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Review

From Rock Pools to Aquaculture: The Genus *Tigriopus* as an Experimental Model and Emerging Aquaculture Resource

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Abstract

Copepods are widely recognized as biologically superior live prey for many marine fish larvae, yet their routine large-scale production remains a major bottleneck in aquaculture. Within this context, the harpacticoid genus *Tigriopus* has attracted increasing attention because it combines broad environmental tolerance, ease of culture, and promising nutritional and biotechnological value. This review critically examines the current state of knowledge on the genus *Tigriopus*, with particular emphasis on its aquaculture relevance, while integrating the biological, ecological and ecotoxicological framework needed to interpret the specific case of the Mediterranean species *T. fulvus*. The available literature shows that in aquaculture, the potential of this copepod genus is supported by complementary evidence across species. *T. californicus* currently provides the strongest proof of concept for pilot-scale biomass production and biochemical valorization, particularly as a source of omega-3- and astaxanthin-rich biomass. *T. japonicus* contributes most clearly to culture optimization and live-feed application, especially with respect to feeding performance and stocking-density effects. *Tigriopus fulvus*, in contrast, remains an earlier-stage but credible Mediterranean candidate, showing promising diet-dependent naupliar production and survival, although its culture technology is still underdeveloped. Overall, *Tigriopus* should be regarded as a genus of growing relevance for aquaculture, not only as live prey but also as a potential source of functional biomass. Future progress will depend on improved mass-culture methods, feeding optimization, harvesting efficiency, and a comparative species-level framework linking biological traits to specific aquaculture applications.

Keywords: harpacticoid copepods; *Tigriopus fulvus*; live feed; marine larviculture; ecotoxicology

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1. Introduction

Copepods are among the most important components of aquatic food webs and play a central role in the transfer of matter and energy from primary producers to higher trophic levels [1]. Beyond their ecological significance, they have long attracted interest in applied research because they can serve both as experimentally tractable model organisms and as nutritionally valuable live feed in aquaculture [2,3]. In marine hatcheries in particular, copepods are widely recognized as biologically superior prey for many fish larvae because they more closely resemble the natural diet of early developmental stages than conventional live feeds such as rotifers and Artemia.

Within this framework, the genus *Tigriopus* occupies a distinctive position, with species characteristically inhabiting supratidal and upper-intertidal rock pools, where salinity, temperature, oxygen availability, pH, and water volume may fluctuate markedly [4–8]. This ecological specialization, together with short generation time, high fecundity, distinct developmental stages, and laboratory culture feasibility, has supported the use of *Tigriopus* as model organism in ecological and ecotoxicological research [2,9–11].

In ecotoxicology, the genus has become increasingly important because it combines ecological functionality with experimental tractability [9]. In aquaculture, it has gained attention because several species unite broad environmental tolerance with nutritionally valuable biomass [12,13]. Recent work on *T. californicus* (Baker 1912) has shown that biomass production can be achieved in pilot-scale, zero-effluent systems [14], whereas *T. japonicus* (Mori 1938) has been used to investigate feeding performance under different culture densities and food supplies [13].

Another important dimension of the growing relevance of the genus concerns its biochemical profile and functional potential. In addition to the copepod-type advantages typically associated with essential fatty acids, *Tigriopus* has attracted attention because of its pigment content. These properties further strengthen the potential applied value of the genus, particularly in the context of alternative feed resources and functional aquafeed development [15,16].

Among Mediterranean copepods, *T. fulvus* is widely used as a model organism in ecotoxicology [10,11,17–19] and has also been proposed as a promising candidate for aquaculture applications [20]. Recent integrative taxonomic work has clarified that *T. fulvus* should be regarded as a single valid species characterized by marked geographically structured genetic diversity across the Atlantic–Mediterranean area, rather than as a complex of independently evolving infraspecific taxa [21].

In their review, Raisuddin et al. [2] summarized the knowledge then available on the genus *Tigriopus*; however, to date, the literature remains dispersed and the strength of knowledge is uneven among species. Due to the growing interest in biology, ecotoxicology and environmental genomic of *Tigriopus* genus, further findings have recently emerged, especially on the Mediterranean species.

The present review aims to highlight recent research regarding *Tigriopus* spp., with particular emphasis on *T. fulvus* (Fischer, 1860), which provides a useful case through which ecological, ecotoxicological, and applied research can be connected [10,11,20,21]. A comparative overview of the *Tigriopus* spp., discussed in the present review, is provided in Table 1.

Table 1. Comparative overview of research on *Tigriopus* spp. The table summarizes geographic context and the principal applications of the species in ecotoxicology, molecular and omics research, and aquaculture.

Species	Geographic Context	Ecotoxicology	Molecular/Omics Resources	Aquaculture Relevance	Main Scientific Applications	References
T. fulvus	Atlantic–Mediterranean	Standardized acute and chronic test; reproductive and multistressor studies	Still limited compared with the best-developed Pacific congeners	Early-stage aquaculture candidate	Focal Mediterranean species in ecology and ecotoxicology studies with preliminary aquaculture relevance	[2,4,11,17–21]
T. californicus	Northeastern Pacific	Reproductive and multistressor studies	Genomic signature of mitonuclear for population analysis	Pilot-scale biomass production and biochemical valorization	Main comparative species for technological aquaculture development	[2,5,6,14,22,23]
T. japonicus	Northwestern Pacific	Ecotoxicogenomic studies	Whole genome available; strong potential for biomarkers and omics-based approaches	Live-feed applications and culture optimization	Main comparative species for advanced mechanistic ecotoxicology and culture optimization	[2,9,12,13,24–26]

2. *Tigriopus* spp. in Ecotoxicology

The need for ecologically relevant model organisms, to be used in ecotoxicology assays, has progressively directed research towards small invertebrates that combine practical laboratory culturing protocols with a meaningful role in marine ecosystems.

Within this framework, species of the genus *Tigriopus* have emerged as particularly valuable because they are relatively easy to culture and can provide responses at multiple biological levels, from survival and development to reproduction and, for some species, molecular and genomic endpoints.

In their seminal review, Raisuddin et al. [2] identified *Tigriopus* as a promising marine model genus for ecotoxicology and environmental genomics, emphasizing its sensitivity to metals, pesticides, antifouling agents, polycyclic aromatic hydrocarbons (PAHs), PCBs and endocrine-active compounds.

Within this broader genus-level context, *T. fulvus* offers several practical advantages for laboratory testing, including small size, short generation time, high fecundity, distinct post-embryonic stages and year-round culture feasibility [10]. These properties explain why the species was explicitly proposed as a target organism in biological assays already in the mid-2000s and why it later became one of the most useful Mediterranean crustaceans for marine bioassays and water-quality assessment [10,11]. These ecotoxicological studies exploring sex- and age-specific sensitivity to cadmium and copper, indicated that *T. fulvus* responses differ among demographic classes and could not always be reduced to a single generic LC50 estimate. Faraponova et al. [27] showed that responses of *T. fulvus* to cadmium and copper varied according to sex and developmental stage, indicating that the species can reveal biologically structured differences in contaminant sensitivity rather than functioning merely as a generic mortality-endpoint organism. Furthermore, other research extended the species' use to multiple heavy metals and mixtures, reinforcing the view that *T. fulvus* was suitable not only for single-compound toxicology but also for more realistic environmental scenarios, involving co-exposure to different pollutants [28].

A major turning point in the consolidation of *T. fulvus* as a test organism was the development and validation of a standardized acute toxicity protocol. Faraponova et al. [11] reported the interlaboratory comparison of the UNICHIM 2396:2014 method based on synchronized nauplii exposed to copper as reference toxicant. The study involved 11 laboratories and showed that the protocol was simple, rapid, reproducible and suitable for routine use, thereby demonstrating that *T. fulvus* had moved beyond being merely a convenient laboratory species and had become a standardized organism for monitoring and regulatory-oriented applications. The robustness of this framework was reinforced by the historical control analysis of Prato et al. [17], who evaluated more than a decade of laboratory data on negative controls and copper positive controls and found persistently low control mortality, in long-term copepod culture, together with stable copper sensitivity over time. Moreover, such long-term laboratory maintenance of *T. fulvus* did not erode responsiveness, in fact the species retained its value as a robust Mediterranean bioindicator. This result is especially valuable because it addresses a recurrent concern in ecotoxicology, namely the possibility that long-maintained cultures may drift away from the physiological profile relevant for environmental assessment.

The use of *T. fulvus* has since expanded well beyond classical acute mortality testing. One of the clearest demonstrations is the study by Biandolino et al. [18], which combined acute with sub-chronic and chronic exposure effects to copper. Results showed that reproductive traits, such as fecundity and total nauplii production, were more sensitive endpoints than sex ratio and growth. This is an important conceptual step because it shows that the ecotoxicological value of *T. fulvus* lies not only in lethality-based assays, but also in its ability to reveal sublethal effects directly linked to demographic performance. A similar

pattern is evident in nanoecotoxicology; Prato et al. [29], in a chronic 28-day study on ZnO nanoparticles, reported delayed appearance of ovigerous females and reductions in nauplii per brood. These results showed that chronic exposure to ZnO nanoparticles impaired reproductive performance in *T. fulvus*, whereas in acute tests the dissolved/ionic Zn forms were more toxic than ZnO nanoparticles.

Prato et al. [30] investigated both acute and chronic endpoints exposing *T. fulvus* to pharmaceutical compounds, such as amoxicillin and carbamazepine. Results showed that even when survival was not directly affected, several reproductive parameters were altered. These findings are highly relevant because they confirm that environmentally realistic concentrations of pseudo-persistent pharmaceuticals may not cause overt mortality yet still impair biologically meaningful processes such as brood production and hatching dynamics. Multistressor effects are even more evident in Parlapiano et al. [31], who showed that commercial glyphosate formulations became more toxic at higher temperature across several marine crustaceans including *T. fulvus*. Parlapiano et al. [19] extended this line of inquiry through a transgenerational full life-cycle study of carbamazepine under contrasting temperatures. Increasing temperature strongly modulated toxicity and the combined effects of chemicals and temperature became more evident in the F1 generation. These findings place *T. fulvus* squarely within contemporary ecotoxicology, particularly in relation to contaminant–climate interactions.

Another important strength of *T. fulvus* is that it has not been confined to single-compound laboratory toxicology. It has also been incorporated into battery bioassays and effect-based approaches for complex environmental matrices. Faraponova et al. [10] explicitly noted that the species has already been included in bioassay batteries before protocol standardization was formalized. This applied dimension is confirmed by Prato et al. [32], who used *T. fulvus* in the acute assessment of *Ostreopsis* cf. *ovata* toxicity alongside other crustaceans, and by Prato et al. [33], who included the species in a bioassay battery for the ecotoxicological screening of marine sediments from the Ionian Sea. In parallel, Tornambè et al. [34] used *T. fulvus* in the evaluation of diethylene glycol and waters from Adriatic offshore gas platforms. Taken together, these studies showed that *T. fulvus* is useful not only as a laboratory model, but also as an applied tool in multispecies ecotoxicological batteries designed for realistic coastal and industrial scenarios.

Compared with *T. japonicus* and, to a lesser extent, *T. californicus*, *T. fulvus* still lacks the richer genomic, transcriptomic and mechanistic toolkit available in some Pacific congeners [23,24]. Raisuddin et al. [2] already summarized this asymmetry clearly, showing that toxicity and stress-response data were available for *T. fulvus,* but that gene expression and broader genomic resources were much stronger in *T. japonicus* and *T. californicus*. This contrast has become even clearer with the publication of the *T. japonicus* genome, which was explicitly proposed as a resource for marine molecular ecotoxicology [24]. This gap should be viewed not as a weakness of *T. fulvus*, but as a clear research opportunity: the species already has a strong whole-organism foundation and is therefore particularly well suited for future integration with biomarkers, transcriptomics, metabolomics and other mechanistic approaches in Mediterranean multiple-stressor contexts [24]. To highlight the progressive development of *T. fulvus* as an ecotoxicological model, the main applications reported so far are comparatively summarized in Table 2.

Table 2. Main ecotoxicological applications of *T. fulvus*. The table summarizes the development of the species from an early test organism for acute metal toxicity to a Mediterranean whole-organism model used in standardized assays, chronic and reproductive toxicity studies, nanoecotoxicology, multistressor experiments, and bioassay batteries for complex environmental matrices.

Stressor/Test Context	Main Endpoints	Main Findings	Relevance for Model Development	Reference
Cadmium and copper	Mortality; sex- and age-related sensitivity	Toxic response differed according to sex and age	Sensitivity varied according to sex and developmental stage	[27]
Cu, Cd, Hg and metal mixtures	Acute toxicity; mixture effects	Confirmed sensitivity to multiple metals and co-exposure scenarios	Extended use beyond single-compound toxicology	[28]
Copper	Naupliar mortality	Standardized protocol was simple, rapid and reproducible across laboratories	Marked the transition to a standardized test organism	[11]
Copper	Naupliar mortality	Low mortality and stable sensitivity were maintained over time	Confirmed long-term robustness and reliability of the model	[17]
Copper	Survival, growth, sex ratio, fecundity, nauplii production	Reproductive traits were more sensitive than growth and sex ratio	Strengthened the value of *T. fulvus* for chronic and sublethal testing	[18]
ZnO nanoparticles	Reproductive timing and brood output	Reproductive delay and reduced nauplii production were observed	Expanded the model to nanoecotoxicology	[29]
Amoxicillin, carbamazepine and mixture	Survival and reproductive parameters	Reproduction was affected even when survival was not clearly impaired	Confirmed the importance of sublethal reproductive endpoints	[30]
Glyphosate formulations under different temperatures	Acute toxicity under warming conditions	Toxicity increased at higher temperature	Positioned the species within multistressor ecotoxicology	[31]
Carbamazepine under contrasting temperatures	Life-cycle and transgenerational responses	Combined effects were stronger under warming and in F1	Extended the model to transgenerational climate-related ecotoxicology	[19]
Ostreopsis cf. *ovata* toxicity	Naupliar mortality	Increasing naupliar mortality	Supported its use in effect-based approaches	[32]
Marine sediments	Naupliar mortality	Contributed to sediment hazard assessment	Confirmed applicability to realistic environmental matrices	[33]
Diethylene glycol	Bioassay response to complex mixtures	Species useful in offshore-related contaminant assessment	Extended relevance to industrial and coastal monitoring	[34]

3. *Tigriopus* spp. in Aquaculture Studies

The first-feeding phase remains one of the major bottlenecks in marine larviculture [35,36]. Many marine larvae require prey of suitable size, motility and biochemical composition, and conventional live feeds such as rotifers and *Artemia* often do not fully satisfy these requirements [37,38]. For this reason, copepods have continued to attract attention as biologically superior live prey, and reviews across the last two decades have consistently identified the diversification of live-feed systems as a key requirement for sustainable larviculture of both food and ornamental species [3,38–40]. This long-standing interest reflects the fact that copepods are natural prey for many fish larvae and typically provide a more favourable nutritional profile than conventional live feeds, especially with respect to long-chain polyunsaturated fatty acids such as DHA and EPA [41,42]. Under comparable algal feeding conditions, copepods can contain higher proportions of DHA and higher DHA/EPA ratios than rotifers [41]. Copepod lipids are also frequently delivered as phospholipids, which may be advantageous for fish larvae with incompletely developed digestive systems [42].

Within this broader copepod framework, *Tigriopus* combines several traits of potential aquaculture value: relative ease of laboratory culture, broad environmental tolerance, and biomass containing compounds relevant to larval nutrition and aquafeeds. Harpacticoids can often be maintained at comparatively high densities because of their benthic or epibenthic habits, although these habits complicate substrate management and harvesting [43,44]. In *Tigriopus*, interest extends to carotenoids, particularly astaxanthin, which has roles beyond pigmentation and has been associated with antioxidant status, immunity, survival, reproductive performance, and overall fitness in cultured aquatic animals [15,16,22]. Prado-Cabrero et al. [14] noted that *Tigriopus* feeds on detrital material, can produce DHA *de novo*, accumulates astaxanthin from dietary carotenoids, and tolerates wide salinity and temperature variation. More broadly, astaxanthin is widely recognized in aquaculture nutrition as a compound associated not only with pigmentation, but also with antioxidant, physiological and health-related benefits in cultured aquatic animals. Prado-Cabrero et al. [22] showed that *T. californicus* produces the 3S,3′S stereoisomer of astaxanthin. In the pilot-scale green-water bioreactor described by Prado-Cabrero et al. [14], harvested biomass contained 0.79 ± 0.29% EPA, 0.82 ± 0.26% DHA, and 1.89 ± 0.60% 3S,3′S-astaxanthin on a dry-weight basis, while extracted oils contained 14.5 ± 2.0 mg g^{-1} astaxanthin on average. The most significant advance in the cited study is clearly the shift from laboratory culture toward pilot-scale production. The bioreactor is arguably the strongest current proof of concept that the genus can move beyond small live-feed cultures toward technologically relevant production platforms. The system operated for 145 days, produced 3.9 kg wet-weight biomass, achieved an essential amino acid index of 97% for juvenile Atlantic salmon, and maintained stable pH together with continuous nitrate and phosphate removal under zero-effluent conditions [14]. For *T. japonicus*, by contrast, the literature contributes most strongly to culture optimization. Hagiwara et al. [12] evaluated *T. japonicus* as live food for red sea bream (*Pagrus major*) larvae, while Chong et al. [13] examined feeding responses under different food concentrations and stocking densities and found that ingestion declines at high density can be partly compensated by increasing feed concentration. Together, these studies make *T. japonicus* especially useful for understanding one of the main practical bottlenecks in copepod production, namely density-dependent loss of productivity.

Tigriopus fulvus occupies an earlier stage in aquaculture evidence base. Carli et al. [20] demonstrated that diet strongly affects fecundity and survival: yeast-fed animals survived longer and sustained reproduction over a more prolonged period, whereas algae-fed adults produced nauplii more rapidly but for a shorter time. The study established the biological feasibility of naupliar production under controlled feeding conditions. However,

it did not evaluate direct feeding to fish larvae, pilot-scale production, harvesting efficiency, or commercial performance. *Tigriopus fulvus* should consequently be considered a promising but insufficiently validated Mediterranean candidate rather than an established aquaculture resource.

The aquaculture evidence is therefore distributed across species; *T. californicus* provides the strongest proof of concept for pilot-scale biomass production and biochemical valorization, *T. japonicus* provides the clearest direct evidence on live-feed use and density-dependent feeding performance, and *T. fulvus* contributes preliminary evidence on diet-dependent survival and naupliar production [20]. This comparative pattern supports the genus as an emerging resource, but it also shows that no single species currently provides complete evidence from laboratory culture through routine commercial application [3,40].

Practical transfer to commercial hatcheries remains the principal limitation. Rotifers and *Artemia* benefit from standardized production protocols, predictable availability, established enrichment procedures, and relatively simple harvesting and delivery systems [3,37,40]. By comparison, harpacticoid culture may require substrate management, careful density control, frequent harvesting, and reduced turbulence, while productivity gains from more complex continuous systems are not always superior to simpler tray cultures [43,44]. For *Tigriopus spp.*, broad environmental tolerance should therefore not be equated with high or stable productivity. The Messolonghi lagoon population, for example, tolerated a wide salinity range but showed optimal reproduction only under intermediate salinities and suitable algal diets [45]. Before routine hatchery adoption, species-specific culture yields, contamination control, harvesting efficiency, nutritional consistency, larval performance, and cost-effectiveness must be validated against established live feeds.

A comparative overview of the current aquaculture relevance of *Tigriopus* taxa is reported in Table 3.

Table 3. Comparative overview of the current aquaculture relevance of *Tigriopus* taxa. The table distinguishes pilot-scale biomass production, direct live-feed evidence, culture optimization, and preliminary Mediterranean culture studies, together with the principal limitations of each evidence base.

Species	Main Aquaculture Evidence	Main Aquaculture Contribution	Current Bottleneck/Limitation	References
T. californicus	Pilot-scale biomass production in a zero-effluent bioreactor	Strong technological scale-up and production of omega-3- and astaxanthin-rich biomass; supports interest in *Tigriopus* as a source of high-value functional compounds for aquafeeds	Routine hatchery integration or direct feeding validation is still limited	[14,22]
T. japonicus	Live feed uses for red sea bream (*Pagrus major*) larvae	Live-feed suitability and culture optimization, especially with respect to feeding performance and density-dependent productivity	Culture productivity and optimization for large-scale routine use still require improvement	[12,13]
T. fulvus	Diet-dependent fecundity and survival	Biological feasibility for naupliar production under controlled feeding conditions	Direct fish-larval feeding, scalable production, harvesting, and commercial feasibility have not been demonstrated	[20]

4. Habitat, Biology and Ecological Traits of *T. fulvus*

T. fulvus is associated with supratidal and upper-shore rock pools, among the most physically variable habitats of rocky coasts. This habitat is defined by strong physico-chemical instability rather than by stable marine conditions. Rock-pool environments can undergo substantial diel and seasonal changes in temperature, salinity, oxygen concentration, and pH, with the most extreme values often occurring in upper pools that remain isolated from the sea for longer periods [4,7,21]. Water renewal is more strongly related to rainfall and storm splash than to regular tidal flushing. Emersion time, evaporation,

rainfall, algal biomass, pool morphology, and episodic marine splash generate marked microhabitat heterogeneity even among neighboring pools [7].

The integrative taxonomic revision by Vecchioni et al. [21] supports *T. fulvus* as a single valid species with marked geographic genetic structuring across the Atlantic–Mediterranean region; previously recognized infraspecific taxa are better treated as junior synonyms. Its currently recognized distribution is summarized in Figure 1.

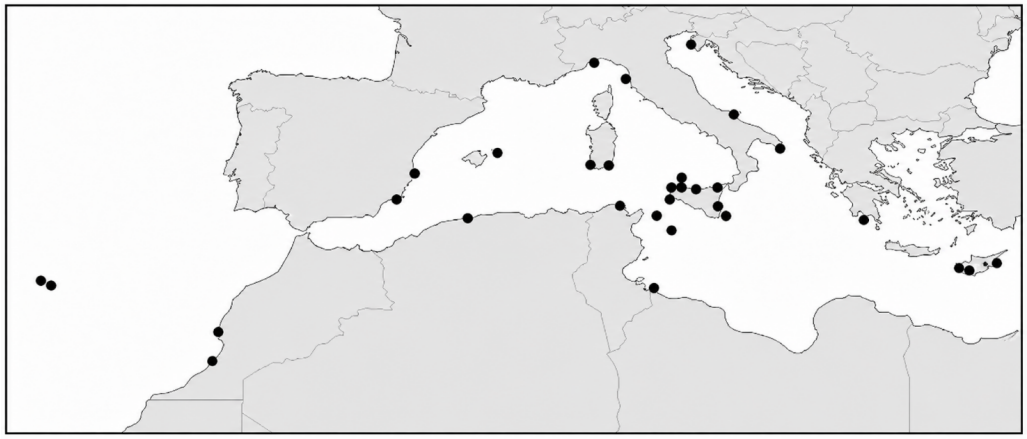


Figure 1. Literature-based geographic distribution of *T. fulvus* across the Atlantic–Mediterranean region. Closed circles indicate occurrence records compiled from the taxonomic and phylogeographic literature [21]. The map was independently generated by the authors and provides the biogeographic framework for the focal species of this review.

Bonello et al. [46] showed that in Ligurian rock pools, the presence and abundance of *T. fulvus* are linked to a combination of salinity, temperature and trophic conditions, and that population buildups coincide with peaks in chlorophyll *a* and total particulate matter. The same study documented a substantial decline in mean copepod density relative to earlier records from the same area, together with warmer conditions and increased salinity, suggesting that *T. fulvus* populations may be vulnerable to ongoing warming and intensified evaporation stress.

From a biological perspective, *T. fulvus* displays life-history traits typical of *Tigriopus* and harpacticoid copepods more broadly. The description of developmental stages nevertheless requires clarification. Fraser [4] described five naupliar stages followed by five copepodid stages before the adult, whereas recent literature generally adopts the standard copepod formulation of 12 post-embryonic stages: six naupliar stages (NI–NVI), five copepodid stages (CI–CV), and the adult stage [2,11]. The latter scheme is therefore used here, while Fraser's account remains an important historical benchmark.

Fraser [4] also reported that the first copepodid stage was reached approximately 15 days after hatching under favorable laboratory conditions, whereas completion of the life cycle required about two months and could be prolonged under unfavorable feeding or environmental conditions. Sex can be distinguished from the fourth copepodid stage onward; females are normally fertilized at the fifth copepodid stage, and a single fertilization can support the production of several egg sacs. No evidence of parthenogenesis was reported. These traits contribute to the experimental tractability of the genus [2].

Reproductive behaviour in *T. fulvus* is more complex than a simple precopulatory clasping system and provides further evidence of fine-scale adaptation. Lazzaretto et al. [47] showed that females release a sex pheromone promoting male attraction and recognition, and that this signal is not only species-specific but also slightly differentiated among geographical populations. Males preferentially clasp virgin females, can discriminate among developmental stages, and may remain in the precopulatory phase from one to

15 days depending on female stage. Delayed fertilization does not alter sex ratio, but it reduces offspring production in older parental individuals. These findings suggest that mate recognition, timing of insemination and reproductive output are tightly connected, and that selection in fragmented rock-pool habitats may act not only on physiological tolerance but also on behavioural and chemical communication traits.

The feeding biology of *T. fulvus* deserves more attention than it has generally received in literature. In the genus as a whole, *Tigriopus* is typically described as a generalist feeder capable of exploiting diatoms, protists, particulate organic matter, detrital material and other food items commonly available in splashpools, a flexibility that likely contributes to its success in highly variable habitats [2,48]. In *T. fulvus*, Carli et al. [20] demonstrated that diet composition strongly modulates both fecundity and longevity: algae-fed females showed a shorter but more intense naupliar production phase, whereas yeast-fed copepods survived longer and maintained reproduction over a more prolonged period, ultimately achieving greater cumulative output. Biologically, these results suggest that *T. fulvus* can shift between rapid short-term reproduction and slower, sustained reproductive investment according to trophic conditions, a pattern consistent with field observations linking population increase to trophic peaks in chlorophyll *a* and particulate matter [46].

One of the defining ecological traits of *T. fulvus* is its tolerance to salinity and temperature fluctuations. Fraser [4] described resistance to temporary desiccation and recovery after rehydration under favorable conditions. Ranade [49] later showed experimentally that the species can survive across a broad salinity range and, under extreme salinities, may enter a reversible state of apparent death; lethal temperature also depended on salinity, indicating interaction between osmotic and thermal stress. At the genus level, Davenport et al. [8] emphasized the unusual tolerance of *Tigriopus* species to the physicochemical extremes of upper-shore pools. Quiescence, retreat into crevices or moist sediment, and rapid recovery when conditions improve are therefore central ecological strategies rather than incidental observations [21].

Another biologically relevant aspect, rarely emphasized in general summaries, is cannibalism. Lazzaretto and Salvato [50] demonstrated cannibalistic behaviour in laboratory-reared *T. fulvus* females toward first-stage non-related nauplii, while mothers spared their own offspring, suggesting some form of mother–offspring chemical recognition. However, later experiments by Gallucci and Ólafsson [51], working comparatively on *T. fulvus* and *T. brevicornis* (Müller 1776), reported predation on nauplii under different conditions and challenged the generality of strict kin discrimination. Taken together, these studies indicate that naupliar predation is likely part of *Tigriopus* biology, but that its expression depends on ecological context, including crowding, food availability and kin structure. This makes cannibalism relevant not only to natural population dynamics but also to laboratory and culture conditions.

At the population level, *T. fulvus* is best interpreted as showing metapopulation-like dynamics, although the evidence remains preliminary. Monitoring of Ligurian rock pools documented strong differences among neighboring pools, occasional local extinction, and pool-specific associations with drought, trophic depletion, and rainfall [46,52]. One pool remained stable and did not dry, whereas others showed stronger fluctuations and extinction events, suggesting a possible source–sink configuration. The authors nevertheless noted that genetic evidence would be required to confirm a true metapopulation structure. Comparative studies of *T. brevicornis* and *T. californicus* similarly show local population dynamics, weak coupling among pools, and high turnover in fragmented supralittoral habitats, but not always a simple classical metapopulation pattern [6,53]. These features help explain the value of *T. fulvus* as a Mediterranean ecological and ecotoxicological model. For

genus-level comparison, the Pacific biogeographic context of *T. japonicus* and *T. californicus* is summarized in Figure 2.

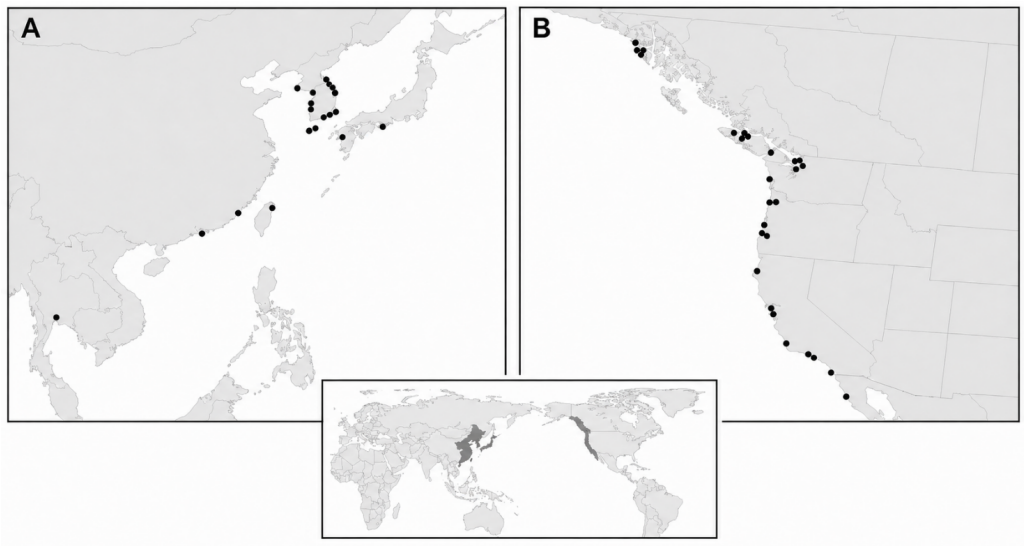


Figure 2. Literature-based geographic distribution of *Tigriopus japonicus* (**A**) and *T. californicus* (**B**). Closed circles indicate occurrence records compiled from the published literature. The maps were independently generated by the authors. The representation of *T. japonicus* follows northwestern Pacific literature and should be interpreted cautiously with respect to legacy Korean records [25,26], whereas the distribution of *T. californicus* is based on published georeferenced localities from the Pacific coast of North America [54].

5. Conclusions and Research Priorities

The literature reviewed here indicates that the genus *Tigriopus* occupies a particularly valuable position at the intersection of ecology, ecotoxicology and aquaculture. Its rock-pool ecology provides a coherent basis for experimental studies of environmental tolerance and adaptation, while its small size, short life cycle, fecundity, and culture feasibility underpin its use in ecotoxicology. Among the principal species considered here, *T. fulvus* has the strongest Mediterranean whole-organism ecotoxicology framework, *T. japonicus* provides the clearest evidence for live-feed testing and culture optimization, and *T. californicus* offers the most advanced demonstration of pilot-scale biomass production.

The aquaculture evidence nevertheless remains less mature than the operational systems available for rotifers and *Artemia*. For *T. fulvus*, current results demonstrate diet-dependent survival and naupliar production, but not routine mass culture, direct hatchery performance, or commercial feasibility. It should therefore be regarded as a promising research candidate whose applied potential requires validation, rather than as an established aquaculture resource.

Four research priorities emerge: (1) harmonize experimental rearing protocol and compare the response of different strains under common conditions; (2) optimize density, diet, substrate, harvesting, and biosecurity in scalable culture systems for aquaculture purposes; (3) evaluate nutritional value, larval performance, and cost-effectiveness directly against established live feeds under hatchery conditions; and (4) expand molecular and omics resources, particularly for *T. fulvus*, given its importance of this species in ecotoxicology studies, to improve understanding of whole-organism responses on different environmental conditions.

Overall, the central conclusion of this review is that *Tigriopus* should now be regarded as a genus of broad interdisciplinary significance. Its ecological specialization helps explain the environmental tolerance underlying its experimental usefulness, while some biological

features support its growing applied relevance in aquaculture. For *T. fulvus*, this review highlights a particularly strong role in Mediterranean ecology and ecotoxicology, together with a promising but still underdeveloped position in aquaculture. More broadly, the future importance of *Tigriopus* will depend on how effectively ecology, ecotoxicology and aquaculture can be integrated into a shared research agenda.

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