* (Tiu et al., 2012) and *Scylla serrata* (Girish et al., 2015). Crustacean RXRcDNA homologs containing intact sequences of DNA binding, hinge, ligand binding, and terminal domains (C-F domains) were isolated (Wang et al. 2007; Nagaraju et al., 2011). Occurrence of RXR transcripts in the embryos of *D. magna* might also indicate the critical role of RXR during embryonic development (Wang et al., 2007).

Non-genomic actions are mediated by MAPK signalling pathways in vertebrates. Nuclear receptors are ligand activated transcription factors that control important functions involved in development, growth, cell differentiation, proliferation, apoptosis, and the maintenance of homeostasis (Mangelsdorf et al., 1994, Chambon, 1996; Wu et al. 2011). RA control and coordinate transactivation of genes via non-transcriptional effects through the phosphorylation activities via activation of mitogen-activated protein kinase MAPK signaling pathway and observed in fibroblasts, mouse embryo carcinoma cells, mammary breast tumor cells, and leukemia cells (Piskunov and Rochette-Egly, 2012). Further, RA mediated signaling kinases such as MAPK and extracellular signal regulated kinases subsequent to the activation of upstream signal transduction events such as Rho GTPases, phosphatidylinositol-3-kinase and protein kinase B suggest the non-transcriptional effects of RA similar to that described for steroid nuclear receptors (Al Tanoury et al., 2013).

**Glucose metabolism**

It has been shown that the regulation of glucose metabolism by vitamin A is wired with genomic and non-genomic actions in vertebrates (Kane et al., 2010; Chen and Chen, 2014; Blaner, 2019; Chen, 2021; Napoli, 2022). Studies from murine beta and alpha pancreatic cell lines revealed that raldh3 (which catalyses the conversion of 13cis-retinaldehyde to 13cis-RA) acts as a novel factor in the regulation of insulin and glucagon levels (Rhee and Plutzky, 2012). Studies also indicated that 9CRA at least in part mediate RXR in the regulation of insulin levels (Chertow et al., 1997; Lenhard et al., 1999; Kane et al., 2010). Surprisingly, RXR but not RAR were discovered in crustaceans and moreover, RXR showed close resemblance to vertebrate RXR, however, no endogenous ligand has been identified in crustaceans against RXR (Andre et al., 2014). Such specific actions of vitamin A in the regulation of glucose metabolism in crustaceans needs to be clarified. Since administration of either CRA induced hyperglycemia in intact crabs/prawns but not in eyestalk ablated crabs/prawns might augment the likelihood of interaction of CRA with its cognate receptor in the eyestalk of crustaceans. Interestingly, expression of RXR has been demonstrated in the eyestalks of crustaceans (Gong et al., 2016; Kluebsoongnoen et al., 2021). Since the RXR isolated from crab has been found to bear a close resemblance to vertebrate RXRs in the ligand-binding domain it is very likely that RA may also have a high affinity to its receptor in eyestalks of the crab.

**Lipid metabolism**

Vitamin A induced effects are mediated by its active metabolite, retinoic acid. Both genomic and non-genomic actions of RA induced regulation of lipid metabolism have been demonstrated in mammals (Amengual, et al., 2010). Non-genomic effects of RA include phosphorylation of p38 MAPK activation eventually leading to the inhibition of transcription of *srebp1* and showed a suppressive role in hepatic lipogenesis (Bonet, et al., 2012; Xiong, et al., 2007; Su et al., 2015). Moreover, the role of vitamin A in lipogenesis was also affected by “genomic effects” (Ziad, et al., 2013) and mediated by RXR which served as heterodimeric partners (Bonet, et al., 2012; Feng, et al., 2019; He et al., 2013; Howell & Chen, 2012). In mammals, the RARE was found inside the promoter of *srebp1* gene, and the expression of which could be induced by activation of RXR (Li, et al., 2011; Repa, et al., 2000). Studies of Huang et al., (2022a) indicated that the RXR mRNA level and *srebp1* mRNA levels are corresponding to each other under high lipid level. Studies of Ren et al. (2023) have shown that the MAPK signaling pathway involved in the regulation of lipid metabolism may play an important role in ovarian development of mud crabs, *S. paramamosian*. This could be attributed to the non-genomic actions of retinoids mediated lipid metabolism.

**Limb regeneration and molting/growth**

The role of ecdysteroids and MF in the regulation of limb regeneration, molting/growth are well acknowledged (Pamuru, 2019). Ecdysteroid hormones play a key role in the regulation of several physiological processes in crustaceans (Subramoniam, 2000). It has been suggested that they can able to bind their cognate partner, ecdysone receptor (EcR), a member of the NR family II. In response to ecdysteroid hormones (e.g. 20-hydroxy-ecdysone and ponasterona A), EcR can able to form obligate heterodimer with RXR [(which is also known as ultraspiracle (USP) in insects] (Techa et al., 2013) and mediate physiological functions like development, metamorphosis, molting, regeneration of appendages, and reproduction (Hall and Thummel, 1998; Hopkins et al., 2008; Lafont and Koolman et al., 2009; Nakagawa et al., 2007; Nowickyj et al., 2008). On the other hand, the role of MF in molting, reproduction, osmoregulation and behaviour is well studied in crustaceans (Nagaraju, 2007). Surprisingly, both RA and MF may act as ligands for RXR in *Uca pugilator* (Hopkins et al., 2008). Studies of Hopkins et al. (2008) indicated the effect of different ligands and their crosstalk with EcR/RXR (isoforms). The findings revealed that EcR binds with ponasterone A with high affinity when it partners with RXR isoform (-33 amino acids) in the presence of ligands 9CRA and methyl farnesoate (MF: a terpenoid synthesized and secreted from mandibular organs in crustaceans and ring gland in insects), while low affinity was observed when EcR partners with RXR isoform (+33 amino acids) in the presence of ligands 9CRA and MF in *U. pugilator* blastemas (Hopkins et al., 2008). In vertebrates, the synergy occurs in RXR/RAR, RXR/thyroid hormone receptor, and RXR/PPAR pairs (Rastenijad, 2022). During synergy of receptors, the transactivation of effects occurs by only one ligand, though both the dimer partners (EcR and RXR) of *U. pugilator* were ligand bounded implying that the RXR subunit of EcR/RXR could be bound to low affinity ligands to maximally ‘sensitize’ the transcriptional activity of the EcR to discrete variation in the concentration of the cognate ligand of its heterodimer partner i.e. EcR (Hopkins et al., 2008). Surprisingly, studies of Wang and LeBlanc, (2009) in *D. magma* demonstrated that RXR can able to bind 9CRA and methyl farnesoate (a terpenoid synthesized and produced by mandibular organs) *in vitro* might indicate EcR-independent RXR signalling pathways. However, such ligand bound RXR might induce transactivation signals or not is yet to be addressed.

**Reproduction**

Studies have indicated that both EcR and RXR at least in part have implications in the regulation of vitellogenesis in crustaceans. Studies of Durica et al., (2002) and Nagaraju et al., (2011) have shown that the reduction in RXR and vitellogenin mRNA levels in the crab, *C. maenas* following treatment with RXR dsRNA and fluctuations in RXR mRNA expression in ovaries during reproduction suggest that RA acts as a reproductive hormone. Nagaraju et al. (2011) showed that the stimulatory effect of MF on vitellogenin expression in the hepatopancreas and ovary of *C. maenas* is greatly reduced when the expression of RXR is knocked down. It was also discovered that RXR forms a heterodimer with the ecdysteroid receptor (EcR) (Nagaraju et al., 2011). This RXR-EcR complex can bind to RA, ecdysteroid (E), or methyl farnesoate (MF) to form a heterotrimeric complex (RXR-EcR-RA/E/MF) and thus regulate a variety of physiological aspects in crustaceans. Studies of Gong et al., (2016) demonstrated that rather than complying with ecdysone or the insect JH, both MF and RXR are thought to play important roles in controlling VTG expression and ovarian development in *S. paramamosain*. Further, Gong et al. (2016) have shown that RXR may be involved in the MF signaling pathway in two routes: a) interacting with EcR through the stimulatory effects of MF and b) interact directly with MF. Studies of Asazuma et al., (2007) investigated that RXR in *M. japonicus* mediates a specific hormonal signal related to reproduction. Studies by Shirley et al. (2012) on the interaction between RXR and farnesoic acid/MF and their effects on target tissues throughout the reproductive cycle, should provide insights into gonad maturation manipulation. Experiments of Cui et al. (2013) indicated that RXR transcripts in the mature ovary of *M. ensis* act as maternal signals for controlling early molting processes during embryonic development. Interestingly, Girish et al. (2018) suggested that the heterodimer, RXR-EcR and its target E75 are important for controlling the synthesis of vitellogenin (VTG) in the hepatopancreas, whereas in the ovary, NR dimers are crucial for controlling the uptake of VTG from the haemolymph, more likely by regulating the levels of VTG-receptor. *In vivo* and *in vitro* studies of Jakkapong et al. (2021) hypothesized that RXR may be an activator protein that modifies VTG expression in shrimp, *P. monodon* ovary by binding to RARE. Studies of Ren et al. (2023) also demonstrated the occurrence of vertebrate type peroxisome proliferator activated receptor (PPAR) viz., ecdysone related proteins (*Sp-Eip75B* and *Sp-Eip78C*) and showed a probable link between MAPK signaling pathway involved during the regulation of ovarian lipid metabolism and PPAR signaling pathway in the regulation vitellogenesis.

**Ligands for Crustacean RXR?**

It is well known that 9-cis retinoic acid is a canonical ligand for RXR in vertebrates (Andre et al., 2014). In vertebrates, the regulation of limb regeneration is controlled and coordinated by retinoic acid signaling including an interplay between 9-cis retinoic acid and RXR (Tabin, 1991). Intriguingly, the regulation of limb regeneration in *U. pugilator* by 9-cis retinoic acid has been demonstrated (Hopkins et al., 2001). Another study by Chung et al. (1998) have shown that the elevated levels of RXR could be associated with limb regeneration followed by exogenous administration of 9-cis retinoic acid. These studies provide a cue towards the occurrence of retinoid signaling pathway in crustaceans. In support to this notion, studies of Hopkins et al. (2008) provided evidence for binding of 9-cis-retinoic acid and MF with RXR.

**Conclusion**

Hormones of diverse nature in several crustaceans exhibit multifunctional properties. For example, peptide hormones of eyestalk XO-SG complex like hyperglycemic hormone which is primarily involved in glucose homeostasis and molt inhibiting hormone which is primarily involved in the regulation of molt cycle participates in molt‐inhibiting activity and glucose metabolism, respectively. Ecdysteroids of the Y-organs which are involved in the regulation of ecdysis/growth also possess morphogenic activity at embryonic stage and also involved in color change and gonadal maturation in crustaceans (Chang et al., 2001). Another cogent example of this trend is the methyl farnesoate of the mandibular organs which are fundamentally involved in morphogenesis at larval period and act as a gonadotropin in adults. These pleiotropism exhibited by crustacean endocrine factors illustrates the amazing economy of nature—a single hormone with multiple functions at different life stages (Chang et al., 2001).

Retinoic acid in crustaceans is another molecule exhibiting multiple biological actions such as regulation of glucose homeostasis, limb regeneration, lipid metabolism and reproduction. At this juncture, an important question arises; how these hormonal signals crosstalk with other endocrine factors and signalling factors to perform many functions in crustaceans during different developmental stages remained to be answered. This is an extremely fertile area for study and may show ultimately unique about the RA that has been conserved during evolution.

Piecing these studies, it can be concluded that the following observations could be deduced: a) endogenous occurrence of retinoids and its metabolites in crustaceans is evident; b) retinoid signalling cascades i.e. CRABPs and RXRs have been identified in crustaceans; c) exogenous supplementation of vitamin A and its metabolite, though limited to few crustaceans only, have demonstrated the physiological significance of retinoids in crustaceans; d) precise regulation of ovarian development by retinoids in crustaceans is still at its infancy and e) elucidation of role of retinoids in the regulation of crustacean reproduction could act as a tool to control ovarian development in brood stocks in captivity and also act as an alternative tool against the eyestalk ablation technique.

Though some physiological role of RA was reported in crustaceans, they are limited to few crustaceans only and hence, its modus operandi is still remaining a puzzle and a reasonably clear picture of the action of RA is still to be emerged. Endocrine factors have a remarkable feature as such several physiological processes may be acted upon by single hormone or several hormones may act on the same physiological process, exhibiting pleiotropism. As such, the need for a poly‐hormonal approach rather than a mono‐hormonal approach appears a logical necessity and such an approach might enable us in gaining a clear concept of the endocrine control physiological process in crustaceans. As RA exerts its effects via genomic involving retinoid receptors and non-genomic actions, poly-hormonal approaches involving RA might be helpful to get clear cut picture of its endocrine role in the biological framework of crustaceans.

Recent findings of Feng et al. (2019) suggested that vitamin A supplementation ameliorate the antioxidant capacity and immunity in crabs, *E. sinensis* against aroclor 1254, a polychlorinated bisphenol. Studies of Gauthier et al. (2023) demonstrated that some chemicals such as juvenile hormone analogs like Methoprene and RA inhibitors like citral might disrupt the RA signalling in an amphipod female crustacean, *G. fossarum*. Tributyltin, a potent agonist of RXR was found to disrupt lipid and carbohydrate metabolism in crustaceans via RXR signalling and CHH, respectively (Vogt et al., 2018). Thus, understanding the retinoid system and its signalling may be helpful in understanding the mechanisms underlying endocrine disrupting chemicals that involve retinoid signalling.

In order to understand the role of vitamin A and its metabolite, retinoic acid studies should be designed in such as a way that whether treatment with combination with a 9CRA and RXR blocker or RXR antagonist abolishes the occurrence of 9CRA-induced hyperglycemia, lipid metabolism, reproduction and molting process needs to be investigated until then the regulation of RA on glucose homeostasis is not clear.

Disclaimer (Artificial intelligence)

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

**References**

Al Tanoury Z, Piskunov A, Rochette-Egly C (2013) Vitamin A and retinoid signaling: genomic and nongenomic effects: Thematic Review Series: Fat-Soluble Vitamins: Vitamin A. J Lipid Res 54(7):1761-1775.

Ambrosio DN, Clugston RD, and Blaner WS (2011) Vitamin A metabolism: an update. *Nutrients* 3(1):63-103.

Amengual J, Ribot J, Bonet M L, Palou A (2010) Retinoic acid treatment enhances lipid oxidation and inhibits lipid biosynthesis capacities in the liver of mice. Cell Physiol Biochem 25: 657-666.

Andre A, Ruivo R, Gesto M, Castro LF, Santos MM (2014) Retinoid metabolism in invertebrates: When evolution meets endocrine disruption. Gen Comp Endocrinol 208:134-145.

Asazuma H, Nagata S, Kono M, & Nagasawa H (2007) Molecular cloning and expression analysis of ecdysone receptor and retinoid X receptor from the kuruma prawn *Marsupenaeus japonicus*. *Comparative Biochemistry and Physiology Part B: Biochemistry and Molecular Biology. 148*(2):139-150.

Blaner W S (2019) Vitamin A signaling and homeostasis in obesity, diabetes, and metabolic disorders. *Pharmacology & Therapeutics 197*: 153-178.

Blomhoff R, & Blomhoff H K (2006) Overview of retinoid metabolism and function. *Journal of Neurobiology 66*(7): 606-630.

Böcking D, Dircksen H, Keller H (2002) The crustacean neuropeptides of the CHH/MIH/GIH family: structures and biological activities. In K. Wiese (Ed.) The Crustacean Nervous System, Springer, NY, pp 84-97.

Bonet ML, Ribot J, Palou A (2012) Lipid metabolism in mammalian tissues and its control by retinoic acid. *Biochimica et Biophysica Acta (BBA) - Molecular and Cell Biology of Lipids 1821*(1): 177-189.

Cahu C, Guillaume J C, Stéphan G, Chim L (1994) Influence of phospholipid and highly unsaturated fatty acids on spawning rate and egg and tissue composition in *Penaeus vannamei* fed semi-purified diets. *Aquaculture 126*(1-2): 159-170.

Cañete A, Cano E, Muñoz-Chápuli R, Carmona R (2017) Role of vitamin A /retinoic acid in regulation of embryonic and adult hematopoiesis. *Nutrients* 9:159.

Carazo A, Macáková K, Matoušová K, Krčmová L K, Protti M, Mladěnka P (2021) Vitamin A update: Forms, sources, kinetics, detection, function, deficiency, therapeutic use and toxicity. *Nutrients 13*(5) Article 1703.

Chambon P (1996) A decade of molecular biology of retinoic acid receptors. FASEB J 10:940-954.

Chang ES, Chang SA, Mulder EP (2001) Hormones in the lives of crustaceans: An overview. Am. Zool 41:1090-1097.

Chen G (2021) The Interactions of Insulin and Vitamin A Signaling Systems for the Regulation of Hepatic Glucose and Lipid Metabolism. Cells10(8):2160.

Chen G, Weiskirchen S, Weiskirchen R (2023) Vitamin A: Too good to be bad? *Frontiers in Pharmacology 14*: Article 1186336.

Chen W, & Chen G (2014) The roles of vitamin A in the regulation of carbohydrate, lipid, and protein metabolism. *Journal of Clinical Medicine 3*(2): 453-479.

Chertow BS, Driscoll HK, Goking NQ, Primerano D, Cordle MB, Matthews KA (1997) Retinoid-X receptors and the effects of 9-cis-retinoic acid on insulin secretion from RINm5F cells. *Metabolism* 46:656–660.

Chung AC, Durica DS, and Hopkins PM (1998) Tissue-specific patterns and steady state concentrations of ecdysteroid receptor and retinoid-X-receptor mRNA during the molt cycle of the fiddler crab, *Uca pugilator*. *Gen Comp Endocrinol* 109:375-389.

Cui J, Wu L, Chan SM, Chu KH (2013) cDNA cloning and mRNA expression of retinoid-X-receptor in the ovary of the shrimp Metapenaeus ensis. Mol Biol Rep 40(11):6233-44.

Das BC, Dasgupta S, Ray SK (2019) Potential therapeutic roles of retinoids for prevention of neuroinflammation and neurodegeneration in Alzheimer’s disease. *Neural Regeneration Research 14*(11):1880–1892.

Davidson VL, & Sittman DB (1999) Biochemistry. Philadelphia PA: Lippincott Williams and Wilkins p 333–340

Durica DS, Kupfer D, Najar F, Lai H, Tang Y, Griffin K, Hopkins PM, and Roe B (2006) EST library sequencing of genes expressed during early limb regeneration in the fiddler crab and transcriptional responses to ecdysteroid exposure in limb bud explants. *Integr Comp Biol* 46:948-964.

Durica DS, Wu X, Anilkumar G, Hopkins PM, Arthur CKC (2002) Characterization of crab EcR and RXR homologs and expression during limb regeneration and oocyte maturation. *Mol Cell Endocrinol* 189:59-76.

Evans RM, Mangelsdorf DJ (2014) Nuclear Receptors, RXR, and the Big Bang. *Cell* 157:255-266.

Fanjul-Moles M L (2006) Biochemical and functional aspects of crustacean hyperglycemic hormone in decapod crustaceans: Review and update. *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology 142*(3-4): 390-400.

 Feng D, Wang X, Li E, Bu X, Qiao F, Qin J, Chen L (2019) Dietary Aroclor1254-induced toxicity on antioxidant capacity, immunity and energy metabolism in Chinese mitten crab *Eriocheir sinensis*: amelioration by vitamin A. *Frontiers in Physiology* 10:722.

 Fuchs B, Wang W, Graspeuntner S, Li Y, Insua S, Herbst EM, Dirksen P, Böhm AM, Hemmrich G, Sommer F, Domazet-Lošo T, Klostermeier UC, Anton-Erxleben F, Rosenstiel P, Bosch TCG, Khalturin K (2014) Regulation of polyp-to-jellyfish transition in *Aurelia aurita*. *Current Biology* 24(3):263-273.

Gauthier M, Daniele G, Giroud B, Lafay F, Vulliet E, Jumarie C, Garric J, Boily M, Geffard O (2023) The retinoid metabolism of *Gammarus fossarum* is disrupted by exogenous all-trans retinoic acid, citral, and methoprene but not by the technical formulation of glyphosate. *Ecotoxicology and Environmental Safety*

 Girish BP, Swetha CH, Reddy PS (2015) Induction of ecdysteroidogenesis, methyl farnesoate synthesis and expression of ecdysteroid receptor and retinoid X receptor in the hepatopancreas and ovary of the giant mud crab, *Scylla serrata*, by melatonin. *General and Comparative Endocrinology* 218:37-42.

Girish, B. P., Swetha, C. H., Srilatha, M., Hemalatha, M., and Sreenivasula Reddy, P. (2018). Evidence for retinoic acid involvement in the regulation of vitellogenesis in the fresh water edible crab, Oziotelphusa senex senex. *Comparative biochemistry and physiology. Part A, Molecular & integrative physiology*, *222*, 1–6.

Gong J, Huang C, Shu L, Bao C, Huang H, Ye H, Zeng C, Li S (2016) The retinoid X receptor from mud crab: new insights into its roles in ovarian development and related signaling pathway. *Scientific Reports* 6:23654.

Gu PL, Gunawardene YI, Chow BC, He JG, Chan SM (2002) Characterization of a novel cellular retinoic acid/retinol binding protein from shrimp: Expression of the recombinant protein for immunohistochemical detection and binding assay. *Gene* 288:77-84.Gudas, L. J. (2022). Retinoid metabolism: new insights. *Journal of Molecular Endocrinology*, *69*(4), T37-T49.

 Hall BL, & Thummel CS (1998) The RXR homolog ultraspiracle is an essential component of the *Drosophila* ecdysone receptor. *Development* 125(23):4709-4717.

Hammerling U (2016) Retinol as an electron carrier in redox signaling: A new frontier in vitamin A research. *Hepatobiliary Surgery and Nutrition* 5(1):15-28.

He Y, Gong L, Fang Y, Zhan Q, Liu HX, Lu Y, et al., (2013). The role of retinoic acid in hepatic lipid homeostasis defined by genomic binding and transcriptome profiling. *BMC Genomics* 14:575.

Hopkins PM, Durica D, Washington T (2008) RXR isoforms and endogenous retinoids in the fiddler crab, *Uca pugilator*. *Comparative Biochemistry and Physiology A* 151:602-614.

 Hopkins PM, Durica DS (1995) Effects of all-trans retinoic acid on regenerating limbs of the fiddler crab, *Uca pugilator*. *Journal of Experimental Zoology* 272:455-463.

Hopkins PM (2001) Limb regeneration in the fiddler crab, *Uca pugilator*: hormonal and growth factor control. *Integrative and Comparative Biology* 41:389-398.

Howell ML, Chen G (2012) Is there a role of vitamin A in hepatic glucose and fatty acid metabolism? *Nutrition & Food Sciences* 2.

Huang Q, Wang X, Bu X, Song Y, Han F, Lin Z, Qiao F, Shi Q, Qin J, Chen L (2022c) Role of vitamin A in the ovary development for female *Eriocheir sinensis* in the gonadal development stage. *Aquaculture* 560:2022.

Huang Q, Wang X, Bu X, Song Y, You J, Zhang C, Qin C, Qin J, Chen L (2022a) Dietary vitamin A affects growth performance, immunity, antioxidant capacity, and lipid metabolism of juvenile Chinese mitten crab *Eriocheir sinensis*. *Aquaculture* 548:737556.

Huang Q, You J, Wang X, Bu X, Song Y, Zhang C, Du Z, Shi Q, Qin J, Chen L (2022b) Effect of vitamin A supplement on the growth performance, antioxidant status, and lipid accumulation of Chinese mitten crab *Eriocheir sinensis* fed different lipid levels. *Aquaculture* 554:738123.

Jakkapong K, Sakol P, Tomasz JS, Udomkit A (2021) Retinoid X receptor modulates vitellogenin gene expression in black tiger shrimp, *Penaeus monodon*. *Comparative Biochemistry and Physiology A* 254:110877.

Jannathulla R, Chitra V, Vasanthakumar D, Nagavel A, Ambasankar K, Muralidhar M, Dayal JS (2019) Effect of dietary lipid/essential fatty acid level on Pacific whiteleg shrimp, *Litopenaeus vannamei* (Boone, 1931) reared at three different water salinities – Emphasis on growth, hemolymph indices, and body composition. *Aquaculture* 513:734405.

Jayasankar, V., Tomy, S., and Wilder, M. N., (2020). Insights on Molecular Mechanisms of Ovarian Development in Decapod Crustacea: Focus on Vitellogenesis-Stimulating Factors and Pathways. Frontiers in endocrinology, *11*, 577925.

Kane MA, Folias AE, Pingitore A, Perri M, Obrochta KM, Krois CR, Cione E, Ryu JY, Napoli JL (2010) Identification of 9-cis-retinoic acid as a pancreas-specific autacoid that attenuates glucose-stimulated insulin secretion. *Proceedings of the National Academy of Sciences USA* 107:21884–21889.

Katayama H, Nagata K, Ohira T, Yumoto F, Tanokura M, Nagasawa H (2003) The solution structure of molt-inhibiting hormone from kuruma prawn, *Marsupenaeus japonicus*. *Journal of Biological Chemistry* 278:9620-9623.

Kim HW, Lee SG, Mykles DL (2005) Ecdysteroid-responsive genes, RXR and E75, in the tropical land crab, *Gecarcinus lateralis*: Differential tissue expression of multiple RXR isoforms generated at three alternative splicing sites in the hinge and ligand-binding domains. *Molecular and Cellular Endocrinology* 242:80-95.

Kim JA, Jang JH, Lee SY (2021) An updated comprehensive review on vitamin A and carotenoids in breast cancer: Mechanisms, genetics, assessment, current evidence, and future clinical implications. *Nutrients* 13(9)

Kluebsoongnoen J, Panyim S, Sarnowski TJ, Udomkit A (2021) Retinoid X receptor modulates vitellogenin gene expression in black tiger shrimp, *Penaeus monodon*. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology* 254:110877.

Lafont R, & Koolman J (2009) Diversity of ecdysteroids in animal species. In: Smagghe G (Ed.), *Ecdysone: Structures and Functions*, Springer Verlag, Netherlands, pp. 47–71.

Lampert JM, Holzschuh J, Hessel S, Driever W, Vogt K, Von Lintig J (2003) Provitamin A conversion to retinal via the beta,beta-carotene-15,15'-oxygenase (bcox) is essential for pattern formation and differentiation during zebrafish embryogenesis. *Development* 130:2173-2186.

Lenhard JM, Lancaster ME, Paulik MA, Weiel JE, Binz JG, Sundseth SS, Gaskill BA, Lightfoot RM, Brown HR (1999) The RXR agonist LG100268 causes hepatomegaly, improves glycemic control, and decreases cardiovascular risk and cachexia in diabetic mice suffering from pancreatic beta-cell dysfunction. *Diabetologia* 42:545–554.

Li R, Chen W, Li Y, Zhang Y, Chen G (2011) Retinoids synergized with insulin to induce Srebp-1c expression and activated its promoter via the two liver X receptor binding sites that mediate insulin action. *Biochemical and Biophysical Research Communications (BBRC)* 406:268-272.

Linan-Cabello M, Paniagua J, Zenteno S (2003) Carotenoids and retinal levels in captive and wild shrimp, *Litopenaeus vannamei*. *Aquaculture Nutrition* 9:383-389.

Linan-Cabello M, Paniagua-Michel J (2000) Carotenoids and retinoids metabolites as precursors of receptor-specific bioactive compounds. *Advances in Shrimp Nutrition*, pp. 19-22.

Linan-Cabello MA, Medina-Zendejas R, Sanchez-Barajas M, Herrera AM (2004) Effects of carotenoids and retinol in oocyte maturation of crayfish *Cherax quadrucarinatus*. *Aquaculture Research* 35(9):905-911.

Ma H, Sun J, Xu W, Gao W, Hu G, Lai X, Yan B, Gao H (2020) Cloning and functional study of lipocalin: Retinol-binding protein-like gene family of the ridgetail white prawn, *Exopalaemon carinicauda*. *Molecular Genetics and Genomics* 295(2):453-464.

Maden M, & Hind M (2003) Retinoic acid, a regeneration-inducing molecule. *Developmental Dynamics* 226(2):237-244.

Mangelsdorf DJ, Umesono K, Evans RM (1994) In: Sporn MB, Roberts AB, Goodman DS (Eds.), The Retinoids: Biology, Chemistry, and Medicine. Raven Press, New York, pp. 319-350.

Mantiri DM, Negre-Sadargues G, Castillo R, Trilles JP (1995) Evolution of carotenoid metabolic capabilities during the early development of the European lobster *Homarus gammarus* (Linna000000000eus 1758). *Comparative Biochemistry and Physiology Part B: Biochemistry and Molecular Biology* 111B:553-558.

Marill J, Idres N, Capron CC, Nguyen E, Chabot GG (2003) Retinoic acid metabolism and mechanism of action: a review. *Current Drug Metabolism* 4(1):1-10.

Matsuda S, & Kitagishi Y (2013) Peroxisome proliferator-activated receptor and vitamin D receptor signaling pathways in cancer cells. *Cancers* 5(4):1261-1270.

Md Noh MF, Gunasegavan RDN, Mustar S (2019) Vitamin A in health and disease. In: *IntechOpen*.

Menezes MSS, Almeida CMM (2024) Structural, functional, nutritional, and clinical aspects of vitamin A: A 00000000000000review. *PharmaNutrition* 27

Nagaraju GPC, Rajitha B, Borst DW (2011) Molecular cloning and sequence of retinoid X receptor in the green crab *Carcinus maenas*: A possible role in female reproduction. *Journal of Endocrinology* 210:379-390.

Nagaraju GPC (2007) Is methyl farnesoate a crustacean hormone? *Aquaculture* 272:39-54.

Nakagawa Y, Sakai A, Magata F, Ogura T, Miyashita M, Miyagawa H (2007) Molecular cloning of the ecdysone receptor and the retinoid X receptor from the scorpion *Liocheles australasiae*. *The FEBS Journal* 274(24):6191-6202.

Napoli JL (2022) Retinoic acid: Sexually dimorphic, anti-insulin, and concentration-dependent effects on energy. *Nutrients* 14(8)

Nemec V, Kodrik D, Matolin S, Laufer H (1993) Juvenile hormone-like effects of retinoic acid in insect metamorphosis, embryogenesis, and reproduction. *Journal of Insect Physiology* 39(12):1083-1093.

Niederreither K, Dolle P (2008) Retinoic acid in development: Towards an integrated view. *Nature Reviews Genetics* 9(7):541-553.

Niranjanaa VBS, Supriya V (2023) Association between vitamin A and cancer: A review. *Sri Ramachandra Journal of Health Sciences* 3:42-45.

Nowickyj SM, Chithalen JV, Cameron D, Walker VK (2008) Locust retinoid X receptors: 9-cis-retinoic acid in embryos from a primitive insect. *Proceedings of the National Academy of Sciences* 105(28):9540-9545.

Ouraji H, Abedian Kenari AM, Shabanpour B, Shabani A, Nezami SA, Sodagar M (2010) Growth response and muscle lipid quality of Indian white shrimp fed different oils at two dietary lipid levels. *Journal of Food Quality* 33(4):405–423.

Pamuru, R. R., (2019). Endocrinology of Reproduction in Crustaceans. IntechOpen.

Pares X, Farres J, Kedishvili N, Duester G (2008) Medium- and short-chain dehydrogenase/reductase gene and protein families: Medium-chain and short-chain dehydrogenases/reductases in retinoid metabolism. *Cellular and Molecular Life Sciences* 65(24):3936-3949.

Perona JS (2017) Membrane lipid alterations in the metabolic syndrome and the role of dietary oils. *Biochimica et Biophysica Acta (BBA) - Biomembranes* 1859(9, Part B):1690-1703.

Piskunov A, Rochette-Egly C (2012) A retinoic acid receptor RARα pool present in membrane lipid rafts forms complexes with G protein αQ to activate p38MAPK. *Oncogene* 31(28):3333-3345.

Priya TAJ, Li F, Zhang J, Wang B, Zhao C, Xiang J (2009) Molecular characterization and effect of RNA interference of retinoid X receptor (RXR) on E75 and chitinase gene expression in Chinese shrimp *Fenneropenaeus chinensis*. *Comparative Biochemistry and Physiology Part B: Biochemistry & Molecular Biology* 153(1):121-129.

Rastinejad F (2022) Retinoic acid receptor structures: The journey from single domains to full-length complex. *Journal of Molecular Endocrinology* 69(4)

Ramachandra, R. P., Kishori, B., (2017). Crustacean Endocrinology: Intriguing Towards Quality Protein Production. J Endocrinol Thyroid Res. 1(2)

Reddy PS, Sainath SB (2008) Effect of retinoic acid on hemolymph glucose regulation in the freshwater edible crab *Oziotelphusa senex senex*. *General and Comparative Endocrinology* 155:496-502.

Reddy PS, Srilatha M (2015) 13-Cis-Retinoic acid-induced hyperglycemia in the freshwater edible crab *Oziotelphusa senex senex* is mediated by triggering release of hyperglycemic hormone from eyestalks. *Journal of Aquaculture Research & Development* 6:356.

Ren Y, Wang W, Fu Y, Liu Z, Zhao M, Xu L, Zhan T, Huang T, Luo M, Chen W, Ma C, Zhang F, Jiang K, Ma L (2023) Comparative transcriptome analysis identifies MAPK signaling pathway associated with regulating ovarian lipid metabolism during vitellogenesis in the mud crab *Scylla paramamosain*. *Fishes* 8(3):145.

Repa JJ, Liang G, Ou J, Bashmakov Y, Lobaccaro J-MA, Shimomura I, Shan B, Brown MS, Goldstein JL, Mangelsdorf DJ (2000) Regulation of mouse sterol regulatory element-binding protein-1c gene (SREBP-1c) by oxysterol receptors, LXRα and LXRβ. *Genes & Development* 14:2819-2830.

Rhee EJ, Plutzky J (2012) Retinoid metabolism and diabetes mellitus. *Diabetes & Metabolism Journal* 36(3):167–180.

Rothwell CM, de Hoog E, Spencer GE (2017) The role of retinoic acid in the formation and modulation of invertebrate central synapses. *Journal of Neurophysiology* 117(2):692-704.

Sainath SB, Reddy PS (2010) Melatonergic regulation of hemolymph sugar levels in the freshwater edible crab *Oziotelphusa senex senex*. *Journal of Experimental Zoology* 313:201-208.

Sainath SB, Swetha C, Reddy PS (2013) What do we (need to) know about the melatonin in crustaceans?. *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology* 319:365-377.

Shiau SY, Chen Y (2000) Estimation of the dietary vitamin A requirement of juvenile grass shrimp *Penaeus monodon*. *The Journal of Nutrition* 130(1):90-94.

Shirley HKT, Ekaterina FH, Koichiro JY, Stephen ST (2012) Farnesoic acid and methyl farnesoate production during lobster reproduction: Possible functional correlation with retinoid X receptor expression. *General and Comparative Endocrinology* 175(2):259-269.

Su CC, Chang CS, Chou CH, Wu YH, Yang KT, Tseng JK, Chang YY, Chen YC (2015) L-Carnitine ameliorates dyslipidemic and hepatic disorders induced by a high-fat diet via regulating lipid metabolism, self-antioxidant capacity, and inflammatory response. *Journal of Functional Foods* 15:497-508.

Subramoniam T (2000) Crustacean ecdysteroids in reproduction and embryogenesis. *Comparative Biochemistry and Physiology Part C: Pharmacology, Toxicology and Endocrinology* 125(2):139-156.

Tabin CJ (1991) Retinoids, homeoboxes, and growth factors: Toward molecular models for limb development. *Cell* 66:199-217.

Techa S, Chung JS (2013) Ecdysone and retinoid-X receptors of the blue crab, *Callinectes sapidus*: Cloning and their expression patterns in eyestalks and Y-organs during the molt cycle. *Gene* 527(1):139-153.

Theodosiou M, Laudet V, Schubert M (2010) From carrot to clinic: An overview of the retinoic acid signaling pathway. *Cellular and Molecular Life Sciences* 67:1423-1445.

Tiu SHK, Hult EF, Yagi KJ, Tobe SS (2012) Farnesoic acid and methyl farnesoate production during lobster reproduction: Possible functional correlation with retinoid X receptor expression. *General and Comparative Endocrinology* 175(2):259-269.

Venkaiah K, Reddy MH, Kiran JP, Sainath SB (2023) Effect of selected retinoids on carbohydrate metabolism in the freshwater monsoon prawn, *Macrobrachium malcolmsonii*. *International Journal of Aquatic Biology* 11(1):22-29.

Venkaiah D, Thathapudi SB, Sainath (2019) Detection and mode of action of retinoids on ovarian development in the mud crab, *Scylla serrata*. *International Journal of Aquatic Biology* pp. 245-253.

Venne P, Yargeau V, Segura PA (2016) Quantification of ecdysteroids and retinoic acids in whole daphnids by liquid chromatography-triple quadrupole mass spectrometry. *Journal of Chromatography A* 1438:57-64.

Vogt ÉL, Model J, Vinagre A. (2018) Effects of organotins on crustaceans: Update and perspectives. *Frontiers in Endocrinology* 9:65.

Wang XD, Russell RM, Liu C, Stickel F, Smith DE, Krinsky NI (1996) Beta-oxidation in rabbit liver in vitro and in the perfused ferret liver contributes to retinoic acid biosynthesis from beta-apocarotenoic acids. *Journal of Biological Chemistry* 271(43):26490-8.

Wang YH, LeBlanc GA (2009) Interactions of methyl farnesoate and related compounds with a crustacean retinoid X receptor. *Molecular and Cellular Endocrinology*.

Wang YH, Wang G, LeBlanc GA (2007) Cloning and characterization of the retinoid X receptor from a primitive crustacean *Daphnia magna*. *General and Comparative Endocrinology* 150(2):309-318.

Wang J, Chen X, Hou X, Wang J, Yue W, Huang S, Xu G, Yan J, Lu G, Hofreiter M, Li C, Wang C (2022) “Omics” data unveil early molecular response underlying limb regeneration in the Chinese mitten crab, *Eriocheir sinensis*. *Science Advances* 8(37).

Wołoszynowska-Fraser MU, Kouchmeshky A, McCaffery P (2020) Vitamin A and retinoic acid in cognition and cognitive disease. *Annual Review of Nutrition* 40:247-272.

Wu Q, Chambliss K, Umetani M, Mineo C, Shaul PW (2011) Non-nuclear estrogen receptor signaling in the endothelium. *Journal of Biological Chemistry* 286:14737–14743.

Xing C, Wang M, Chen Z, Li Y, Zhou X, Wang L, Zhong Y, Li W, Shen X, Gao H, Wang P (2024) Morphological and molecular changes during limb regeneration of the *Exopalaemon carinicauda*. *Animals (Basel)* 14(5):685.

 Xiong Y, Collins QF, An J, Lupo E, Liu H-Y, Liu D, Robidoux J, Liu Z, Cao W (2007) p38 mitogen-activated protein kinase plays an inhibitory role in hepatic lipogenesis. *Journal of Biological Chemistry* 282:4975-4982.

Yamakawa S, Morino Y, Honda M, Wada H (2018) The role of retinoic acid signaling in starfish metamorphosis. *EvoDevo* 9:10.

Yee MMF, Chin KY, Ima-Nirwana S, Wong SK (2021) Vitamin A and bone health: A review on current evidence. *Molecules* 26(6):1757.

Yue W, Yuan R, Jang D, Guo X, Li F, Qian X (2023) Transcriptome analysis of *Litopenaeus vannamei* during the early stage of limb regeneration process. *Israeli Journal of Aquaculture - Bamidgeh* 75:1–10.

Ziad AT, Piskunov A, Rochette-Egly C (2013) Vitamin A and retinoid signaling: genomic and nongenomic effects. *Journal of Lipid Research* 54:1761-1775.

Zou E, Bonvillain R (2003) Effects of 9-cis- and all-trans-retinoic acids on blood glucose homeostasis in the fiddler crab, *Uca pugilator*. *Comparative Biochemistry and Physiology* 136:199-204.