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IMMUNOLOGICAL APPROACHES TO DISEASE MANAGEMENT IN SUSTAINABLE AQUACULTURE

Ulviye KARACALAR[1]

1. INTRODUCTION

Infectious diseases pose a significant threat to the sustainability of aquaculture, causing significant economic losses and endangering global food security. The global aquaculture industry must expand to meet increasing demand for protein. Outbreaks controlled by the use of antibiotics have resulted in mortality rates of up to 90% and the loss of entire fish populations. Antimicrobial resistance, environmental pollution and food safety concerns are the main consequences of this practice.

The shift in practice is evolving towards preventive strategies that focus on activating the organisms' natural defense mechanisms rather than treating diseases. Fish and shellfish have a fully functional immune system with both immediate innate immunity and memory adaptive immunity. Once these systems are fully understood, a host prophylaxis approach can be developed. This approach provides valuable contributions to the literature.

Recent literature is reviewed on the use of vaccines and other immune stimulants, such as β-glucans and vitamins, probiotics, and new strategies, including DNA vaccines and

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aptamers, to clinically enhance innate and adaptive immunity in a variety of immunological systems in aquaculture studies. Even though significant advances have been made in developing vaccines for a range of bacterial and viral diseases in the aquaculture sector, there are still substantial knowledge gas, especially in understanding the immune responses in invertebrates and different fish species. One of the major limitations at this stage is the ability to elicit a broad range of immune responses, particularly in invertebrates and across other species; however, it is well known that current knowledge of the invertebrate immune system is also limited.

The present study assesses the role of immunoprophylaxis as a sustainable alternative to traditional antibiotics, with a view that in the future, the establishment of robust systems will contribute to further understanding and integration of host-pathogen interactions and thus ultimately improve the sustainability of aquaculture. The study also investigates the impacts of various immunostimulants and nutritional supplements, vaccination practices, microbiome and probiotic manipulation, and new tools to be developed and applied to support sustainability in aquaculture, while providing a framework on immunology.

2. VACCINATION STRATEGIES IN AQUACULTURE

2.1. The Foundation: Classical Vaccination Approaches

The development of aquaculture health management systems has embraced and continues to expand the use of vaccination as a key component of proactive disease management at the aquaculture facility level. Currently, over 50% of the major bacterial and viral diseases seen in aquaculture can be managed with commercially available vaccines, representing a significant advance in preventive medicine.

The cornerstones of this success are bacterins, vaccines made from inactivated bacterial suspensions. These vaccines have proven exceptionally effective against important pathogens such as *Yersinia ruckeri* and various Vibrio species. These vaccines, with their elegant mechanism of presenting a neutralized version of the pathogen to the immune system, stimulate the production of specific antibodies, resulting in lasting and adaptive immunity.

However, there is a notable exception to this success story. The development of antiparasitic vaccines has been hampered by the challenging process of culturing complex parasites in the laboratory. This process remains prohibitively expensive and technically challenging, leaving a critical gap in the prophylactic arsenal.

2.2. The Next Generation: Advanced Vaccine Technologies

Innovations in vaccine design are pushing the boundaries of disease prevention. Multivalent vaccines, which protect against multiple pathogens in a single dose, are a groundbreaking solution for aquaculture, where mixed infections are common (Priya et al. 2022).They also reduce labor costs by minimizing handling stress on animals.

Meanwhile, subunit vaccines represent a shift toward precision medicine. By utilizing only specific, immunogenic protein fragments of the pathogen rather than the entire organism, they offer a superior safety profile and can be designed to elicit a more targeted immune response. Synthetic peptide vaccines take this a step further, providing unparalleled consistency by using defined amino acid sequences to trigger immunity.

2.3. A Genetic Leap: DNA Vaccines

DNA vaccination is a revolutionary frontier with particular promise for aquatic species. This approach bypasses the need to inject a protein antigen; instead, it introduces a plasmid containing the genetic code for a key pathogen antigen directly into the host's cells. The host's own cellular machinery then produces the antigen, mimicking a natural infection and often provoking a stronger, more comprehensive immune response.

Studies consistently show that DNA vaccines effectively trigger specific antibody production across various fish species (Collins et al. 2019). While comparing results can be complex due to differing conditions, the reliable engagement of the adaptive immune system underscores the potential of this technology to become a pillar of future disease prevention.

2.4. Challenging Dogma: Vaccination in Invertebrates

One of the most exciting developments in recent years challenges a long-held belief. Invertebrates like shrimp lack the immune memory necessary for vaccination (Rowley and Pope 2012). However, groundbreaking research on Pacific White Shrimp has shown that these animals can selectively mount a strengthened immune response upon a second exposure to a pathogen.

Studies with both commercial and laboratory-prepared Vibrio vaccines have documented measurable increases in antimicrobial activity after exposure, suggesting a form of immune memory, or at least a triggered response. This discovery challenges previous assumptions and opens up new possibilities for protecting valuable crustacean stocks against devastating diseases like vibriosis and white spot syndrome.

3. IMMUNOSTIMULANTS AND DIETARY INTERVENTIONS

3.1. Power of Polysaccharides: β-Glucans and Chitosan

Among immunostimulants, polysaccharides, particularly β-glucans, have been the subject of the most extensive research. These complex sugars powerfully activate the innate immune system, enhancing phagocytic cells to more effectively locate and destroy pathogens. They also support critical circulating immune factors such as lysozyme and complement proteins. The advantages of β-glucans are varied and significant. β-Glucans stimulate immune cells in fish, which boosts their ability to engulf and destroy harmful germs (Cook, Hayball, Hutchinson, Nowak and Hayball 2003; Ai et al. , 2007). They also enhance the activity of important proteins in fish blood, such as lysozyme and complement (Ai et al. 2007). Research shows that β-glucans improve the phagocytosis of hemocytes, increase the activity of phenoloxidase, and boost respiratory burst activity. Additionally, they strengthen shrimp's defenses against the white spot virus (WSSV). (Chang, Su, Chen and Liao 2003; Wang, Chang and Chen 2008). In shrimp, they enhance immune parameters such as phagocytosis and phenoloxidase activity, and they can also be degraded into growth-supporting compounds. This dual effect of strengthening defenses and promoting growth makes them particularly attractive for sustainable agriculture (Song et al.2014)

Chitosan, a versatile polysaccharide, is known to promote growth, enhance immune responses, and possess natural antimicrobial properties. Numerous studies have also demonstrated that its ability to bind to particles can provide indirect health benefits by helping improve water quality in culture systems.

3.2. Hormonal Aids: Growth Factors and Lactoferrin

The link between growth and immunity is exploited by hormonal immunostimulants. Studies have shown that growth hormone improves both development and immune function in shrimp larvae. Similarly, supplementing the diet of giant freshwater prawns with bovine lactoferrin increased immune indices and survival rates after bacterial challenge, demonstrating that some mammalian immune molecules can be effectively repurposed in aquaculture.

3.3. Essential Support: The Role of Vitamins C and E

Vitamins C and E are essential nutrients that also act as potent immunomodulators. Vitamin C has been shown to increase lysozyme activity and white blood cell count in turbot, support growth and disease resistance in senescent Asian swamp eel, and improve growth, meat quality, and nonspecific immunity in grass carp. Gao, Wang, Yang, Qu, Liang, Chang, Zhu, and Ma (2008) found that adding 250 mg of vitamin C per kg to the diet of turbot fish greatly boosted the activity of lysozyme and increased the overall number of white blood cells in their blood. Similarly, Cao, Luo, and Yu (2009) showed that vitamin C helps the growth and early development of the Asian Swamp Eel, known as *Monopterus alba*, and enhances its ability to handle stress and fight diseases as it matures. Studies have shown that vitamin E, known as a tocopherol, increases antibody formation and complement activity in response to antigens. Lee and Shiau (2004) reported that diet containing different doses of vitamin E significantly increased the total hemocyte count in *Penaeus monodon* compared to the control group. Zhou, Niu, and Sun (2004) mixed vitamins C and E in diet given to *Trionyx sinensis* (Chinese Softshell Turtle) and found significant improvements in most physiological indices, including blood cell phagocytosis rate, serum bacteriolytic activity, bactericidal activity, and levels of complement proteins C3 and C4. Vitamin E is also known to enhance antibody production and complement activity, for example, significantly increasing hemocyte count in black tiger shrimp.

4. PROBIOTICS AND PREBIOTICS: MANAGING THE MICROBIOME

4.1. Probiotic Applications: Introduction of Beneficial Bacteria

Probiotics have emerged as a powerful strategy in the fight against pathogens. Their flexibility as a feed additive or water supplement makes them highly practical. Studies on probiotics have shown remarkable efficacy in specific strains. *Aeromonas sobria* GC2 bacteria provided 100% survival in rainbow trout battling a deadly parasite, while certain Bacillus strains have been shown to increase the respiratory burst and lysozyme activity in trout and carp, leading to significantly higher survival rates after Aeromonas infection. Nayak, Swain, and Mukherjee (2007) showed that bait supplemented with 108 CFU g-1 *Bacillus subtilis* improved the immunity of carp. Newja-Fyzul et al. (2007) found that 107 CFU g-1 *B. subtilis* AB1-containing bait given to rainbow trout for 14 days significantly improved respiratory burst, antibacterial, serum and intestinal lysozyme activities, and subsequently increased mortality in Aeromonas-infected rainbow trout. Studies have shown that combinations can be even more potent. Salinas, Cuesta, Esteban, and Meseguer (2005) discovered that feeding fish a mix of Lactobacillus and Bacillus at a level of 107 CFU g-1 for three weeks boosted their immune responses. This combination helped Nile tilapia grow faster, increased the activity of their immune cells, and offered strong protection against many different types of harmful bacteria. Studies have even shown striking success with yeast probiotics. For example, the yeast *Debaryomyces hansenii* is known to provide complete protection against a deadly parasite in juvenile leopard groupers.

4.2. Prebiotic Strategies: Feeding Good Bacteria

Instead of adding beneficial bacteria, prebiotics take a different approach, providing specific nutrients that aid the growth of the host's natural beneficial bacteria. Research has shown that when rainbow trout are fed a diet containing 0. 2% ß-glucan, they become less vulnerable to the parasite Ichthyophthirius multifiliis, and their blood shows higher levels of lysozyme activity (Lauridsen and Buchmann 2010). Additionally, feeding *Seriola dumerili* various types of mannan oligosaccharides provided protection against the marine parasitic flatworm *Neobenedenia girellae* (Fernández-Montero et al. 2019). One study found that β-Glucan, which acts as both an immunostimulant and a prebiotic, reduced susceptibility to parasites in rainbow trout, while mannan oligosaccharides provided greater protection against pathogens.

In one promising study, goldfish fed a prebiotic-supplemented diet showed increased lysozyme activity and improved survival rates after parasitic infection with velvet disease, suggesting that prebiotics may be an important tool against protozoan infections that have historically been difficult to control.

5. HERBAL IMMUNOSTIMULANTS: NATURE’S PHARMACY

5.1. Traditional Chinese Medicines

The use of herbal supplements, particularly those derived from Traditional Chinese Medicine, is scientifically validated. Research has demonstrated that the ability of blood white blood cells to engulf and destroy harmful particles in crucian carp, which were fed Chinese herbs (like *R. officinale*, *A. paniculata*, *I. indigotica*, and *L. japonica*), significantly increased during weeks 3 and 4. Additionally, vaccinated fish showed even greater phagocytic activity at week 5 when compared to fish that were not vaccinated (Chen, Wu, Yin, and Li 2003.Furthermore, another study observed a sustained increase in phagocytic activity, a key first line of defense, in fish treated with herbal mixtures such as Astragalus, Andrographis, and Lonicera. One study found significantly higher survival rates in Nile tilapia fed a mixture of Astragalus and Lonicera when experimentally infected with Aeromonas hydrophila. Astragalus (*Astragalus propinquus*) has also been reported to increase phagocytosis of blood cells in soft-shelled turtles (*Pelodiscus sinensis*) (Cao, Sun, and Sheng 1999; Zhou, Niu, and Paz 2003; Misra, Das, Mukherjee, and Meher 2006; Misra et al. 2006; Yin, Ardó, Thompson, Adams, Jeney, and Jeney 2009).

5.2. Antimicrobial and Growth-Promoting Plants

Research has revealed that some plants possess numerous direct growth-promoting and anti-pathogenic properties. A study found that Scutellaria root extract boosts the immune system and directly fights germs like Streptococcus and Pseudomonas (Tan and Vanitha 2004). Additionally, plants like *Alternanthera sessilis*, *Eclipta alba*, and *Cissus quadrangularis* have been seen to increase appetite in freshwater shrimp and enhance the activity of digestive enzymes such as protease, amylase, and lipase (Radhakrishnan, Saravana, Seenivasan, Shanthi, and Poongodi 2014).

Other plants, such as American ginseng and green tea, have also been shown to act as appetite stimulants and to enhance digestive enzyme activity, enhancing nutrient utilization and growth in species such as Nile tilapia and freshwater shrimp.

6. EMERGING TECHNOLOGIES: THE FUTURE OF DIAGNOSTICS AND THERAPEUTICS

6.1. Monoclonal Antibodies: Sensitive Diagnosis

Monoclonal antibodies (MAbs) are crucial reagents for their applications in aquaculture (Gupta et al. 2025). They are molecules with a single type of immunoglobulin structure that can specifically bind to a specific region of an antigen. They are widely used in pathogen classification, disease diagnosis, epidemiological research, and vaccine development (Jeena et al. 2025). These highly specific antibodies enable rapid and accurate identification of pathogens such as Vibrio strains, Aeromonas salmonicida, and various fish parasites. The use of MAbs against viruses in seafood has been revisited for the detection of different IPNV serotypes based on ELISA, and MAbs have also been produced to protect salmonid fish from Infectious Hematopoietic Necrosis (IHN) infection caused by critical and acute IHN virus (IHNV). Currently, MAbs of pathogenic protozoans are being developed primarily for diagnostic and epidemiological studies of *Aphanomyces invadans* and white spot syndrome virus (WSSV) associated with EUS (Epizootic ulcerative syndrome), which will provide valuable feedback for early diagnosis and effective outbreak control.

6.2. Aptamer Technology

Aptamers are synthetic DNA or RNA molecules that, like antibodies, can be designed to bind to specific targets, are stable, easy to synthesize, and precisely tuned. While their use in aquaculture is still emerging, initial results are promising (Yu et al. 2021). The first study on RNA aptamers made by *Rhodovulum sulfidophilum* showed strong antiviral effects against the viral hemorrhagic septicemia virus (VHSV) and Hirame rhabdovirus (HIRRV). Recently, DNA aptamers created to target viruses affecting groupers have greatly lowered the death rate in infected fish. Additionally, similar antiviral effects were seen when antiviral DNA aptamers were used to stop the softshell turtle iridovirus. This technology offers a versatile and promising new frontier in combating aquaculture diseases.

7. RECOMMENDATIONS FOR A HEALTHIER AQUACULTURE INDUSTRY

To realize the potential of immunological strategies for sustainable aquaculture, coordinated action by all stakeholders is essential. Structured and data-driven, constructive recommendations provide a roadmap for producers, researchers, and policymakers.

7.1. Practical Integration for Success at the Aquaculture Industry Level

For the practitioners in the front line, successful adoption of immunoprophylaxis requires strategic implementation and careful management. The whole process of changing from a reactive stance to being proactive can be visualized as a multi-layered health shield. A roadmap could be created based on a set of key indicators in certain stages of this process:

- A Vaccination-Based System: Base a system on the use of all commercially available animal vaccines and consider it not as a cost but the most efficient type of insurance against devastation due to bacterial and viral diseases.
- Immunostimulants as a Strategic Tool: To develop strategies that will lay the groundwork for continued use and not just supplementation of well-researched immunostimulants, such as β-glucans, vitamin C, and vitamin E, to enhance innate immunity during predictable periods of stress, including but not limited to handling,

transportation, and seasonal changes when animals are more vulnerable.

- Healthy Gut Microbiome: Incorporate tested and tried probiotics or prebiotics into regular feeding schedules for the establishment of structural resistance, getting a dual advantage in enhancing both disease resistance and feed conversion.
- Creating an Optimal Environment: Even the most advanced immunological tools can be compromised by poor water quality, overcrowding, or inadequate nutrition; hence, it is important to be fully aware that a non-stressful environment is a prerequisite for the effectiveness of any immune strategy.
- Creating a Data-Driven Operational Framework: Careful record keeping regarding vaccinations, treatments, and mortalities gives very valuable insights. In that respect, the ability to recognize that this information is crucial to enhancing health management plans, showing their value, and making informed decisions for continuous improvement.

7.2. Fostering Innovation for Researchers and Closing Knowledge Gaps

The research community holds the key to the next generation of tools that are going to be applied in the prevention of diseases. At this stage, the preoccupation shifts from mere observation of how things work to understanding how and why they do work, and that findings match with real conditions.

- Mechanism Elucidation: From simply documenting the efficacy, the focus needs to shift to elucidation of cellular and molecular pathways through which these interventions act if intelligent design of next-generation solutions is to be done.

- Standardization and Comparison: The developing field requires comparative studies conducted under standardized conditions. The consensus protocols for assessing immune responses will help make meaningful comparisons between strategies and further advance the field.
- Embracing Combination Therapies: The future for aquaculture health is integrated. Active investigation into the synergistic or antagonistic effects of combining vaccines, immunostimulants, and probiotics will enlighten how this combination can be put to practical use.
- Validating Field Findings: It involves not only the making of laboratory breakthroughs but also the allocation of resources for rigorous field trials under commercial conditions to determine practical efficacy, economic viability, and acceptance by producers.
- Decoding Invertebrate Immunity: The discovery of immune memory-like responses in shrimp is an important paradigm shift. More intensive research will be needed to unravel the mechanisms involved before any form of effective vaccination may be developed for these critically important species.
- Next-Generation Technologies: Additional investment in newer, innovative platforms such as DNA vaccines and aptamer technology is warranted. Although challenging, those are major leaps in efficacy for the world's most elusive pathogens, with a host of new applications.

7.3. Creating an Enabling Environment for Change for Policy Makers

Policy makers can be powerful catalysts for industry-wide transformation by implementing a regulatory and financial environment that fosters innovation and adoption.

- Basic Research Investment: A continuous search for sustainable, long-term funding of research infrastructure is crucial in aquaculture immunology; it will underpin resilience in the sector. Capturing the remaining fundamental knowledge gaps contributes to reducing environmental impact.
- Modernizing vaccine regulations streamlines the vaccine registration process with consideration for the special biology of aquatic species and the scale of aquaculture production without compromising safety or efficacy, removing unnecessary barriers, and supporting rapid delivery of new tools to the market.
- Clarification of the Regulatory Environment for Supplements: Clearly defined science-based regulatory frameworks for immunostimulants, probiotics, and prebiotics will encourage product development and underpin manufacturer confidence in the products they use.
- Promoting the Use of New Ideas or Technologies: Speeding up the shift away from antibiotics through incentive programs will help cost-share vaccination and technical support and provide public recognition to farms that show exemplary reduction in antimicrobial use.
- Closing the Knowledge Gap: Strong extension services, promotional projects, and educational programs require funding and support to allow for effective knowledge transfer that accelerates widespread adoption.

8. KEY ISSUES DISCUSSED

8.1. The importance of integrated immunological management

The most resilient aquaculture operations will be those adopting multilayered health strategies that incorporate immunological interventions at many points. Intervention via vaccination offers the advantage of being targeted and long-lasting but requires a preparation-specific process and is not available for all diseases. Immunostimulating drugs are an ideal choice in times of stress, offering rapid, broad-spectrum support for innate immunity. Probiotics and prebiotics support health by establishing a beneficial microbiome but require consistent application.

Various studies have indeed evidenced that in a synergistic approach, supplementation of feed with immunostimulants during periods of high risk, vaccination with key pathogens, and maintenance of healthy gut flora through probiotics could considerably reduce the need for therapeutic interventions by creating a robust defense against diseases.

8.2. Overcoming Biological and Practical Barriers

One of the main challenges with immunotherapy is the extreme diversity in immune systems among aquaculture species. For instance, a working protocol in Atlantic salmon may fail in Nile tilapia or Pacific white shrimp, and hence, species-specific research becomes a very important consideration. The discovery of immune memory-like responses in shrimp in recent times underlines the vast unknowns related to invertebrate immunity and thus is at once a challenge and a huge opportunity.

Equally important is translating success in the laboratory to commercial reality. The inevitable variability in water quality, especially temperature and stocking densities, of farm environments will compromise the efficacy of many interventions. Logistical and economic barriers, with the major stresses being cost and labor costs, also exist for injectable vaccines.

8.3. Knowledge Gaps and Future Research Directions

Thus, the cellular mechanisms underlying the effects of many immunostimulants remain poorly understood, which, in turn, obstructs the optimization of their use. In this regard, there are critical steps that determine the priorities of basic research:

1. Mechanistic Studies: Elucidating the cellular and molecular pathways of immunomodulation.
2. Comparative Immunology: Systematic mapping of immune responses across commercially important species
3. Protocol Optimization: Assessing the best dosing, timing, and combinations.
4. Field Validation: Full-scale testing of promising methods under relevant aquaculture industry conditions.

9. CONCLUSION

But the pursuit of sustainable aquaculture goes beyond being an economic or environmental challenge; it is an urgent imperative to assure global food security. At the root of this effort, though, is a fundamental shift in how aquatic animal health is maintained. Immunology has emerged as the cornerstone of this new paradigm-a paradigm that shifts from a reactive reliance on antibiotics to one that is proactive and preventive. This is more than a technical improvement; it's a transformation respectful of the complex biology of the animals raised, of the ecosystems within which they operate, and of the consumers. By harnessing the immune system of the animals, one builds not only a more productive system but also one that is more ethical and resilient.

Success stories are both exciting and instructive. Vaccination is the testimony of what is possible. The process has evolved from helplessly watching epidemics decimate stocks to having commercially available vaccines for many of the most devastating bacterial and viral pathogens. This is an enormous achievement, saving countless animals and securing their livelihoods. This innovation goes on with new generations, like DNA and multivalent subunit vaccines, offering more sensitive and flexible protection, particularly for species challenging to treat, such as shellfish. These new developments are not just iterative steps forward; they represent an evolution in the way it is possible to coexist with pathogens without resorting to chemical warfare.

A strong defense requires more than just targeted attacks. This is where the concept of building biological resistance comes into being. Immunostimulants, such as β-glucans, herbs, and vitamins, work by strengthening the animal's basic, innate immune defenses. This broad-spectrum support perfectly complements the specialized intelligence provided by vaccines. Likewise, probiotics and prebiotics are a paradigm of working with nature, not against it, cultivating in the gut a healthy microbiome, hence a naturally hostile internal environment for pathogens, and it has been demonstrated how successful some probiotic strains are in creating a living internal shield for the animal, protecting against a wide array of foes, from bacteria to viruses and parasites.

The future is being shaped in the lab today, and new technologies are extending the envelope. Monoclonal antibodies are revolutionizing disease diagnosis, allowing rapid identification of pathogens with pinpoint accuracy well before an outbreak gets out of control. Aptamers, artificial antibodies, provide a vision of highly specific therapies of the near future that have no, or significantly less, environmental impact. While these newer tools are still in their infancy, their potential to solve some of aquaculture's most significant disease problems is near boundless.

But this wide range of cultured organisms, from fish to crustaceans, does beg the question as to whether there could ever be a universal solution. The immune system of a salmon is very different from that of a shrimp, requiring species-specific, specialized research. There is still a distinct lack of understanding about the mechanisms of action behind many immunostimulants, which hampers efforts toward the optimization of their usage. Perhaps the biggest failing, however, remains the translation of promising, often highly successful, laboratory results into reliable large-scale commercial use-a translation that very often falls short when real-world factors such as water quality and stocking density come into play.

The future of aquaculture health, therefore, is less about finding that one magic solution but is about smart integration. The operations that integrate a web of strategies will be the most successful. Core vaccination programs, strategic use of immunostimulants during periods of high stress, consistent microbiome support through probiotics, and a strong emphasis on optimal environmental conditions are all holistic approaches that will positively reinforce the notion that animal health is a complex, interconnected system. Ultimately, the role and importance of immunology in aquaculture go much further than disease control and underline the fact that immunology is at the heart of making aquaculture genuinely sustainable. By addressing animal welfare, producing safer food, and reducing chemical pollution of ecosystems, it speaks directly to the "One Health" trilogy: the health of animals, humans, and the environment.

Although in a basic sense, the tools are there, the immediate imperative is not to invent but to implement. It will involve placing intelligent strategies at the heart of worldwide aquaculture practice and overseeing the global challenge through collaboration. It is only then that a healthy and plentiful protein source will be available for future generations.

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ANTIMICROBIAL ACTIVITY OF THE ESSENTIAL OIL OF ZATER, LAUREL AND LAVENDER FROM TURKEY ON SOME PATHOGENS

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1. INTRODUCTION

Infectious diseases have posed a serious threat since the existence of life and have caused high rates of morbidity and mortality (Kanra and Kara, 2003). Bacteria that lead to infectious diseases and are very common in nature can be pathogenic for humans and animals. Especially gram-positive species such as Staphylococcus aureus and Enterococcus faecalis and gram-negative species such as *Klebsiella pneumoniae* and *Pseudomonas aeruginosa* can cause infections in both humans and fish and can cause deeper infections due to their toxins.

Staphylococci cause soft skin infections in humans (Gümral, 2009), while in fish, they are characterized by inflammatory reactions and follow a spontaneous and chronic course (Arda et al., 2005). *Enterococci,* on the other hand, cause wound infections and bacteremia in humans (Başustaoğlu and Aydoğan, 2002) and high antibiotic resistance mechanisms and mortality in fish (Rizkiantino et al., 2020). *Pseudomonas* can easily reproduce in humid environments and cause serious

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problems in patients, such as cancer and bone marrow (Şener, 2002), while in fish, it usually causes spontaneous infections and hemorrhagic septicemia (Zeng, 2004).

The success rate in the treatment of fish diseases is generally low. For this reason, prophylactic measures always occupy a crucial place in aquaculture conditions. However, these measures are not enough to prevent diseases, and it has become important to investigate and apply many treatment methods.

The antibacterial effect of medicinal and aromatic plants is of great significance in alternative medicine (Faydaoğlu and Sürücüoğlu, 2011; Küçükgül et al., 2013). In addition, it has been observed that the addition of essential oils obtained from aromatic plants to foods delays oxidative and microbial spoilage and increases storage time, aroma and consumability (Karaton, 2019; Karaton et al., 2021). The unique odors and aromas of these plants have been used in the treatment of diseases for many years, and their therapeutic effects are caused by chemicals such as flavonoids, alkaloids, terpenoids, tannins, berberine, quinine, and emetines, which are the raw materials of the drugs used today (Altınterim et al., 2012; Hosseinzadeh et al., 2015; Küçükgül et al., 2014).

Zater (*Thymbra spicata* L.), which is one of the valuable plant species due to its high content of carvacrol, γ-terpinene, and p-cymene in essential oil components, belongs to the Lamiaceae (Labiatae) family and has been used as food and medicine for many years, especially in Kilis, Hatay and Gaziantep regions of Southeastern Anatolia (Bozkaya et al., 2023; Kılıç, 2006; Küçükgül et al., 2019; Ulusoy, 2008). *Lavandula stoec* has L., popularly known as French lavender, belonging to the same family, grows in many regions of our country and provides antibacterial properties with linalool (20-45%) and linalyl acetate in its content (Ata et al., 2024). It has been reported in many literatures that its antibacterial property is due to the synergistic effect of the minor and major components it contains (Jianu et al., 2013). Laurel (*Lauris nobilis* L.), which is evaluated as a phytotherapeutic with essential and fixed oils of different structures contained in its leaves and fruits, has been the subject of many studies as it is a crucial export plant (Sangun et al., 2007; Karadeniz, 2001). Among the essential oil components, 1,8 cineole (eucalyptol), which is the main component (35-70%), is responsible for the antibacterial effect and has been emphasized by many studies (Tural et al., 2019).

In this study, herbal treatment, which is considered a new treatment strategy against bacterial diseases, one of the leading infectious agents, was emphasized. For this purpose, the antibacterial activity of essential oils obtained from za'atar (*Thymbra spicata* L.), french lavender (*Lavandula stoechas* L.), and laurel (*Lauris nobilis* L.) plants on gram-negative (*Pseudomonas aeruginosa* and *Klebsiella pneumoniae*) and gram-positive (*Enterococcus faecalis* and *Staphylococcus aureus*) bacteria were investigated by disk diffusion and microdilution broth methods.

2. MATERIALS AND METHODS

2.1. Herb

The leaves of za'atar (*Thymbra spicata* L.), french lavender (*Lavandula stoechas* L.), and laurel (*Lauris nobilis* L.) plants collected from Hatay (Turkey) in autumn were dried at 35 ^{o}C and stored.

2.2. Microorganisms

Gram-negative *Pseudomonas aeruginosa* ATCC 27853, *Klepsiella pneumoniae* and gram-positive *Enterococcus faecalis* ATCC 29212, *Staphylococcus aureus* ATCC 29213 clinical isolates obtained from Infectious Diseases Clinical Microbiology Laboratory of Istanbul Medical Park Göztepe Hospital were used in the study.

2.3. Essential oil extraction and Gas chromatography-mass spectroscopy (GC-MS) method

The essential oil was extracted from the dried plant leaves using the hydrodistillation method using Clevenger-type apparatus. The methodology followed by Şarer et al. (1996) and Rasooli and Mirmostafa (2003) was used for this method. The obtained essential oils were stored in glass bottles with dark-colored lids at +4 ^{0}C.

For GC-MS analysis using a Thermo Scientific ISQ SingleQuadrupole model gas chromatograph, a TG-Wax MS-A model, 5% PhenylPolysilphenylene-siloxane, 0.25 mm inner diameter x 30 m length, 0.25 µm film thickness column was used. 70 eVionization energy; m/z 1.2-1200 amu mass range; 250 °C MS transfer line temperature; Auto injector temperature was set to 220 °C. The temperature was programmed to increase from 50 °C to 220 °C by three °C per minute (Adams, 2007). In data collection, the structure of each compound was determined by using the mass spectra with the Xcalibur program using the scan mode (ScanMode).

Hexane (4 ml) was used as a solvent on the obtained essential oils, and antimicrobial analysis was performed.

2.4. Disk diffusion method

First, at the end of incubation (35±1 °C for 24 h) of the bacterial strains inoculated in Nutrient Broth, turbidity was adjusted according to McFarland (0.5) standard tube. Then, they were inoculated onto sterile 45-50 °C Muller-Hinton agar at a ratio of %1 (106 bacteria/ml), shaken well, and 15 ml each were placed in 9 cm diameter sterilized boxes to ensure homogeneous distribution of the medium. Then, 200 µL disks impregnated with plant essential oil samples were placed on the solidified agar and incubated (24 hours at 37±1 °C). The results were determined by taking inhibition zone measurements (mm) in three replicates. The standard antibiotic ampicillin-sulbactam was used as control (Collins and Lyne, 1987).

2.5. Microdilution Broth Method (MIC)

The microdilution test was performed as specified in the NCCLS standard methods with the following modifications (CLSI, 2012). Mueller Hinton Broth (Accumix® AM1072) medium was used for bacteria. Passages of microorganisms were prepared at 37±1 ºC for 18-24 h. Broth cultures were prepared at 25±0.1 ºC, and turbidity was adjusted to 0.5 McFarland standard. These essential oils were first analyzed at a maximum concentration of 100 µL, and then five serial 2-fold dilutions from 100 µL to 6.25 µL were made on aseptic microtiter plates containing broth. Dilutions were checked in broth cultures by reading on an optical density meter. Bacteria were then incubated (18-24 hours at 37±1 ºC) to evaluate the microplates for growth. 50 µL of microorganism suspension was added to each well at $5x10^5$ CFU/mL bacteria. The nominal value of the plants used to prevent the proliferation of microorganisms was defined as the smallest value of that sample, and the last tube without color change in the wells, i.e., without microbial growth, was considered as the MIC value of the plant samples used (mg mL^{-1}). Tests were performed in triplicate.

2.6. Statistical Analysis

Statistical analyses were performed using SPSS 20 (Windows) package program. The conformity of the data to normal distribution was evaluated by the Shapiro-Wilk test. One-Way ANOVA was used to determine the differences between groups, and the Tukey test was used for multiple comparisons.

Quantitative data were expressed as mean ± standard error of the mean (mean ± SD) and $p<0.05$ was considered significant.

3. RESULTS

The chemical composition of the essential oils obtained by hydrodistillation is given in Table 1. As a result of the analysis, considering the proportional size of the main components in the essential oils, it was determined that the main component of Za'atar essential oil was Gamma-Terpinene (35.27%), laurel was Eucalyptol (43.82%), and the french lavender herb was Fenchone (46.12%) (Table 1).

When the disk diffusion findings were evaluated, it was found that it showed a microbiostatic effect on all test microorganisms except *K. pneumoniae* ($p>0.05$) (*P. aeruginosa*: 10.33 ± 0.3^{c} mm, *E. faecalis*: 10.33 ± 0.3^{c} mm and *S. aureus*: 8.6 ± 0.3^{c} mm inhibition zone diameter-1) (Table 2, Figure 1) ($p<0.01$). Compared to the standard antibiotic ampicillin-sulbactam (29.3 ± 0.3^{c}-29.6 ± 0.3^{cd} mm), *P. aeruginosa* showed the same spectrum of effect, while *K. pneumoniae*, *E. faecalis* and *S. aureus* showed a lower ($p<0.01$) or no ($p>0.05$) effect. The inhibition zone ranges determined in za'atar essential oil were 10.3 ± 0.3^{c} mm for *P. aeruginosa* and *E. faecalis*, 8.6 ± 0.3^{c} mm for *K. pneumoniae* and 12.3 ± 0.3^{d} mm for *S. aureus* (Table 2). French lavender essential oil showed a growth inhibitory effect on all tested bacteria except *K. pneumoniae* (10.3 ± 0.3^{c}-8.6 ± 0.3^{c} mm).

When the MIC values of the essential oils were examined, it was determined that for laurel essential oil, *P. aeruginosa* was 100 µL, *E. faecalis*, and *S. aureus* was 50 µL, and at lower concentrations, bacterial growth occurred but was not effective (Table 3). Za'atar essential oil was ineffective (did not inhibit growth) at all MIC values on *P. aeruginosa*, 50 µL on *K. pneumoniae* and *E. faecalis*, and 25 µL on *S. aureus*. The lowest concentration of french lavender essential oil was found to be 25-50 µL in all bacteria except *K. pneumoniae* (Table 3).

Table 1. Chemical composition of essential oils (%)

No	Component	RT	Cas #	TS (%)	LN (%)	LS (%)
1	α -Pinene	3.56	80-56-8	1.34	6.18	3.99
2	β - Pinene	3.62	127-91-3	0.70	3.33	-
3	D-Limonene	3.68	5989-27-5	0.84	-	-
4	Eucalyptol	8.93	470-82-6	-	**43.82**	16.13
5	γ –Terpinene	9.57	99-85-4	**35.27**	0.66	-
6	Cis-sabinene	10.07	3387-41-5	-	12.57	-
7	Fenchone	10.62	1195-79-5	-	-	**46.12**
8	Linalool	11.05	78-70-6	-	-	11.32
9	Borneol	13.12	507-70-0	0.18	0.33	0.30
10	3-Cyclohexen-1-ol	13.39	562-74-3	2.06	1.55	2.28
11	Terpineol	13.85	98-55-5	-	-	1.40
12	D-Carvone	15.38	2244-16-8	-	-	0.82
13	Trans-Sabinenehydrate	15.97	17699-16-0	0.34	1.01	-
14	α –Thujene	16.16	998166-30-8	3.45	1.47	-
15	Chamazulene	16.92	529-05-5	-	-	0.37
16	Thymol	17.11	89-83-8	5.25	-	-
17	Carvacrol	17.39	499-75-2	25.04	-	-
18	Camphene	18.35	79-92-5	-	14.02	3.09
19	β -Bisabolene	18.37	495-61-4	0.30	-	1.54
20	LinalylAcetate	19.27	115-95-7	-	3.18	2.25
21	p-Cymene	19.84	99-87-6	13.30	2.34	0.63
22	α –Terpinene	19.85	99-86-5	6.46	1.99	-
23	Eugenol	19.94	97-53-0	-	2.84	-
24	Caryophyllene	20.02	87-44-5	-	-	0.84
25	α-Cadinine	22.33		0.73	-	-
26	β-Myrcene	22.64	123-35-3	3.27	-	1.29
27	Spathulenol	25.50	6750-60-3	-	0.60	-
28	β – Caryophylleneoxide	25.58	1139-30-6	-	-	2.24
29	T-muurolol	25.23	19435-97-3	-	-	2.74
30	β-eudesmol	26.31	473-15-4	-	2.71	-
31	Terpinolene	28.6	586-62-9	-	0.22	-
	Total			**98.53**	**98.82**	**97.35**

TS: Thymbra spicata; LN: Lauris nobilis; LS: Lavandula stoechasRT: Retention time on a HP-5MS column

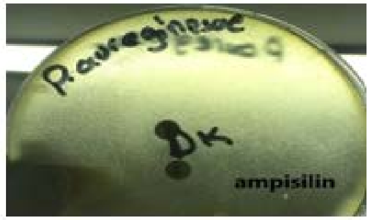
Table 2. Disc diffusion results to understand whether *Lauris nobilis, Thymbra spicata, Lavandula stoechas* essential oils or not prevent the proliferation of microorganisms

Fish Pathogen Microorganisms	**Inhibition Zone Diameter (mm inhibition zone^{-1})**			
	Herb essential oil			**Positive control**
Bacteria	LN	TS	LS	**Standard Antibiotic**
P. aeruginosa	10.3±0.3 c	10.3±0.3	10.3±0.3c	10.3±0.3 c
K. pneumoniae	-	8.6±0.3c	-	29.6±0.3 cd
E. faecalis	10.3±0.3 c	10.3±0.3	8.6±0.3c	29. 3±0.33 cd
S. aureus	8.66±0.3c	12.3±0.3d	10.3±0.3c	29.3±0.33 c

LN: *Lauris nobilis,* TS: *Thymbra spicata,* LS: *Lavandula stoechas,* **Positive Control:** ampicillin-sulbactam 20 µg disk^{-1}. Negative control was not used. Interpretation of zone diameters (mm); zone diameter>11 mm (bactericidal; p<0.0001; cd, p<0.001; d), bacteriostatic= 8-10 c: p<0.01, not sensitive (-) (a: p>0.05)

Table 3. Antibacterial effects of LN: *Lauris nobilis*, TS: *Thymbra spicata*, LS: *Lavandula stoechas* essential oils at the lowest dosage (MIC:100 µL)

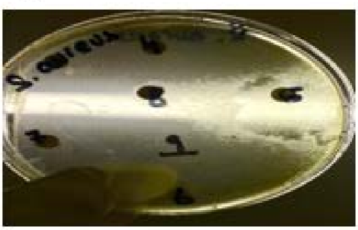
Microorganisms	**MIC(µL)**		
	MIC Levels		
Bacteria	*Lauris nobilis*	*Thymbra spicata*	*Lavandula stoechas*
P. aeruginosa	**100**	**-**	**50**
K. pneumoniae	**-**	**50**	**-**
E. faecalis	**50**	**50**	**25**
S. aureus	**50**	**25**	**50**

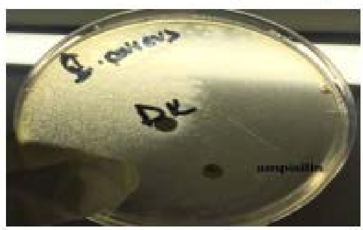


P. aeruginosa *P. aeruginosa*

K. pneumoniae *K. pneumoniae*

E. faecalis *E.faecal*





S. aureus *S. aureus*

Figure 1. Disk diffusion method (250 µL disc^{-1}) and antimicrobial properties of 4. *Lauris nobilis*, 5.*Thymbra spicata*, 9. *Lavandula stoechas* essentials in petri dishes ampicillin-sulbactam:20µg disc^{-1}.

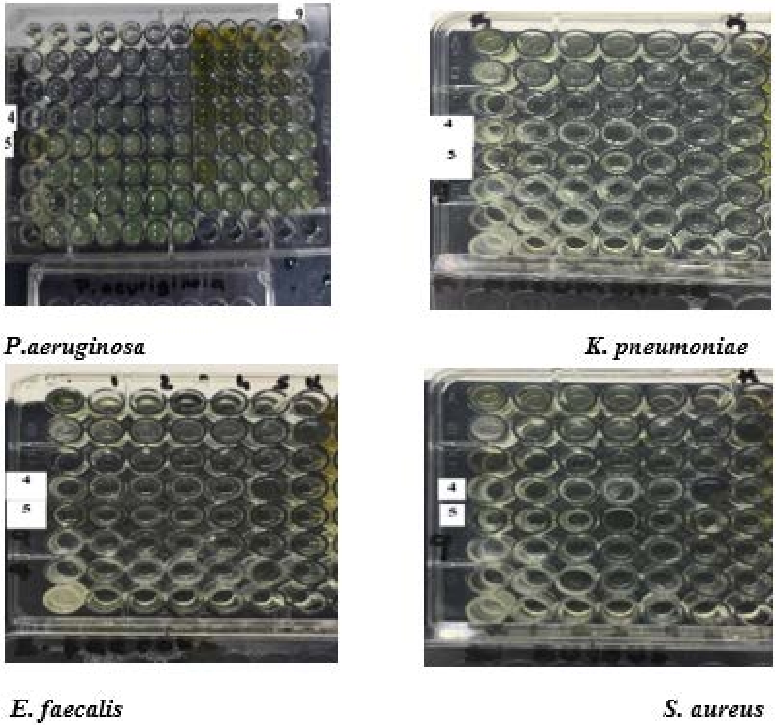


Figure 2. Minimum inhibition concentration (MIC: 100 µL) and antimicrobial properties of 4. *Lauris nobilis,* 5. *Thymbra spicata*, 9. *Lavandula stoechas* essentials in microplate. There are five wells in the microtiter. Well 1; cultures of microorganisms added to essential oil. Dilutions were made in wells 2.3.4.5.6 in the microplate. From wells 2 to 6, broth media (100, 50, 25, 12.5, 6.25 µL of essential oil addition + 50 µL of microorganism cultures). Wells marked with 4, 5, and 9 are the concentrations of essential oils from 100µL to 6.25 µL.

3. DISCUSSION

Bacterial infections, which are the leading infectious diseases that occur in stress and stress-related conditions, bring serious problems. Antibiotic treatment, which has been used for many years in the treatment of these diseases (Timur and Timur, 2003), has been reported to cause more harm than good as a result of antibiotic resistance, and therefore new treatment strategies have been sought (Deniz et al., 2024; Peterson et al., 2002; Schouten et al., 1999).

The fact that Turkey has a rich flora, the awareness of medicinal and aromatic plants, especially since ancient times, and the knowledge of their therapeutic efficacy, as well as many other advantages that can be counted, have focused scientists on working on this subject and led them to the conclusion that it can be applied as an alternative to eliminate the negativities of chemical drug applications.

In this study, the antibacterial activity of essential oils obtained from various parts of za'atar, french lavender, and laurel plants on *P. aeruginosa*, *K. pneumonia*, *E. faecalis* and *S. aureus* bacteria was investigated in terms of chemical components, disk diffusion, and MIC properties and the results were compared with other studies, and their importance was emphasized.

Lauraceae family laurel (*L. nobilis*) is one of the characteristic plants of the Mediterranean (Seçmen et al., 1995, and stands out with its antibacterial activity (especially the essential oil content of its leaves) (Sangun et al., 2007). In a study conducted in Hatay, the essential oil contents of laurel leaves were evaluated, and 1,8-cineole (46.61-59.94%) was obtained as the major component (Sangun et al., 2007). In another study, 1,8-cineole (31.87-67.56%), α-terpinyl acetate (4.09-22.22%), α-terpineol (0.94-16.08%), linalool (0.40-13.04%), terpinen-4-ol (2.31-9.22%) and sabinene (0.56-9.08%) were detected (Karık et al. 2015). In this study, eucalyptol (1,8-cineole) (43.82%), camphene (14.02%), α-pinene (6.18%), linelilacet (3.18%), p-cymene (2.34%), α-terpinene (1.99%), etc. were determined and were in agreement with other studies. Active substances such as carvacrol and thymol in the content of za'atar, a commercial product in the Lamiaceae family, have been studied by many researchers and reported to be a strong antiseptic (Kılıç, 2006; Kubulay et al., 2016). Koçer (2021) obtained cymene (7.17%), c-terpinene (12.30%), ocimene (10.05%), and carvacrol (65.15%) as major components. In another study, it was reported that the highest percentage (29.08%) was carvacrol, followed by γ-terpinene (18.11%), P-cymene (11.22%) and α-Terpinene (4.14%) (Maral and Kırıcı, 2019). Bayan et al. (2017) reported 78.53% carvacrol, 10.42% γ-Terpinene, and 5.49% p-cymene as the main components in T.spicata essential oil. Our results are consistent with previous studies. French lavender, which belongs to the family of honeybushes, originates from the Mediterranean region, and flavonoids obtained especially from the flower parts show a bacteriostatic effect (Nakipoğlu and Otan, 1994). In many studies, it has been determined that the major components of french lavender essential oil contain fenchone and camphor (Giray et al., 2008; Hassiotis, 2010). In a study in which linalool (20-45%) and linalyl acetate (25-46%) were determined as major components, minor components were reported as limonene, eucalyptol, terpin-4-ol and lavandulol (Góra and Lis, 2012). In this study, which is in parallel with the literature, the main component was reported as fenchone (46.12%). In conclusion, the chemical constituents of the essential oil of these species were very similar to other studies. However, the variations observed in the amounts are estimated to be caused by the effect of harvesting, the period when the plant was collected, climatic conditions, local differences, etc.

In the evaluation of the antibacterial effects of the applied essential oils, the inhibition zones formed around the pathogens give important clues. In a study in which the antimicrobial activity of *L. nobilis* leaves was determined on *S. aureus, B. subtilis, P. aeruginosa, E. coli, Candida albicans* and *Aspergillus niger* bacteria, Santoyo et al. (2006) found that *S. aureus* was the most sensitive microorganism with the highest inhibition zone (25 mm). Many essential oils of plants, including za'atar, were examined for antibacterial activity on some microorganisms, and it was reported that the most resistant microorganisms were *S. pyogenes* and *S. aureus* with a zone diameter between 8-50 mm (Akcan et al., 2007). In another study by Ünlü et al. (2009), *T. spicata* essential oil was tested on 21 bacteria and seven fungal species, and a strong antimicrobial activity was determined with a zone diameter between 10-50 mm. In previous studies, it has been reported that the essential oil of french lavender is a strong antiseptic on bacteria such as *Staphylococcus aureus* and S. *epidermidis* (Dülger and Uğurlu, 1998), *E. coli*, *Listeria monocytogenes*, *Salmonella Typhimurium* and *S. aureus* (Dadalioglu and Evrendilek, 2004). In our study, which was in parallel with other studies, it was observed that inhibition zones ranged between 8-13 mm and the highest antibacterial activity was achieved with 12.3 mm of za'atar essential oil against S. *aureus*. The lowest inhibition zone diameter (8.66 mm) was determined for *K. pneumoniae*, *E. faecalis* for french lavender, and *S. aureus* for laurel essential oil. As stated in the literature, it is thought that the antibacterial activity of essential oils in this study may be related to the synergistic effect of major and minor compounds in the essential oil composition (Ünlü et al., 2002; Cimanga et al., 2002).

Another test that determines the antibacterial effect is MIC values. In studies on the subject, Alzoreky and Nakahara (2003) reported that laurel (*Laurus nobilis*) essential oil has bactericidal activity against *L. monocytogenes* and other pathogens; Çenet and Toroğlu (2006) reported that it showed an antibacterial effect on *S. aureus*, *E. coli*, and other pathogens. In a study investigating the antimicrobial activity of *T. spicata* essential oil against some bacteria (*E. coli*, *S. typhimurium*, *S. aureus* and *L. monocytogenes*), MIC values were reported as 0.30, 0.30, 0.60 and 1.25, µg/mL, respectively (Markovic et al., 2011). In another study, *T. spicata* essential oil showed a broad spectrum effect on many bacterial and fungal species, and the range of MIC values was reported to be 0.60-4.5 mg/ml (Ünlü et al., 2009). Oyardı (2015) showed that *T. spicata* essential oil showed lower MIC values (16-64 µg/ml) on all microorganisms except *M. tuberculosis* (MIC: 128 µg/ml). The laurel essential oil's MIC values in this study were determined as *P. aeruginosa* 100 µL, *E. faecalis* and *S. aureus* 50 µL. Za'atar essential oil did not inhibit the growth of *P. aeruginosa*, but effective MIC values were observed on others (*K. pneumoniae* and *E. faecalis*-50 µL, *S. aureus*-25 µL. The lowest concentration of french lavender essential oil was found to be 25-50 µL in all bacteria except *K. pneumoniae*. The differences observed between the MIC and disk diffusion results in this study, which are consistent with other studies, are probably due to species differences, application doses, and seasonal differences affecting the chemical structure of the essential oil.

4. CONCLUSION

In our study, laurel and french lavender essential oils showed a microbiostatic effect on other microorganisms except for *K. pneumoniae* ($p>0.05$), while za'atar essential oil showed a microbiostatic effect on S. *aureus* ($p<0.01$) and microbicidal effect on others ($p<0.001$). Studies have suggested the synergistic effect of small components in the chemical composition in relation to the antimicrobial activity of essential oils (Gill et al., 2002). The interaction between essential oil compounds can produce four possible types of effects: indifferent, additive, antagonistic, or synergistic. Essential oils containing aldehydes or phenols such as cinnamaldehyde, citral, eugenol, carvacrol, or thymol as main components have been reported to show the highest antibacterial activity, followed by essential oils containing terpene alcohols. From this point of view, it is understood that the components such as eugenol, carvacrol, and thymol, which are major in the essential oil components we tested, provided an antibacterial effect, and results were obtained in accordance with other studies. In addition, the antibacterial activity of the natural plant oils used in our study, based on the statements in previous literature studies, the absence of residue problems, and the microbicidal and microbiostatic effect of these essential oils proved that these essential oils have the quality of curing diseases caused by resistant bacteria.

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Conflict of Interests

The authors declare that there are no conflict of interests.

The Animal Welfare and Ethics Statement

This study was in vitro and no animals were used. Therefore, ethical approval is not required.

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MORPHOLOGICAL ANOMALIES IN ROTIFERS AND CLADOCERAN

Ahmet BOZKURT[1]

1. INTRODUCTION

Zooplankton, as the second link in the food chain for energy transfer from producers to consumers, are a vital component of the aquatic environment (Sharma et al., 2010). They play an essential role in the aquatic food chain and significantly contribute to the development and functioning of aquatic ecosystems (Moss, 1988; Lampert and Sommer, 1997). This group of planktonic organisms purifies various aquatic environments by filtering water in natural ecosystems and serves as a crucial food source for many fish larvae and invertebrates (Sharma, 2020). Zooplankton abundance and composition are closely linked to water quality and, depending on the trophic levels of the aquatic environment, act as indicator organisms for assessing water characteristics, pollution levels, and eutrophication status (Berzins and Pejler, 1987). Zooplankton significantly influence the pelagic food web by transferring photosynthetic energy to higher trophic levels and are important in regulating the annual catch rates of commercial fish populations, especially during the first feeding stage of fish larvae and in later stages.

Rotifera, a vital component of freshwater biota, are essential for the functioning of aquatic ecosystems. Rotifers, one of the three principal groups within freshwater aquatic

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ecosystems, serve as model organisms and play a crucial role in numerous trophic networks (Wallace et al. 2006). This phylum comprises around 2,200 documented species, predominantly found in freshwater habitats (Fontaneto et al. 2008; Wertheimer 2024).

Polymorphism is the phenomenon in which several monogonont rotifers display phenotypic variations in response to environmental stimuli, typically attributed to kairomones from predators, as well as fluctuations in water temperature and trophic levels. Polymorphism in rotifers is significant because morphological variation can influence life history, population dynamics, and ecological interactions (Gilbert, 2017). Laboratory biological tests have shown that environmental contamination from common metals can alter the size and morphology of rotifers (Ríos-Arana et al., 2007; Xue et al., 2017). Rotifer morphological abnormalities have been reported as a result of both identified and unidentified factors (Alvarado-Flores et al., 2015; Pérez-Yañez et al., 2019; Coelho et al., 2019). Some researchers have linked environments contaminated by industrial and urban waste to the occurrence of morphological anomalies in zooplankton (Omair et al., 1999; Elmoor-Loureiro, 2004; Zanata et al., 2008; Sousa et al., 2011). Biological studies have also shown that certain environmental toxins can cause morphological defects in cladocerans (Shurin and Dodson, 1997; Otha et al., 1998). Significant anomalies in cladocerans and copepods, presumably due to human activity, have been recorded in Lake Michigan (Omair et al., 1999). Sex-linked character abnormalities in postabdominal males and ephippial females of Alona affinis have been documented, similar to those observed in an adult male from a Russian lake (Sinev, 2000).

Numerous contaminants from domestic wastewater and stormwater runoff infiltrate urban drainage systems, resulting in significant pollution (Rodak et al., 2019; Bega et al., 2021). Urban reservoirs contaminated by various pollutants pose a serious threat to aquatic organisms (Pérez-Coyotl et al., 2019). Toxic compounds entering surface water bodies can eradicate more vulnerable species and cause morphological and physiological changes in other populations, leading to a decline in ecosystem services.

Appendage asymmetry, sexual integration, and deformation of postabdominal claws are the most common anomalies observed in cladocerans, which are a major component of aquatic ecosystems (Smirnov, 1974; Shurin and Dodson, 1997). Notably, several previously undocumented unusual specimens of Ilyocryptus spinifer Herrick, 1882 (Crustacea, Anomopoda, Ilyocryptidae) were discovered in the Apipucos urban reservoir in northeastern Brazil (Elmoor-Loureiro, 2004).

Cladoceran morphological abnormalities have been associated with various natural and environmental events. Factors contributing to the acceleration of eutrophication in aquatic environments include: a) removal of vegetation, urbanisation, agriculture, and sewage discharge (Brito et al., 2011); b) increased nutrient concentrations in water due to faeces and uneaten feed from aquaculture in reservoirs, leading to nutrient enrichment; c) proliferation of cyanobacteria, such as Microcystis aeruginosa, which produce toxic compounds (Hanazato, 1991; Reichwaldt et al., 2013); and d) the presence of hormones, pharmaceuticals (Flaherty and Dodson, 2005), pesticides (Hanazato, 2001), and the degradation of physical and chemical water parameters. The continuous influx of pollutants into aquatic ecosystems reduces the reproductive rates of organisms, resulting in the extinction of larger species. These conditions hinder energy transfer within the food chain (Sibley and Hanson, 2011) and biogeochemical cycles (Romo et al., 2013), thereby compromising ecosystem functionality (De Melo et al., 2017; Mallasen et al., 2012).

Pesticide-induced environmental contamination affects organisms at various biological levels. These impacts are globally significant, as Kohler and Triebskorn (2013) identified 120 pesticides as endocrine disruptors (EDs), particularly affecting aquatic organisms, with documented consequences such as deformities, stunted growth, and embryo mortality. Vinclozolin (VZ), a pesticide found as a contaminant in drinking water, is a commonly used fungicide for fruits and vegetables and causes significant harm to invertebrate species (Papadopoulou-Marukidou 1991).

Substances such as cadmium, iron, copper, lead, and manganese have been associated with alterations in the ventral margin of the shell in various Daphniidae species (Zanata et al., 2008). Deformation of the shell and a coiled caudal spine have been reported in Daphnia gessneri Herbst, 1967. Herbst (1967) also identified Ceriodaphnia silvestrii Daday, 1902, Bosmina longirostris (Müller, 1776), and Bosmina tubicen Brehm, 1953, and noted intestinal problems in Chydorus pubescens (Sars, 1901) as being linked to sewage discharge and eutrophication (De Melo et al., 2017). Soesbergen (2021) suggested that trunk deformation observed in B. longirostris resulted from exposure to certain xenobiotics.

2. SUBSTANCES AFFECTING ZOOPLANKTON MORPHOLOGY

2.1. Impact of cadmium on the rotifer *Philodina cf roseola*

Deformations were observed in the foot, head, and mid-body of the rotifer *Philodina cf. roseola*. Cadmium has been reported to affect the cuticle structure and hardness of Bdelloidea rotifers, causing morphological alterations that vary with exposure duration and concentration (Pérez-Yañez et al., 2019).

In a 24-hour cadmium toxicity assessment, the irregularities shown in Figure 1 were found in 0.76% of organisms at a concentration of 0.282 mg/L Cd, 23.4% at 0.47 mg/L, and 55.9% at 1.0 mg/L (Pérez-Yañez et al., 2019).

Cadmium, present in aquatic ecosystems through both anthropogenic and natural sources, poses significant risks to aquatic organisms and human health (Bernard, 2008). The ionic form of cadmium (Cd_2^+) is commonly released into the environment as compounds with oxygen (CdO_2), chloride ($CdCl_2$), or sulphate ($CdSO_4$) (Kabata-Pendias, 2001), with an estimated annual release of around 300,000 tonnes (Nava-Ruiz and Mendez-Armenta, 2011). Cadmium, noted for its high persistence and widespread distribution in groundwater, has been documented at concentrations between 0.02 and 0.062 mg/L, and is recognised as persistent, toxic, and bioaccumulative (Mackay et al., 2018).

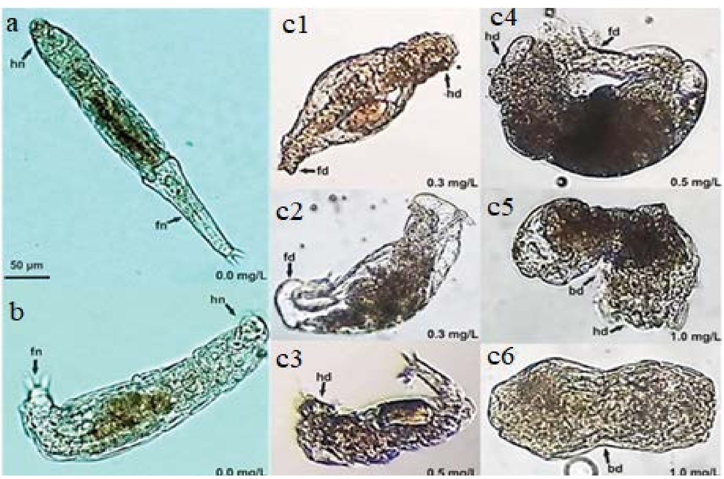


Figure 1. Cadmium-induced deformations in *Philodina cf roseola*. a-b) Normal individuals. c1-c6) Organisms in which deformations were observed at various cadmium concentrations: fn) normal foot, hn) normal head, hd) head deformation, fd) foot deformation, bd) deformation in the mid-body part (Pérez-Yañez, et al., 2019).

2.2. Impact of Vinclozolin Applications on *Brachionus Calyciflorus* Pallas 1766

Vinclozolin (VZ) fungicide was found to cause significant morphological alterations in Brachionus calyciflorus Pallas 1766 (Alvarado-Flores et al., 2015). Tests with VZ on *B. calyciflorus* showed that it induced abnormalities in females at exposure levels between 0.4 and 5.6 mg/L. At a concentration of 1.2 mg/L VZ, aberrant female production was observed in 0.66% of the total female population. Additionally, various abnormalities were detected in all examined rotifers using scanning electron microscopy. The identified deformities included: a) enlarged vitellarium (Figure 2b), b) dwarfism (Figure 2c, c1), c) bent spines (Figure 2d, d1), d) squared morphology of the rotifer body (Figure 2d), e) visibly deformed mastax (Figure 2e), f) altered cuticle (Figure 2e1), g) feet anomalously attached to the head (Figure 3b, b1), h) vestigial feet or absence of feet (Figure 3c, c1), i) three toes on the foot instead of two (Figure 3d1), j) curved body (Figure 3d, d2), and k) malformed spines (Figure 3e, e1) (Alvarado-Flores et al., 2015).

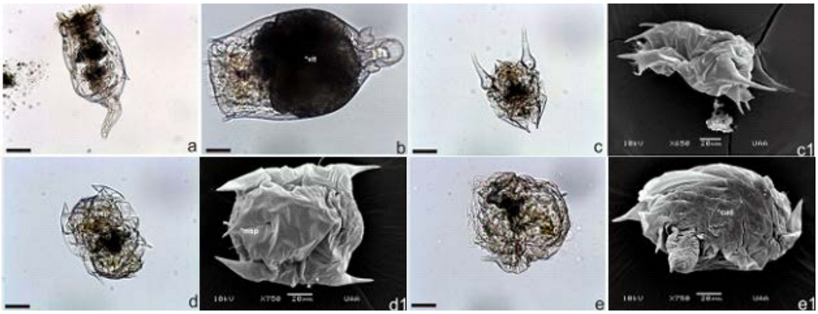


Figure 2. Morphological changes in females of *Brachionus calyciflorus* treated with 1.2 mg/L vinclozolin. a) Normal female with normal vitellarium; b) female with enormous vitellarium; c, c1) dwarfism; d, d1) curvature of median spines; e, e1) cuticle deformation (Bars: 100 µm) (Alvarado-Flores et al., 2015).

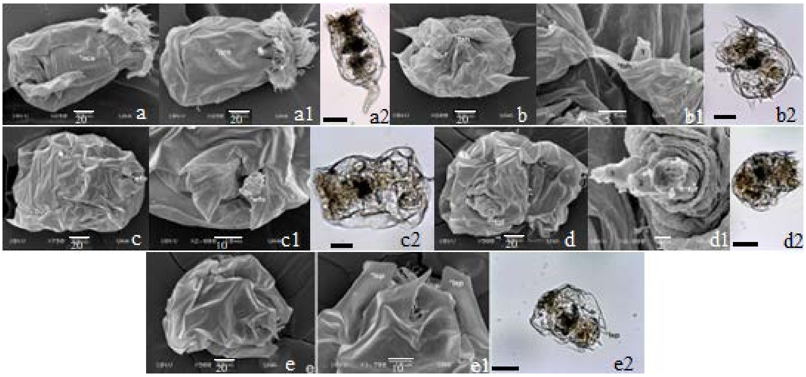


Figure 3. Morphological changes induced by vinclozolin 1.2 mg/L application in *B. calyciflorus* females. a, a1, a2) normal female showing normal cuticle surface; b, b1, b2) rotifer body with curved and head-attached foot; c, c1, c2) footless females; d, d1, d2) three-toed foot; e, e1, e2) deformation and fusion of lateral spines in females (Bar: a2, b2, c2, d2, e2 100 µm) (Alvarado-Flores et al., 2015).

Results from nearly all VZ concentrations administered to rotifers indicated that females exhibited circular movement, their bodies were out of synchronisation, they were incapable of feeding or assimilating food, and their lifespan was limited to 2 days. Moreover, the findings indicated that these anomalies were inherited by successive generations of rotifers (Alvarado-Flores et al., 2015).

2.3. Concavity in *Testudinella patina* (Hermann, 1783) and *T. mucronata* (Gosse, 1886)

Concavities were observed in the loricae of the rotifer species *T. patina* (Hermann, 1783) and *T. mucronata* (Gosse, 1886) in Lake Panema and Lake Coqueiral, both part of the ultra-oligotrophic Paranapanema River system (São Paulo State, Brazil) (Figures 4 and 5). The connection of these lakes to the riverbed may lead to the formation of concavities due to colder river flow (Coelho et al., 2019). Research on lacustrine ecosystems in the same area has linked the influence of lateral river flow to changes in limnological parameters and the planktonic community (Henry et al., 2011). De Smet (2009) suggests that the concavities (flattening) on the lorica of *T. elliptica* (Ehrenberg, 1834) may be related to vitellarium development and developmental stage (Coelho et al., 2019).

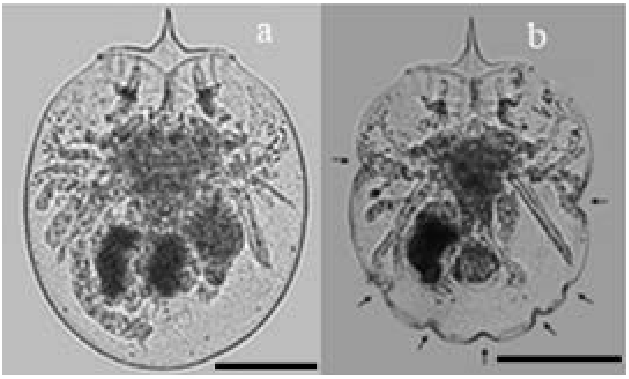


Figure 4. *Testudinella mucronata*. a) normal individual, b) presence of concavities. Arrows indicate concavities (Scale bars: a 20 µm, b 50 µm) (Coelho et al., 2019).

Figure 5. *Testudinella patina*. a) normal individual, b) Type 1, c) Type 2 pits. Arrows indicate pits (Scale bars: 50 µm) (Coelho et al., 2019).

The presence of concavities in *T. mucronata* and *T. patina* may be attributed to (i) temperature, (ii) predation, or (iii) recent hatching (Coelho et al., 2019).

2.4. Anomalies in *Keratella* species exposed to allelochemicals

A significant degree of polymorphism has been observed in *Keratella cochlearis* (Gosse, 1851) exposed to allelochemicals (Gilbert and Kirk, 1988). Individuals of *K. cochlearis* may change their size and stiffness or develop elongated spines to avoid predation when predators are present (Segers and De Smet, 2008). In contrast, deformations have been reported in the spines of *K. cochlearis* exposed to sulphides or their derivatives in water from a sulphur mine pool (Zurek, 2006). Figures 6 and 7 show the morphological changes in the spines of *K. cochlearis* and *K. americana* Carlin, 1943, resulting from various factors.

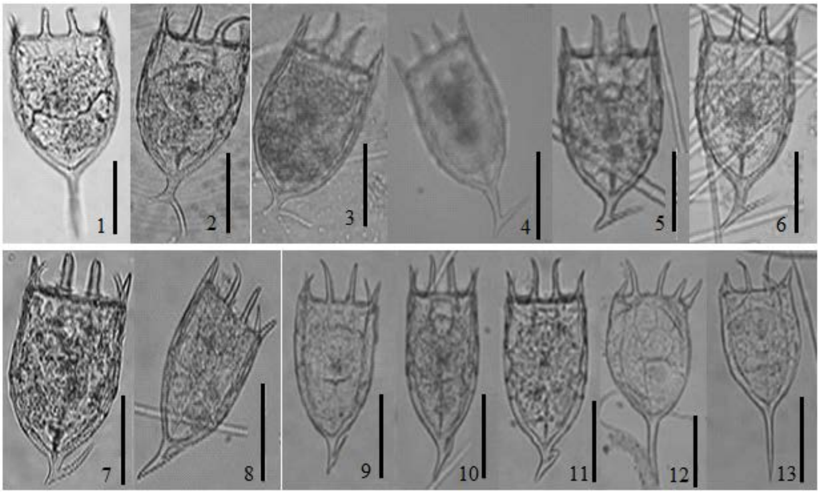


Figure 6. Morphological changes in the spines of *Keratella cochlearis*. 1) Typical structure of the anterior and posterior spines, 2-11) Abnormal structure of the posterior spine with a type of branching clearly visible at the tip of the spine, 2, 8, 12-13) Abnormally curved anterior spines (Espinosa-Rodríguez, et al., 2020).

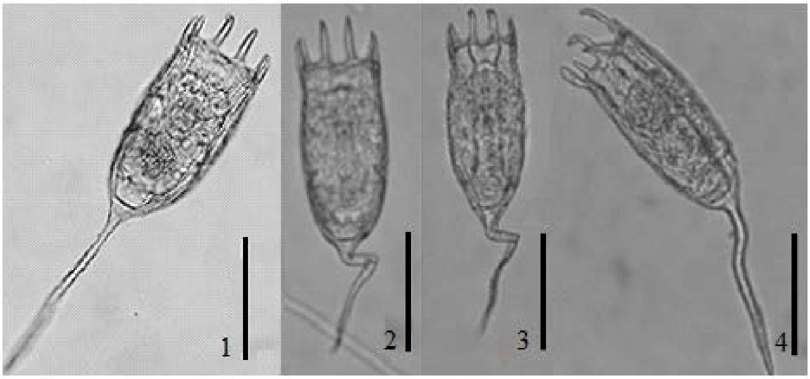


Figure 7. Morphological changes in *Keratella americana* spines. 1) Typical structure of *K. americana*. 2-4) Changes in posterior spines (Espinosa-Rodríguez, et al., 2020).

Figure 6.1 shows the standard configuration of the anterior and posterior spines, while Figures 6.2–11 depict the atypical structure of the posterior spine, characterised by distinct branching at its apex. Figures 6.2, 8, and 12–13 present abnormally curved anterior spines, and Figures 7.2–4 show alterations in the posterior spines of *K. americana* (Espinosa-Rodríguez et al., 2020).

The presence of several pollutants has severely deteriorated water bodies, posing threats to human health and other species. These pollutants originate from various sources and activities, including untreated sewage, agriculture, livestock, and microplastics. Sewage discharges contribute significantly to widespread contamination through phosphate and nitrogen compounds, which promote the proliferation of cyanobacterial populations and increase cyanotoxin concentrations (Mijangos-Carro et al., 2008). The cause of the morphological alterations observed in *Keratella* species remains unidentified; however, it has been documented that these modifications may result from diverse pollutants originating from multiple sources, including untreated sewage, agricultural practices, livestock, and microplastics (Espinosa-Rodríguez et al., 2020).

2.5. Other abnormal conditions on rotifers

Morphological alterations in zooplankton may result from anthropogenic influences on aquatic ecosystems (De Oliveira-Dias et al. 1999; Souza et al. 2011; De Melo et al. 2017). Ecotoxicological assessments have shown that heavy metals and pesticides induce morphological alterations in the rotifer *Plationus patulus* (Müller, 1786) (Ríos-Arana et al. 2007) and *Brachionus calyciflorus* (Alvarado-Flores et al. 2015). Conversely, polymorphism is recognised in certain Rotifera species within the Brachionidae family (Stemberger and Gilbert 1984; Gilbert 1999). This phenomenon may result from several environmental causes, including temperature fluctuations (Gilbert 2018; Ge et al. 2018). For instance, elevated temperatures induce elongation of the spines in *B. falcatus* lorica (Ahad and Rao, 2017), while reduced temperatures diminish the growth rate of *K. cochlearis*, leading to the development of animals with elongated tail spines (Lindström and Pejler, 1975). Additional factors contributing to morphological variations in rotifers are proposed to include food availability and susceptibility to predation (Garza-Mouriño et al. 2005; Gilbert 2009). Gilbert (1967, 1980) indicated that the development of defensive lateral spines in *B. calyciflorus* is an induced reaction to a chemical secretion (kairomone) from the predator *Asplanchna*.

2.5.1. Anomalies in Cladocera

2.5.1.1. Anomalies observed in *Bosmina freyi* specimen

Recent reports of morphological abnormalities in Cladocera have been documented for taxa such as *Ilyocryptus* (Kotov and Dumont, 2000; Elmoor-Laurero, 2004), *Daphnia* (Zanata et al., 2008; De Melo et al., 2017), *Coronatella* (Sousa et al., 2011), *Ceriodaphnia*, *Chydorus*, *Bosmina*, and others (De Melo et al., 2017).

In Brazil, specimens of *Bosmina freyi* De Melo and Hebert (1994) exhibited anomalies in three shallow, eutrophic reservoirs located along a river in Parque Leda Campos Borges, an urban park in the municipality of Frutal. The abnormalities are shown in Figure 8: complete absence of A1; absence of sensory setae between the eye and rostrum; partially developed A1 lacking sensory setae; A1 oriented upwards; A1 oriented sideways with irregular setae distribution (Figure 8b); A2 with incomplete segmentation in both branches; A2 with distinct segmentation and deformed setae in each branch; and A2 with a single, segmentless branch and reduced number of setae (Figure 8c) (Panarelli et al., 2023). Abnormalities in *B. freyi* individuals were observed at varying rates between seasons, with a notable prevalence during the dry season (July and August) (Panarelli et al., 2023).

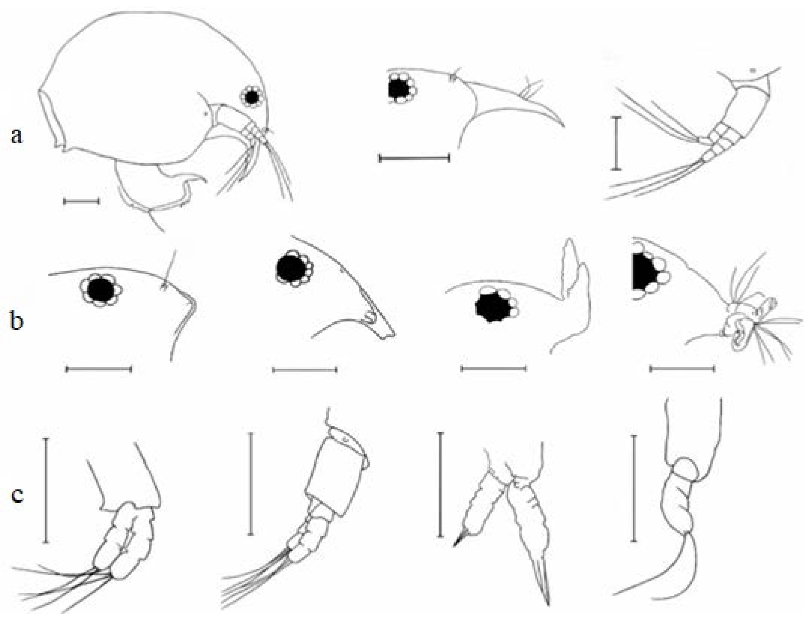


Figure 8. *B. freyi*. a) typical organism (De Melo and Hebert 1994); b) anomalous rostrum; c) atypical A2 (Panarelli et al., 2023).

Numerous experts have reported the following findings and predictions regarding the mechanisms responsible for the anomalies: The anomaly in the reservoir is pronounced, with elevated concentrations of metals such as lead, chromium, and nickel detected in both the water and sediment (Panarelli et al., 2023). Other researchers have focused on different anomalies and their causes in studies of cladoceran anomalies. Smirnov (2017) stated that inorganic and organic xenobiotics can cause abnormal hair growth on the antennae and lead to the loss of antennal segments in cladocerans. This may result in deficits in chemical sensing of the environment, including the loss of sensory hairs responsible for taste and smell, distortion of the A1, and difficulties in food selection and predator avoidance. The absence or distortion of the A2 segments, which are essential for swimming in cladocerans, may impair movement and complicate tasks such as foraging and evading predators (Weiss, 2015; Smirnov, 2017).

2.5.1.2. Effects of eutrophication on the morphology of cladocerans

In research conducted in the Furnas Reservoir, formed by damming the Grande and Sapucaí Rivers in Brazil, morphological anomalies were observed in several cladoceran species (De Melo et al., 2017). A deformation of the rostrum and a curled caudal spine were found in a single specimen of *Daphnia gessneri* (Figure 9.a), while intestinal abnormalities were noted in one specimen each of *Ceriodaphnia silvestrii* Daday, 1902 and *Bosmina longirostris* (Müller, 1785) (Figures 9.b, c). In *Bosmina tubicen* Brehm, 1953, morphological structural anomalies were present in 6.3% of the population (Figure 9.d) (De Melo et al., 2017).

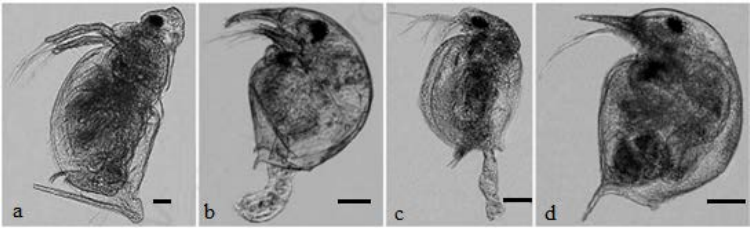


Figure 9. Anomalies in specimens of a) *Daphnia gessneri*, b) *Bosmina longirostris*, c) *Ceriodaphnia silvestrii*, d) *Bosmina tubicen* (Scale bars: 50 µm) (De Melo et al., 2017).

Abnormalities in the cladoceran *C. pubescens* have been documented during the dry season at elevated population densities and are categorised as type 1 and type 2 abnormalities. Type 1 is characterised by an increase in intestinal length and loop size, while type 2 is associated with intestinal prolapse (Figure 10) (De Melo et al., 2017).

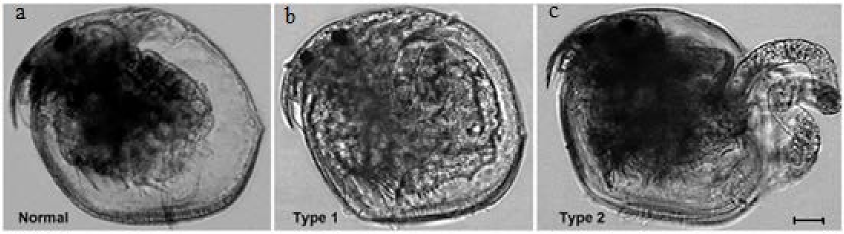


Figure 10. a) *Chydorus pubescens* normal individual (no abnormality), b) type 1, c) type 2 abnormalities (Scale bar: 50 µm) (De Melo et al., 2017).

Anomalous individuals have been recorded in samples from coastal and shallow waterways affected by sewage. Furthermore, *C. pubescens* exhibiting type 1 abnormalities were associated with reduced total phosphorus and increased inorganic phosphate levels, while type 2 abnormalities were linked to higher chlorophyll-a concentrations (De Melo et al., 2017).

Smirnov (1974) reported that anomalies in different body regions may sometimes result from physical injuries sustained during embryonic or postembryonic development in a small proportion of Chydoridae populations. The deterioration of water quality and increased organic load due to anthropogenic impacts may contribute to the continued proliferation of *Microcystis aeruginosa*. Several studies indicate that cyanobacteria are harmful to herbivorous zooplankton, have low nutritional value, block the digestive tract, inhibit food intake, and produce toxins (Hanazato and Yasuno, 1987; Gliwicz and Lampert, 1990). In a hypereutrophic pond in Rio de Janeiro, blooms of *Microcystis aeruginosa* were identified as potentially harmful to cladoceran populations (Ferrão-Filho, 2009).

2.5.1.3. Effects of some heavy metals on the morphology of *Bosmina longirostris*

Anomalies were identified in certain specimens of *Bosmina longirostris* collected from Assen Forellenplas, Weert Roompot, and Assen Baggelhuizerplas, Netherlands (Soesbergen, 2021). The typical subjects in the study are shown in Figure 11.

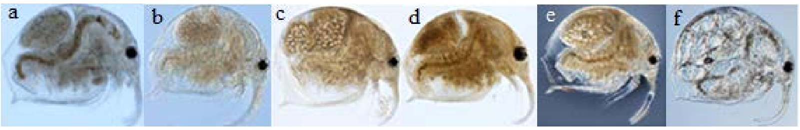


Figure 11. Normal individuals at six locations a) Forellenplas; b) Roompot; c) Baggelhuizen; d) Vosseven; e) Bultpark; f) Groningen (Soesbergen, 2021).

The anomalies in Assen Forellenplas were classified into three main categories (Figures 12–13): blunt, knob- or balloon-shaped (Figures 12a, f and 13f); elongated (Figures 12b, e); and deformed (Figures 12c and 13c). It has been established that different types can coexist within a single animal (Figures 12a, b and 13a, b) (Soesbergen, 2021).

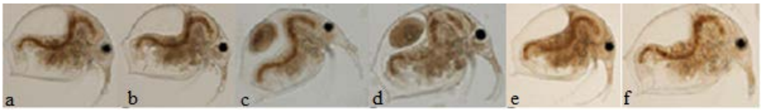


Figure 12. Abnormalities in *B. longirostris*, Assen forellenplas. a) Balloon-shaped; b) Elongated, c) Deformed; d) Elongated and slightly deformed; e) Elongated; f) Knob-shaped (Soesbergen, 2021).

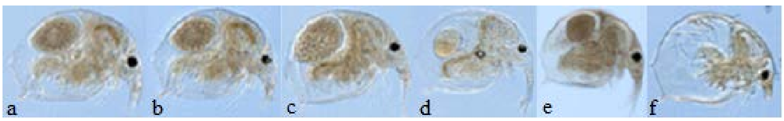


Figure 13. Abnormalities in *B. longirostris*, Weert Roompot. a) Blunt; b) Deformed, c) Deformed; d) Deformed; f) Deformed; f) Blunt (Soesbergen, 2021).

Timm (1904) also noted the deformed antennae of *B. cornuta* (Jurine 1820) and provided details in Figure 14. Although these injuries may be repaired, sometimes showing limited regrowth, the pattern of anomalies in Assen indicates that these lesions do not heal.

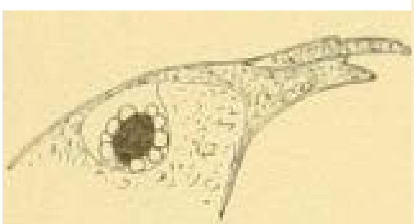


Figure 14. Crippled *B. cornuta* (Timm, 1904)

Figure 15. *B. cornuta* during molting (Timm, 1904)

Numerous factors contributing to anomalies in cladocerans have been documented in the literature. These include hazardous compounds (Sakomoto et al., 2009; Zanata et al., 2008; Sousa et al., 2011), eutrophication (De Melo et al., 2017), and extreme habitats (Kotov and Dumont, 2000; Soesbergen, 2019). De Melo et al. (2017) observed anomalies in the gastrointestinal tracts of *Bosmina*, presumably due to eutrophication of the reservoir. Deformed corpses were reported to be shorter than typical individuals, with overall changes in body length attributed to temperature and predation. The literature indicates a correlation between antenna length and shell length, influenced by temperature or predation (Chang and Hanazato, 2003; Razak and Saisho, 2011). A significantly higher incidence of anomalies was observed in the Assen Forellenplas and Weert Roompot ponds. The abnormalities may be attributed to: i) increased fishing pressure in Assen Forellenplas and Weert Roompot, ii) the use of Assen Forellenplas for trout aquaculture, and iii) the previous severe contamination of Weert Roompot with cadmium and zinc from the zinc manufacturing facility (Soesbergen, 2021).

Kerfoot (1978) defines an attack in his article on the competition between the predatory copepod and Bosmina, as well as the resulting anomaly. The copepod often seizes a mucro or antenna, either squeezing or cutting the appendage; this damage is temporary, as the part regenerates in the subsequent moult. The mucro and the body (antennae) sustain injuries from these attacks. No regenerated or anomalous shell spines were detected in the specimens, indicating that predation is not the source of the anomalies. The response may relate to a vulnerable phase during moulting (Figure 15). During moulting, the body is pliable (Timm, 1904), resulting in increased permeability to all substances. Xenobiotics influence somatic growth (Sakomoto et al., 2009), moulting, and may induce antennal malformations (Smirnov, 2014).

The use of ponds for fishing may introduce xenobiotic chemicals through bait and fishing equipment, resulting in eutrophication (De Melo et al., 2017). Lead is a xenobiotic known to accumulate in cladocerans (Smirnov, 2014). In the Netherlands, fishermen annually lose between 2 and 11 tonnes of lead to freshwater (Van der Hammen, 2019). Lead can impair nerve cells and ganglia, as well as alter cellular structure and enzymatic function (Eisler, 1988). The impact of lead on organisms is especially significant at elevated water temperatures and reduced pH in soft waters, particularly with prolonged exposure (Van der Hammen, 2019). Additives, including various dyes, flavours, perfumes, luminescent agents, and solvents, whether natural or synthetic and used in concentrated forms, serve as sources of xenobiotics. Feeding influences fish chemoreception (Atema, 1980; Jones, 1992), which in turn stimulates the development of defensive features (e.g., elongated antennae) in cladocerans, mediated via chemoreception (Weiss et al., 2012). Numerous organic and inorganic xenobiotics have been documented to induce abnormalities in the shell or antennae (Shcherban, 1986). The construction of defensive structures induced by kairomones activates the endocrine system in the chitinase pathways related to moulting, suggesting this system may contribute to the onset of abnormalities (Miyakawa et al., 2010; Lürling, 2012). Pesticides and heavy metals are reported to interfere with the chemical signalling systems of cladocerans, and the interruption of stem growth post-moult due to a xenobiotic may be responsible for the observed anomalies (Soesbergen, 2021).

2.5.1.4. Anomaly in the postabdomen of *Ilyocryptus spinifer* Herrick, 1882

Multiple anatomical anomalies have been documented in *Ilyocryptus spinifer* from the Apipucos Reservoir (Recife urban area, Pernambuco State), Brazil. The aberrant individuals observed were indistinguishable from normal individuals except for their postabdomen (Figs. 16–17). No consistent pattern of postabdominal alteration was identified; instead, various degrees of deformity were noted. The aberration involved a decrease or absence of several lateral and marginal postanal spines, while the overall postabdominal anatomy remained unchanged (Fig. 16b). The most significant abnormality observed was the total absence of terminal claws and postanal spines (Fig. 16f). Diminished and altered terminal claws were also observed (Figs. 16c, e) (Elmoor-Loureiro, 2004).

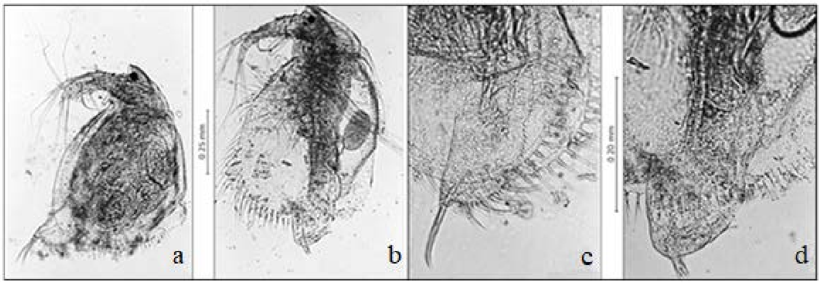


Figure 16. *Ilyocryptus spinifer* female: a) Lateral view of a normal individual, b) Lateral view of an abnormal individual, c) Normal postabdomen, d) Abnormal postabdomen (Elmoor-Loureiro, 2004).

The incidence of malformations increased with individual size, as the smallest (or youngest) specimens showed no malformations near the abdominal cavity, while the largest (or oldest) specimens exhibited the most severe malformations. Additionally, most abnormal individuals were documented to produce eggs (Figure 16b) (Elmoor-Loureiro, 2004).

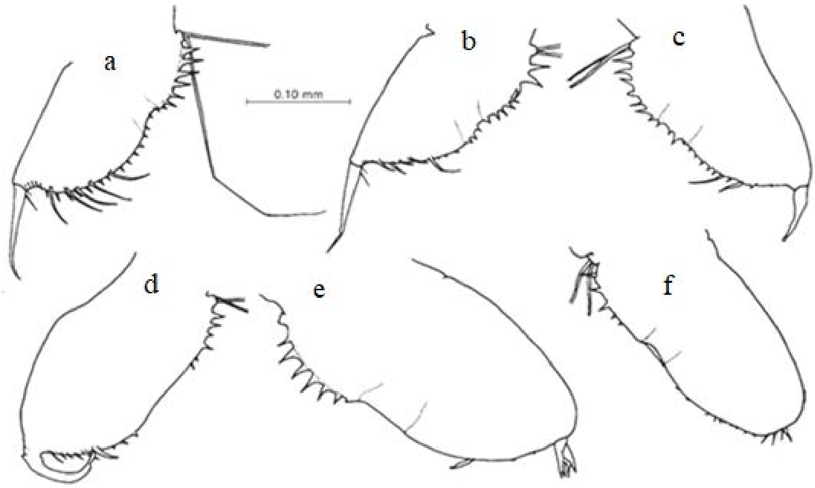


Figure 17. *I. spinifer*, female postabdomen: a) Normal; b, c) Minor abnormalities; d, e, f) Severe abnormalities (Elmoor-Loureiro, 2004).

The analysis of the anomaly in I. spinifer, based on several literature sources, indicates that the frequency distribution of abnormalities by size suggests they are induced by an environmental influence. Eggs produced by atypical adults consistently yielded juveniles with normal postabdominals. As aberrant postabdominals are not a genetic trait, this characteristic was absent in juveniles (Elmoor-Loureiro, 2004).

Kotov and Dumont (2000) identified atypical individuals within the *I. spinifer* species group, attributing these anomalies to the environmental conditions during their development. Some atypical specimens exhibited clusters of lateral spines on the postabdominal region. Hudec (2000) observed abnormalities in the terminal claws of *Kurzia polyspina* Hudec, 2000, and suggested that these may be "postreproductive characters resulting from continuous growth." The Apipucos Reservoir is classified as a eutrophic ecosystem with significant organic contamination. The reservoir is affected not only by regular household waste disposal but also by petroleum derivatives leaking from a petrol station and organic waste from pigsties, pens, and poultry slaughterhouses (Neumann-Leitão et al., 1989). These cases support the hypothesis that the morphological anomalies observed in *Ilyocryptus* were induced by a toxic agent (Elmoor-Loureiro, 2004).

2.5.1.5. Impact of xenobiotics on morphological defects in zooplankton

Evidence indicates that xenobiotics can cause abnormalities in zooplankton. For example, substances such as mercury (Khangarot and Das, 2009) and organic pollutants (Wang et al., 2011) have been shown to alter the characteristic morphology of the cladoceran *Daphnia magna* Straus, 1820. In contrast, vinclozolin has been reported to cause lorica deformations in *Brachionus calyciflorus* (Alvarado-Flores et al., 2015) (Figure 21).

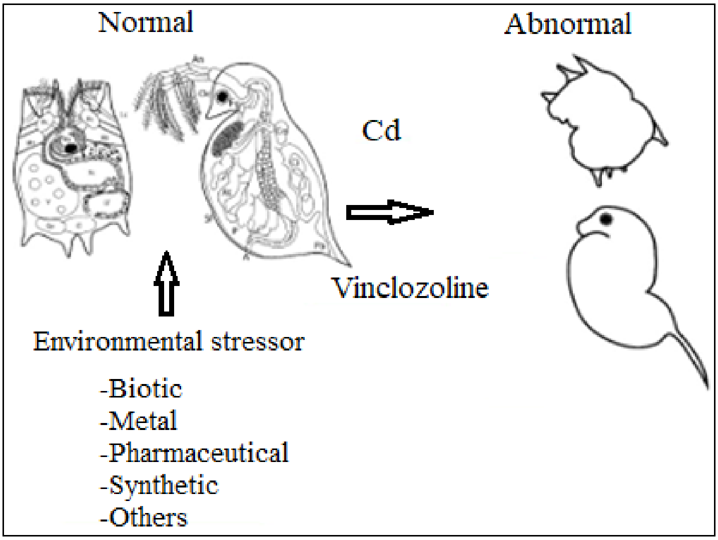


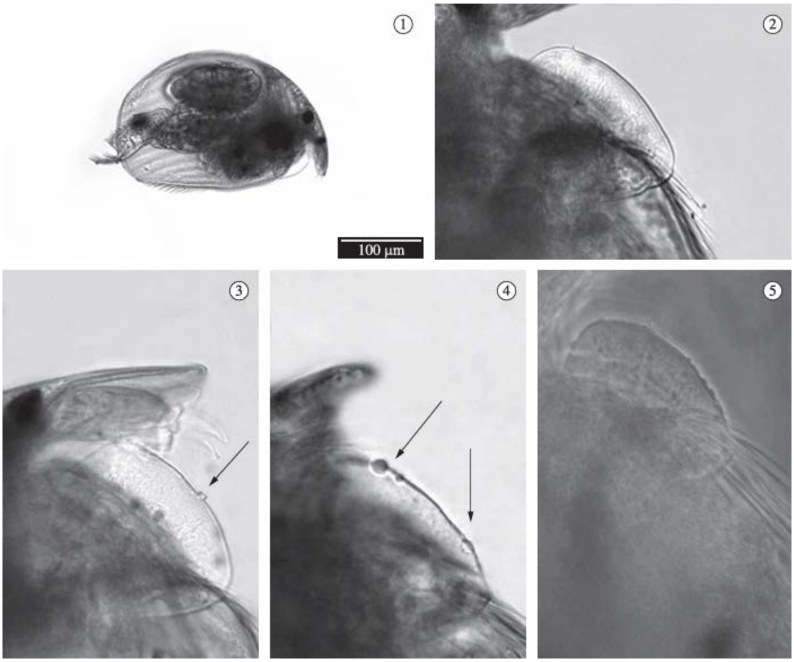
Figure 21. Morphological alterations induced by environmental stressors (Cadmium and Vinclozoline) (Alvarado-Flores et al., 2022).

Creatures collected from both unpolluted and contaminated regions have been examined to assess the potential correlation between the physicochemical characteristics of water and anomalies in planktonic organisms. Larval development is influenced by eutrophication resulting from anthropogenic activities and phytoplankton blooms. These activities alter water chemistry and cause structural changes in cladocerans and copepods (De Melo et al., 2017). Zooplankton undergo morphological changes when exposed to harmful chemicals and environmental stresses (Table 1). Ya-Li et al. (2018) identified three morphotypes of *Keratella quadrata* (Müller, 1786). The morphotype lacking posterolateral spines was classified as anomalous (5%) and was not expected in the population. The morphotype with two posterolateral spines was common in the population and conferred a survival advantage by reducing predation risk. Additionally, it has been reported that the lorica size of Brachionus plicatilis (Müller, 1786) increased by 9.6% when exposed to juvenile hormone and gamma-aminobutyric acid at concentrations of 0.05 and 5 mg L^{-1} (Assavaaree and Hagiwara, 2011). In contrast, 20-hydroxyecdysone, triiodothyronine, and human chorionic gonadotropin hormones reduced lorica size by 3.9 to 8.2% (Gallardo et al., 1997), while follicle-stimulating hormone and luteinising hormone have been reported to induce morphological changes and infertility in *B. calyciflorus* (Alvarado-Flores and Rico-Martínez, 2019).

Aquatic ecosystems are polluted with various harmful compounds that can induce morphological changes, thereby increasing understanding of the potential adverse effects of xenobiotics on aquatic systems and organisms. The continuous presence of hazardous substances in an ecosystem can significantly threaten aquatic life and lead to the extinction of ecologically important species. Toxic agents that have caused morphological changes in rotifers during laboratory tests include cadmium, mercury, nonylphenol, ethylene thiourea, and vinclozolin. These toxic substances induce morphological changes, with their harmful cellular effects primarily resulting from their structural similarity to or mimicry of essential biomolecules; for example, lead, calcium, cadmium, and zinc cause significant damage by disrupting normal cellular biochemical pathways (Clarkson, 1993). In contaminated environments, rotifers exhibit smaller body sizes compared to those in unpolluted habitats, resulting in reduced feeding efficiency (Alva

2.5.1.6. Tumor-like formations on the labral spine of *Coronatella monacantha* (Sars 1901)

In zooplankton samples collected from Garibas Stream (São Gonçalo do Amarante, Ceará, Brazil), tumour-like formations were observed on the labral spines of *Coronatella monacantha* (Sars 1901) specimens (Figures 22.1–5). A total of 47 *C. monacantha* specimens were examined, revealing irregular and varied structures on the labral spine surface in 27.70% of cases (Figures 22.3–5). No morphological alterations were observed in the overall body shape, carapace, antennae, antennules, or posterior abdomen of the specimens (Sousa et al., 2011).



Figures 22. 1-5 *Coronatella monacantha* from Garibas Creek, Ceará, Brazil. 1) adult female; 2) normal labral spine; 3-5) abnormal labral spine (Sousa et al., 2011).

Agricultural and industrial activities can adversely affect water quality by introducing trace element contamination into aquatic ecosystems, resulting in changes to biological communities at the individual level (Zou and Bu, 1994). This study identified low dissolved oxygen levels (<2.0 mg/L) and acidic pH values (<6.0), although these remained within permissible ranges. However, total and soluble iron concentrations exceeding 0.6 mg/L were recorded, significantly surpassing the recommended threshold of 0.3 mg/L for the protection of aquatic organisms and human consumption (Sousa et al., 2011). The causes and consequences of the morphological abnormalities observed in microcrustaceans remain insufficiently explored, but they are believed to result from anthropogenic environmental factors. This study suggests that elevated total and soluble iron concentrations may accumulate in the tissues of C. monacantha, potentially causing the observed alterations in the labral spine of certain individuals (Sousa et al., 2011).

2.5.1.7. Morphological anomalies seen in daphnids

Morphological anomalies were identified in cladoceran species collected during routine surveys in the middle and lower sections of the Tietê River basins (São Paulo State, Brazil). Alterations were observed on the ventral margin of the carapace in *Daphnia gessneri*, *D. laevis* (Birge, 1879), *D. ambigua* (Scourfield, 1947), *D. lumholtzi* (Sars, 1885), *Ceriodaphnia silvestrii* (Daday, 1902), and *C. cornuta* Sars, 1885, as well as on the helmet and rostrum of *Daphnia* (Zanata et al., 2008). Analysis of cladoceran samples indicated several stages of the anomaly, with the highest density observed in the *D. gessneri* population (Figure 23). The overall density of *D. gessneri* exhibiting morphological alterations in the carapace ranged from 160 ind/m³ to 387 ind/m³. The proportion of abnormal individuals to the total population of healthy *D. gessneri* was documented as 0.03%. In addition, reduced intensity and frequency of malformations were observed in *Daphnia ambigua* Scourfield, 1947 and *Ceriodaphnia* (Zanata et al., 2008).

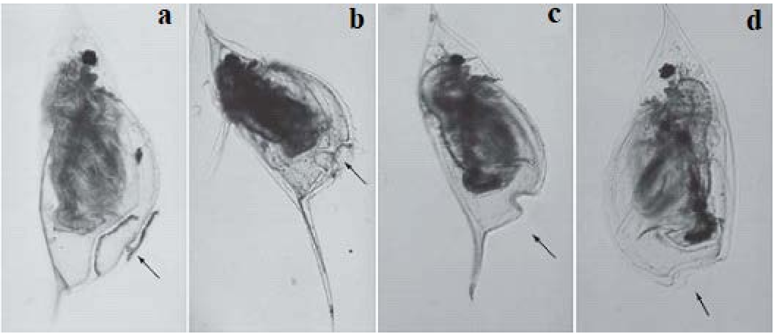


Figure 23. Morphological alterations in the shell of *Daphnia*. a) *D. laevis*; b) *D. lumholtzi*; c-d) *D. gessneri* (Zanata et al., 2008).

An additional anomaly was identified at the dam entrances of the Bariri and Três Irmãos reservoirs, observed in *Daphnia* individuals exhibiting alterations only in the helmet and rostrum (Figure 24) (Zanata et al., 2008).

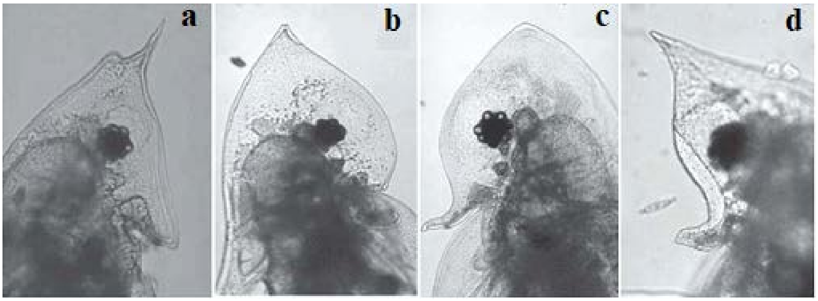


Figure 24. Morphological anomalies seen in the cephalic region of *Daphnia* (a, b, c, and d) (Zanata et al., 2008).

The observed anomalies, along with indications of environmental pollution, may result from chemical contaminants or microorganisms, including bacteria and viruses (De Oliveira-Dias, 1999; Otha et al., 1998). Hanazato and Dodson (1993) demonstrated that *D. pulex* (Leydig, 1860), *D. galeata mendotae* (Hebert, 1995), *D. lumholtzi*, and *D. retrocurva* Forbes, 1882 showed morphological alterations in response to the insecticide carbaryl. Several publications have highlighted the presence of harmful chemicals in the Tietê River. Calheiros (1993) confirmed persistent organochlorine contamination in the Barra Bonita reservoir. Toxicity assessments in the Tietê River confirmed the presence of deleterious chemicals such as cadmium, iron, copper, lead, and manganese in the aquatic ecosystem (Fracácio, 2001). Furthermore, it has been noted that the aetiology of morphological anomalies in microcrustaceans may be congenital, with the underlying causes remaining poorly understood and therefore indeterminate (Elmoor-Loureiro, 2004).

2.5.1.8. Body anomalies in the *Pleuroxus aduncus* (Jurine, 1820) population

A significant portion of the variation in *Pleuroxus aduncus* (Jurine, 1820) has been clarified by Frey (1993), Smirnov et al. (2006), and Smirnov (2014). The number of teeth at the postero-ventral corner of the shell typically ranges from 1 to 3, with rare cases of 0 to 4 teeth, represented as (0) 1–3 (4) (Herbst, 1962; Smirnov, 1974; Frey, 1991; Flösner, 1974, 2000). The distribution of tooth number across five populations in the Netherlands is regular, with 50–60% of individuals having 2 teeth, although one population shows only 4% with four teeth. In contrast, the Bamberg (Germany) well population exhibited a range of zero to five teeth, whereas only the Koopmanspolder (Netherlands) population reported more than three teeth. In addition to the standard number of denticles, various additional anomalies were identified in the same specimens, categorised into five main types (Figures 25–26): furcate denticles (Figure 26B), higher-set (normal) denticles (Figures 26B–C), diminutive (extra) denticles (Figure 26D), higher-set reduced denticles (Figure 26E), and higher-set hairy setae (Figure 26F). Combinations of these anomalies are also common. In a Dutch population, anomalies were documented in 2% of certain furcate denticles (Soesbergen, 2019).

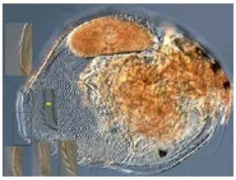


Figure 25. Female *Pleuroxus aduncus* from the Bamberg well exhibiting aberrant denticles at the postero-ventral corner of the valves; the yellow arrow denotes a row of diminutive setules (Soesbergen, 2019).

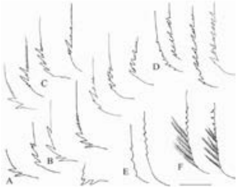


Figure 26. Anomalies at the postero-ventral corners of valves in the Bamberg well population. A) standard denticles; B) bifurcated denticles; C) denticles and setal row; D) with supplementary small denticles; E) elevated reduced denticles; F) elevated downy setae (Scale bar: 50 µm) (Soesbergen, 2019).

These anomalies are attributed to several sources, including the influence of harmful compounds (Elmoor-Laurero, 2004; Zanata et al., 2008; Sousa et al., 2011), eutrophication (De Melo et al., 2017), and culture media (Kotov and Dumont, 2000). The environment of the well, where the anomaly is most frequently detected, resembles that of the culture environment, characterised by consistently low temperature, low conductivity (78 µS/cm), elevated pH (8.7), slow flow, and minimal vegetation. The suboptimal conditions of isolated locations may make population isolation a significant factor. The colonisation of a solitary female can initiate a colony, while the colonisation of a genetically predisposed animal may result in more anomalies (Soesbergen, 2019).

3. CONCLUSION

Trace elements from urban, agricultural, and industrial activities directly affect water quality by polluting aquatic environments. This leads to changes in biological communities, particularly among zooplanktonic organisms at the individual level, causing morphological abnormalities (Zanata et al., 2008; Sousa et al., 2011). For example, deformations and respiratory problems have been reported in some invertebrates following exposure to arsenic, mercury, and methylmercury (Martinez et al., 2006; Skinner and Bannett, 2007). Similarly, elements such as cadmium, iron, copper, lead, and manganese have been reported to cause shell deformations in various Daphniidae species (Zanata et al., 2008). However, research on the effects of trace elements on aquatic invertebrates is still in its early stages.

Zooplanktonic organisms are highly sensitive to environmental conditions and act as natural water purifiers in ecosystems. This makes them suitable as biological indicators of water quality. This community of planktonic organisms is one of the most important groups in aquatic ecosystems, serving as a vital food source for many fish larvae and invertebrates (Sharma, 2020).

Toxic compounds entering surface water bodies pose a serious threat to aquatic organisms, causing the extinction of more vulnerable species and morphological and physiological changes in other populations, thereby reducing ecosystem services (Pérez-Coyotl et al., 2019). The continuous influx of pollutants into aquatic ecosystems reduces the reproductive rates of organisms, leads to the extinction of larger species, and jeopardises ecosystem functionality by inhibiting energy transfer in the food chain.

Environmental pollution from pesticides has been shown to particularly affect aquatic organisms, causing deformities, stunted growth, and embryonic death. These effects significantly impact organisms at various biological levels and on a global scale (Kohler and Triebskorn, 2013). Human-induced negative impacts disrupt the aquatic food chain, preventing or limiting energy availability to higher trophic levels. To protect ecosystem health, it is crucial to avoid releasing waste and harmful substances into the environment in quantities the environment cannot process and to ensure the proper functioning of every stage of the food chain.

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ABNORMAL FORMATIONS IN THE COPEPOD BODY STRUCTURE

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1. INTRODUCTION

Copepods are small aquatic crustaceans and are among the most numerous metazoan groups in aquatic communities, as well as one of the most ecologically successful taxa on Earth (Morales-Ramírez et al., 2014). Throughout their long evolutionary history, copepods have been present on all continents since the Lower Cretaceous and have successfully colonised all available aquatic habitats (Selden et al., 2010). At present, approximately 21,000 valid species of copepods have been recorded and described (Walter and Boxshall, 2021). Copepods inhabit a wide range of salinities, from subterranean caves to hypersaline conditions, and occupy environments ranging from ponds formed in bromeliad leaves or moist leaf litter, through streams, rivers, and lakes, to the open ocean and underlying sediment layers. Their habitats extend from the highest mountain lakes to the deepest ocean trenches, and from the cold polar ice-water interface to hot active hydrothermal vents (Boxshall and Defaye, 2008).

Free-living copepods play a significant role in aquatic habitats and provide numerous benefits to aquatic ecosystems. Copepods have high nutritional value and are therefore important in aquatic food webs (Turner, 2004). Because of their nutritional value, they are a potential food source for aquaculture and human nutrition (Eysteinsson et al., 2018). Ecologically, planktonic

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copepods feed on microscopic algal cells and are in turn eaten by other planktivores, including juvenile fish and some whales, thus playing a functionally important role in maintaining balanced and healthy aquatic ecosystems and the aquatic food chain. Copepods and their nauplii, with their high nutritional value, serve as prey for many zooplankton species (Aragão et al., 2004) and are an essential food source for juvenile fish and larvae (Sampey et al., 2007). Copepods also contribute to nutrient cycling in the water column, helping to maintain overall ecosystem health (Walter and Boxshall, 2025).

Copepods are often referred to as the "engineers of the oceans" because of their vital role in energy transfer throughout the aquatic food chain. As they consume primary producers, copepods convert the energy stored in phytoplankton into a form usable by higher-level consumers. This energy transfer ensures the maintenance of diverse marine life and contributes to the overall productivity and biodiversity of aquatic ecosystems. Recognising the importance of copepods in maintaining healthy aquatic environments is crucial for the stability and resilience of our oceans. Because copepod populations are highly sensitive to the impacts of climate change and human activities, they are a good model group for ecological and ecotoxicological studies (Kulkarni et al., 2013; Montagna et al., 2013). Furthermore, their high reproductive capacity and short life cycle allow their populations to grow rapidly, recover quickly from environmental disturbances, and adapt rapidly to changing environmental conditions. These characteristics contribute to their survival even in challenging environments.

Copepods encompass a diverse range of feeding groups, including herbivores, detritivores, omnivores, carnivores, and parasitic forms (Heuch et al., 2007). They possess exceptional hunting abilities and are often used as natural biological control agents. In aquatic environments, copepods play a crucial role in regulating population growth and preventing pest outbreaks. By feeding on various organisms, including harmful algal blooms, disease-causing pathogens, and pest species, copepods are highly effective in maintaining the balance, stability, and health of aquatic ecosystems. Furthermore, in freshwater, copepods have the potential to serve as a biological control mechanism against malaria by consuming mosquito larvae (Walter and Boxshall, 2025).

Some researchers have linked environments contaminated by industrial and urban waste to the occurrence of morphological anomalies in zooplankton (Omair et al., 1999; Sousa et al., 2011). Significant anomalies in copepods, presumably due to human activity, have been documented in Lake Michigan (Omair et al., 1999).

Numerous contaminants from domestic wastewater and stormwater runoff enter urban drainage systems, resulting in considerable pollution (Rodak et al., 2019; Bega et al., 2021). Urban reservoirs contaminated by various pollutants significantly threaten aquatic organisms (Perez-Coyotl et al., 2019). Toxic compounds entering surface water bodies can eradicate more vulnerable species and cause morphological and physiological changes in other populations, leading to a decline in ecosystem services.

Pesticide-induced environmental contamination affects organisms at various biological levels. The consequences of these effects are globally significant, as Kohler and Triebskorn (2013) identified 120 pesticides as endocrine disruptors (EDs), particularly impacting aquatic organisms, with documented outcomes such as deformities, stunted growth, and embryo mortality. Vinclozolin (VZ) is a pesticide detected as a contaminant in drinking water. VZ is a widely used fungicide for fruits and vegetables, causing significant harm to invertebrate species (Papadopoulou-Marukidou 1991).

Tissue protrusions indicating notable morphological anomalies on the cephalothorax and urosome of copepods were first reported in Lake Michigan (USA) and subsequently observed in many locations worldwide, including various freshwater lakes, estuaries, coastal marine environments, and deep ocean ridges (Messick et al., 2004; Skovgaard, 2004; Mantha et al. 2013). Studies have shown that these anomalies in copepods vary in size, morphology, structure, and location. The term 'tumour-like aberrations' (TLA) refers to several copepod morphological abnormalities recorded globally (Omair et al. 1999; Bhandare and Ingole 2008). These unusual protrusions typically appear as extensions of internal trunk tissue onto the shell surface (Bridgeman et al., 2000). In addition to spontaneous anomalies of unknown origin, they may also arise from stressful environmental conditions, including changes in phytoplankton and bacterial populations, freshwater influx, environmental alterations, exposure to pollutants (Weis et al., 1992), somatic mutations (Vaupel Klein and Koomen, 1993), exposure to intense ultraviolet (UV) radiation (Naganuma et al., 1997), parasitic diseases (Primavera and Quinitio, 2000), and predation (Souissi et al., 2013; Jagadeesan and Jyothibabu, 2016). Copepods host several parasites, including ectoparasitic ciliates, tantulocarids, and ellobiopsids (Savchenko and Kolbasov 2009), which are believed to induce the development of tumour-like protrusions on their exoskeletons (Manca et al. 1996; Skovgaard 2004).

The exceptional scientific focus on Lake Michigan research stems from concerns that TLA in copepods could pose an increasing risk to the integrity of global plankton food webs. Consequently, numerous international initiatives have been undertaken to understand the occurrence and determinants of

TLA in copepods (Bhandare and Ingole 2008; Mantha et al. 2013).

2. COPEPOD BODY ABNORMALITIES

2.1. Numerical variations observed in copepod appendages

Certain anomalies, such as an excess or deficiency of limbs, have been noted in individuals of specific copepod species, deviating from the established species-specific systematic structure. The most apparent instance of this is the scenario documented by Takeda (1939). The circumstance delineated in the study is as follows, and it exposes variances in some anatomical structures (Takeda, 1949).

Leg anomaly 1): The second leg on either side of the adult female (Fig. 1-I) possesses two spines (circled) within the second segment of the exopodite, rather than one, and the terminal segment exhibits 9 spines instead of 7. This female possesses a third right leg (Fig. 1-II). The exopodite exhibits near bilateral symmetry along the longitudinal axis; the terminal podid remains in the copepodid III stage; the protopodite has also undergone proliferation; the fourth legs (Fig. 1-III) possess terminal segments with 8 spines rather than 7; and the fifth legs (Fig. 1-IV) display proliferation akin to that of the third legs. No progeny of this individual have been documented as having been acquired (Takeda, 1949). The irregularities concerning the fourth and fifth legs are seen in Figs. 1-III and 1-IV.

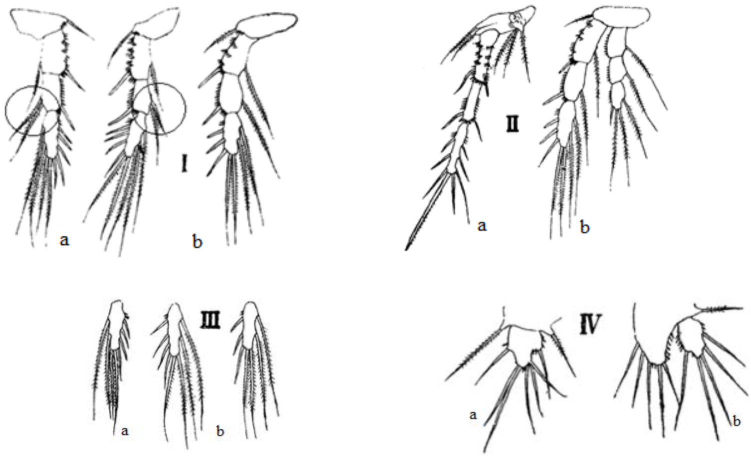


Figure 1. I. Exopods of second legs, a) Abnormal b) Normal, II. Third legs, a) Symmetrical, b) Normal, III. Terminal segments of fourth legs, a) Abnormal, b) Normal, IV. Fifth legs, a) Abnormal, b) Normal (Takeda, 1949).

Leg anomaly 2): In the second leg of an adult male (Fig. 2.a), two spines are present on the inner border of the second segment of the exopodite instead of one (Takeda, 1949).

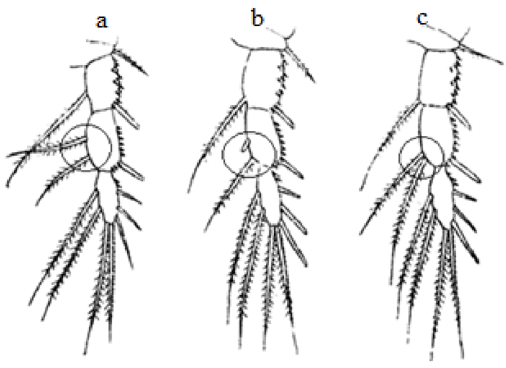


Figure 2. Hereditary abnormality of the second leg. In the second leg, two spines instead of one are present on the inner margin of the second segment of the exopodite (Takeda, 1949).

Antennae abnormality 1): The initial antennae have an atypical morphology, positioned between the male and female antennae (Figure 3-II).

Antennae abnormality 2): The initial antennae exhibit a significantly aberrant form (Figure 3-III).

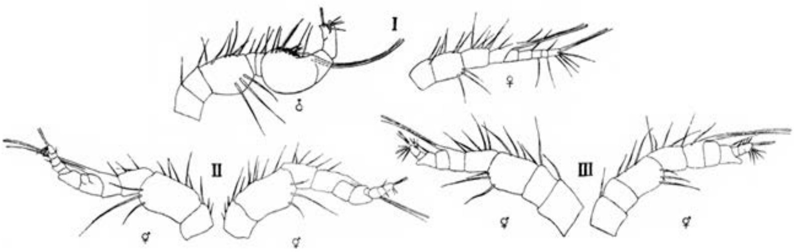


Figure 3. I. First antennae of typical males and females, II III. First antennae of intersex specimens (Takeda, 1949)

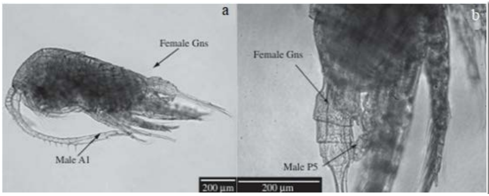
The heritability of such sexual cross-reactivity remains uncertain and necessitates additional investigation. The majority of the defects are believed to be malformations caused by injuries incurred during the larval stage, and it has also been noted that the sex of this copepod is considerably affected by environmental factors (Takeda, 1949).

2.2. Sexual anomaly in *Temora stylifera* (Dana, 1849)

Various morphological and sexual defects, such as congenital deformities, intersexuality, gynandromorphism, parasitic castration, and sex reversal, have been documented in calanoid copepods (Bayly and Shiel, 2008). These include:

1) Gynandromorphic individual: The organism possesses reproductive structures, including the female genital somite, ovary, and oviducts, while other sexual characteristics, such as the antenna (A1) and fifth leg (P5), are predominantly male (Figure 4). Males exhibiting geniculation on both antennae have been observed in vivo and display swimming behaviour comparable to that of normal males. This animal has double

geniculation on A1, with no other morphological abnormalities described (Figure 5) (Martinelli-Filho et al., 2009).



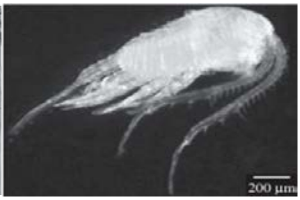


Figure 4. Paired genital somite complex (Gns) of an atypical individual exhibiting masculine traits alongside a female. a) whole specimen; and b) detail of female Gns and male P5 (Martinelli-Filho et al., 2009).

Figure 5. An atypical male *Temora stylifera* exhibiting geniculation on both antennae (Martinelli-Filho et al., 2009).

Geniculation of both antennae is common in cyclopoid families such as Fratiidae, Cyclopidae, and Cyclopinidae, but is rare in calanoids (Boxshall and Halsey, 2004). The unusual geniculation anomaly observed here may be interpreted as evolutionary evidence, as it resembles the condition found in copepod ancestors (Boxshall and Huys, 1998). Intersexuality is common among copepods, although its aetiology remains incompletely understood and may be linked to nutritional deficiency (Gusmão and McKinnon, 2009). Abnormal individuals are typically considered sexually dysfunctional, potentially affecting copepod population dynamics. Further investigation into these anomalies and their behavioural consequences is necessary to fully understand their ecological significance (Martinelli-Filho et al., 2009).

2.3. Abnormalities in copepod *Eurytemora affinis* (Poppe, 1880) eggs

In oviparous specimens of *Eurytemora affinis*, several anomalies have been observed, typically involving either a single giant egg (Figure 6a) or multiple small eggs (Figure 6b) within the same egg sac (Souissi and Souissi, 2020). Additionally, irregularly shaped eggs (Figure 6c) and malformed eggs (Figure 6d) have been noted in the egg sac. Infected eggs (Figure 7) and infected egg sacs (Figure 8) have also been observed, along with anomalies such as protrusions identified in the urosome of females carrying numerous eggs (Figure 9) (Souissi and Souissi, 2020).

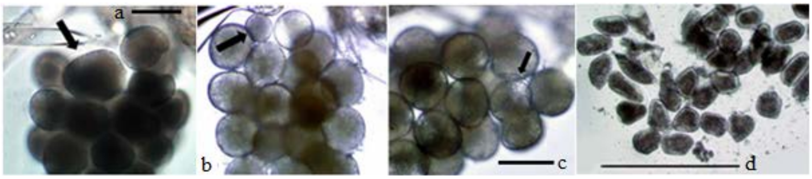


Figure 6. Anomalous egg dimensions within a solitary egg sac amid typical eggs of *Eurytemora affinis*: a) an exceptionally large egg, b) an exceptionally small egg, c) the presence of an irregularly shaped egg in the egg sac (black arrow), d) malformed eggs (Scale bars: a, c, 100 µm; d, 500 µm) (Souissi and Souissi, 2020).

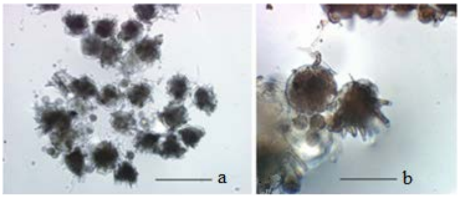


Figure 7. Eggs of *Eurytemora affinis* infected with the fungus, a) General view of the eggs, b) detail of two infested eggs (Scale bars: a, 100 µm; b, 200 µm) (Souissi and Souissi, 2020).

Figure 8. Fungal infested egg sac of *Eurytemora affinis* (Scale bar: 200 µm) (Souissi and Souissi, 2020).

Figure 9. Egg-bearing female of *Eurytemora affinis* showing deformation in the urosome (Tumor-like Anomaly), a) general view, b) detail of the image in a (Scale bars: a, 500 µm; b, 200 µm (Souissi and Souissi, 2020).

Certain anomalies in egg size have attracted the interest of experts and have been the subject of scientific investigation. The occurrence of one egg (sometimes two or more) larger than the other eggs within the same yolk sac has been documented multiple times. The ESD value of this egg was 111.73 µm, while the average ESD value of the other eggs in the same group was 98.03 ± 2.52 µm (Souissi and Souissi, 2020).

Although the reasons for the anomalously small or large size of copepod eggs remain unexplained, such atypical eggs have been recorded under experimental temperature and salinity conditions. Deformed eggs have been observed in situations experiencing abrupt salinity fluctuations (Souissi and Souissi, 2020).

Infested eggs were detected in aquatic environments with a salinity of around 3.5 and a water temperature of 19.8°C during the summer (July 2008). These climatic conditions are expected to be conducive to fungal proliferation on copepod eggs. As with most copepod species, egg production in E. affinis is mainly influenced by temperature, salinity, food quality, and the age of females (Devreker et al., 2009). It was therefore determined that the malformed eggs in the E. affinis specimen examined in this study resulted from other factors, such as inadequate or poor-quality nourishment for the females. Koski et al. (1999) showed that insufficient female feeding adversely affects the hatching success of E. affinis eggs. Furthermore, they demonstrated that substantial infestation of E. affinis by epibiotic ciliates significantly reduced mating success and increased mortality rates of individuals (Souissi et al., 2013)

2.4. Morphological abnormalities of the cyclopoid copepod *Corycaeus speciosus* Dana, 1849

Marine copepods of the genus *Corycaeus* are common and abundant in oceanic environments, particularly in tropical and subtropical waters (Motoda, 1963). Seventeen species of this genus are found in the South Atlantic (Boltovskoy, 1999). *Corycaeus* speciosus Dana, 1849, is an epipelagic species that is widespread and abundant in oceanic waters (Bradford-Grieve et al., 1999). An abnormality at the apex of the prosome was first observed in two female specimens of *C. speciosus* (juvenile and adult copepodites) at different developmental stages in samples collected from the St Peter and St Paul Archipelago in the equatorial Atlantic Ocean (Campelo et al., 2018).

While anomalies in the order Calanoida are well documented, morphological anomalies in Cyclopoida have rarely been reported (Bhandare and Ingole, 2008; Mantha et al., 2013). The anomaly observed in the young female copepodite (stage V) of *C. speciosus* is characterised by a rounded prosomal tip on the left side (indicated by arrows in Figure 10a, b, h), and in the adult, the anomaly also presents as a rounded prosomal tip on the left side (indicated by arrows in Figure 10c, e).

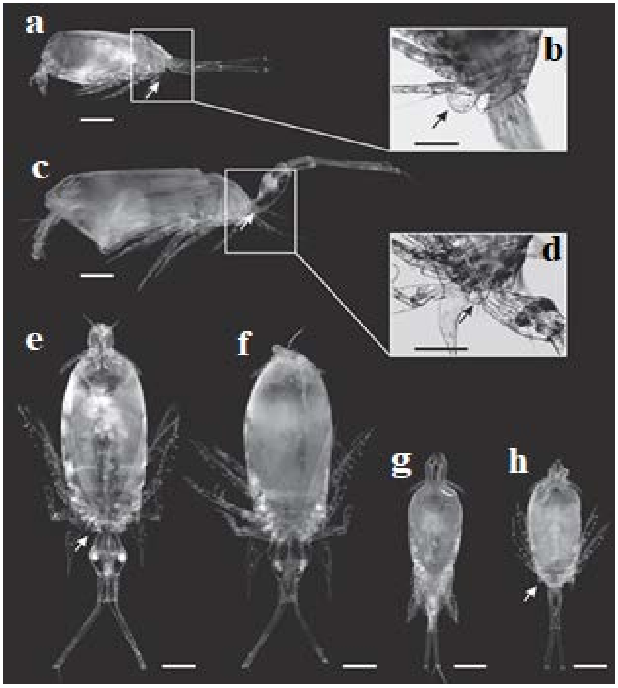


Figure 10. a-h Anomaly shown by female *C. speciosus* (Scale bars: a,c,d,e,f,g,h, 200 µm, b, 100 µm) (Campelo et al., 2018).

The abnormality identified at the apex of the third thoracic segment of the female copepodite *C. speciosus* at stage V is shown in Figure 10a and b. Figures 10c and d show the lateral aspect and details of the anomaly located at the inner end of the left prosomal tip of the adult female. The dorsal aspect of the anomaly at the inner end of the left prosome of the adult female is depicted in Figure 10e, while Figure 10h shows the Copepodite V stage, which displays a notable aberration at the terminal end of the third thoracic segment. Figures 10f and 10g show photographs of the adult and Copepodite V stages without any abnormalities.

Factors contributing to anomalies include exposure to toxic pollutants (Weis et al., 1992), somatic mutations (Vaupel

Klein and Koomen, 1993), significant exposure to ultraviolet (UV) radiation, particularly UVB wavelengths from 280 to 320 nm (Naganuma et al., 1997), parasitic diseases (Primavera and Quinitio, 2000), and encounters with predators (Jagadeesan and Jyothibabu, 2016). Such deformities are unlikely to occur during ontogeny and may result from congenital problems originating during embryonic development (Björnberg, 1972; Crisafi and Crescenti, 1977). Embryonic abnormalities leading to morphological malformations in early copepod stages (nauplius and copepodite) can significantly reduce individual survival prospects. The presence of a population with widespread anomalies can profoundly affect environmental equilibrium. These anomalies negatively impact processes such as development, hatching, swimming performance, and physical fitness (Poulet et al., 1995). Pelagic copepods use bacteria as a nutritional resource in hydrothermal vents and are exposed to numerous toxic compounds and metals in that environment, resulting in the degradation and weakening of their exoskeletons, which causes various structural deformities.

2.5. Abnormal Formations and Tumor-Like Anomalous Structures in Copepods

2.5.1. Tumor-like anomalies (TLA) in copepods

TLA in copepods appears to represent herniated body tissue rather than a neoplastic development as seen in humans (Silina and Khudolei 1994; Manca et al. 2004). Consequently, claims regarding the impact of carcinogenic chemicals on TLA in specific environments (Bhandare and Ingole 2008) lack robust scientific support, as they remain unsubstantiated (Galagovets and Prusova 2016).

The absence of a definitive term for tumour-like anomalies necessitates the use of the term and abbreviation "tumour-like anomalies" (TLA) in international literature. TLAs have been reported in numerous hydrobiont species in both marine and freshwater environments. These conditions are not associated with the "neoplasm" definition of "tumour" and only superficially resemble tumour forms. Due to their prevalence near segment junctions, TLAs are considered particularly susceptible to external influences, especially during the moulting process. Mechanical forces on the shell, particularly the intersegmental tendons, disrupt the hypodermal epithelium, resulting in the protrusion of muscle tissue (Jagadeesan and Jyothibabu 2016).

Copepod tumour-like abnormalities are believed to result from injuries and infections by parasitic protists (Galagovets and Prusova 2016). TLAs in copepods are documented to be globally prevalent and to have common causes (Jagadeesan and Jyothibabu 2016).

TLA cases in copepods have been documented in the coastal waters of Italy (Crisafi and Crescenti, 1975), the southeastern Pacific Ocean (Pasternak et al., 1984), the Bay of Naples (Ianora et al., 1990), the Baltic Sea (Silina and Khudoley, 1994), large lakes (Omair et al., 1999; Bridgeman et al., 2000), the western Mediterranean (Skovgaard, 2004), the Sea of Japan (Konovalova, 2008), and many other aquatic environments, both large and small. According to these reports, hydrothermal vents in the Great Lakes (Omair et al., 2001) and Lake Michigan (Bridgeman et al., 2000; Messick et al., 2004) in the USA, Lago Maggiore (Manca et al., 2004), the Central Indian Ridge (Bhandare and Ingole, 2008) in India, and Kueishantao Island (Mantha et al., 2013) in northeastern Taiwan have emerged as significant threats to aquatic food webs in recent years. Reports indicate that these TLAs can intermittently affect 50–70% of certain copepod species; for example, calanoid copepods appear especially vulnerable to invasion in freshwater environments, while cyclopoid copepods are affected in marine settings, with the occurrence of lesions showing significant variability (Bridgeman et al., 2000; Mantha et al., 2013).

2.5.2. TLA caused by parasites

Tumour-like anomalies (TLAs) were identified in 95% of specimens across 11 copepod species from Sevastopol Bay and Kazachya Bay, exclusively in copepods. Abnormal neoplasms were observed in females, males, copepodids, and nauplii of both sexes at all developmental stages (Figure 11).

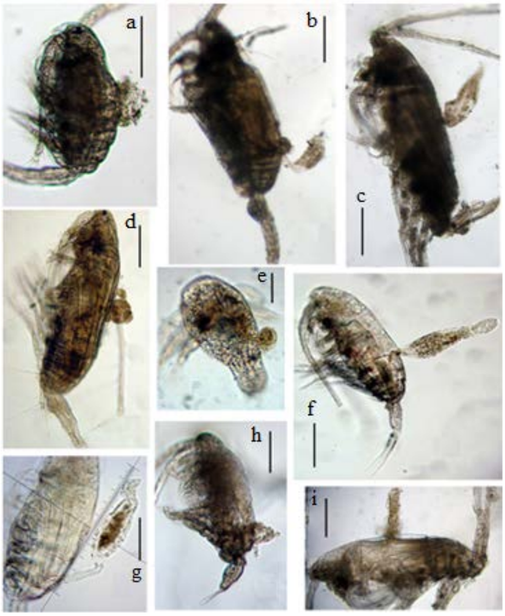


Figure 11. Copepods exhibiting tumor-like anomalies:
a) *Oithona davisae* fifth stage copepodite,
b) *Pseudocalanus elongatus* female,
c, d, i) *Acartia clausi* female,
e) *Calanus euxinus* nauplius,
f) *Paracalanus parvus* female,
g) *Acartia clausi* male,
h) *Centropages ponticus* first stage copepodite (Scale bars: a, e, h 100 µm; b, c, d, f, g, i 200 µm) (Galagovets and Prusova, 2016).

TLAs were predominantly located on the dorsal surface of copepods, specifically at the junction of the first and second prosomal segments, with less frequent occurrences on the ventral side, in the cephalic area, and within the urosome (where the sexual segment meets the last thoracic segment). TLAs were identified as spherical, elongated, dark-containing, and granular translucent stalks directly attached to the shell (Figure 11). Despite considerable diversity in shape and size, they were classified into three main types: 1) generally granular in structure, elongated, spindle-shaped or pear-shaped (Figure 11b, c, f, g, i; Figure 12a, d); 2) round, dense in structure, typically small (Figure 11d, e); 3) amorphous and indistinct in structure (Figure 11a, h) (Galagovets and Prusova, 2016). The prevalence of individuals exhibiting tumour-like malformations in copepods is significant, with the proportion of affected crustaceans in the samples ranging from 0.2% to 20.9% on average (Galagovets and Prusova, 2016).

Reports indicate that TLA structures can display various shapes and configurations, as shown in Figures 12 and 13 (Galagovets and Prusova, 2016).

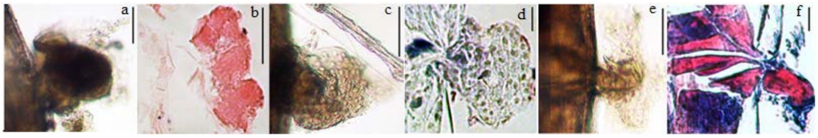


Figure 12. TLA on the dorsal surface of the carapace between the 1st and 2nd prosoma segments of three different *Acartia clausi* individuals. a, c, e) External appearance of abnormal formations in copepods, b, d, f) histological sections (Scale bars: a, b, c, e, 50 µm; d, f, 20 µm) (Galagovets and Prusova, 2016).

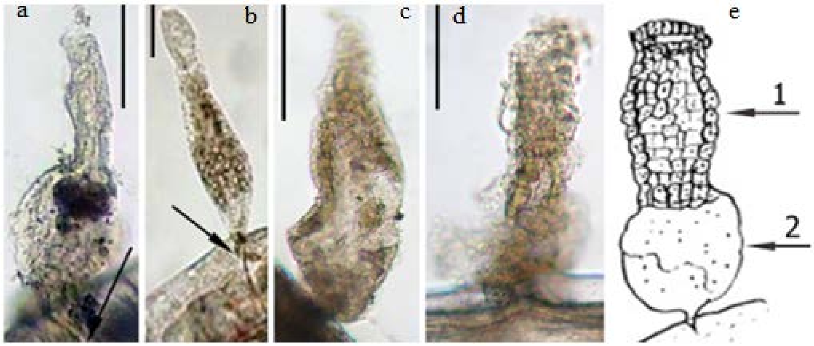


Figure 13. Comparison of tumor-like anomalies in copepods. a-d, arrows indicate the ribbons connecting the TLA to crustacean tissues. Drawing of *Ellobiopsis* sp. at the sporulation stage (e, 1- trophomere; 2- gonomere; according to Konovalova, 2008) (Scale bars: a, b, c, d, 100 µm) (Galagovets and Prusova, 2016).

This suggests that certain TLAs represent the essential functions of parasitic organisms, specifically dinoflagellates from the family Ellobiopsidae, as described by Boschma (1956) and Konovalova (2008). Ellobiopsidae are frequently recorded as parasites of copepods and form a small, diverse group of parasitic protists closely associated with dinoflagellates (Bridgeman et al., 2000). In this context, the injury or infection of crustaceans by parasites has been reported as evidence of TLAs in copepods (Galagovets and Prusova, 2016).

Parasitic infections in copepods significantly influence the functional characteristics of both individuals and communities. Injuries and subsequent physiological debilitation in some crustaceans influence population dynamics (Galagovets and Prusova, 2016).

2.5.3. TLA formed by the movement of the inner trunk tissue to the shell surface

First reported in copepods from Lake Michigan (USA), abnormal tissue protrusions often involving internal body tissue extending onto the shell surface (Bridgeman et al., 2000) have in recent years been observed in planktonic copepods from various regions worldwide (Bhandare and Ingole, 2008). In this study, abnormalities were detected in five copepod species of the order Calanoida: *Temora turbinata* (Dana, 1849), *Pontellopis brevis* (Giesbrecht, 1889), *Centropages velificatus* (Oliveira, 1947), *Centropages typicus* Krøyer, 1849, and *Labidocera fluviatilis* Dahl, 1894 (De Souza et al., 2024). Two types of anomalies have been reported on copepod body surfaces: abnormalities in the intersomital regions between the last prosomal and the first metasomal segment (Al-Aidaroos and Mantha, 2018), and abnormalities in the urosome (Jagadeesan and Jyothibabu, 2016; Souissi and Souissi, 2020) (Figure 14), which also confirms various previous reports.

Figure 14. Anomalous protrusions (black circle) identified on the prosomes and urosomes of copepods from Todos-os-Santos Bay (Bahia, Brazil) (De Souza et al., 2024).

Protrusions identified in the prosome are categorised into three degrees of abnormality (Figure 15). At level 1, the organism shows deeper pigmentation in the intersomal region, resembling a lesion but without herniation of internal tissues. At level 2, herniation of internal tissues is present. At level 3, internal structures, including the digestive tract, extend beyond the body (De Souza et al., 2024).

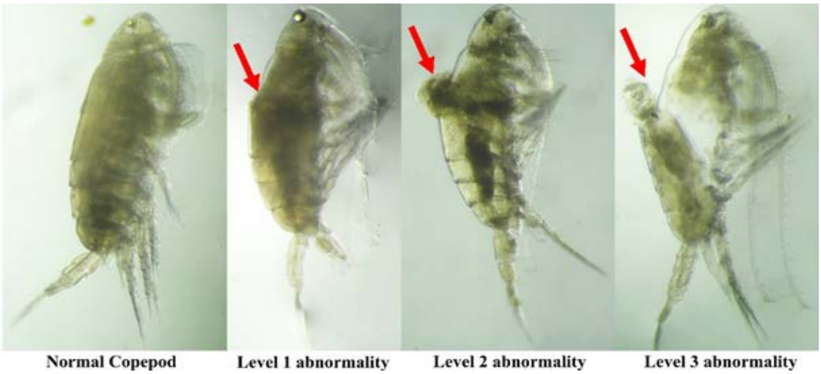


Figure 15. Classification of abnormal protrusion levels identified in copepods from Todos-os-Santos Bay (Bahia, Brazil) (red arrow) (De Souza et al., 2024).

The anomalous protrusion of the urosome has been described as a round, dark-hued morphological feature, predominantly in *Centropages typicus*. Several researchers have reported anomalies in the terminal somite of the urosome in 10% to 30% of copepods (Jagadeesan and Jyothibabu, 2016; Souissi and Souissi, 2020). These anomalies have been described as dark-granular, multilobed, petiolate, diminutive, slightly curved, transparent, and resembling an elongated, stalk-like appendage in *Acartia erythraea* Giesbrecht, 1889, *Acartia danae* Giesbrecht, 1889, *Paracalanus parvus* (Claus, 1863), *Temora turbinata*, and *Pseudodiaptomus serricaudatus* (Scott, 1894) (Jagadeesan and Jyothibabu, 2016). All abnormalities were observed in adult copepods, while no protrusions were found in copepodites or nauplii, supporting the findings of Al-Aidaroos and Mantha (2018), who reported a higher prevalence of abnormalities in adult copepods compared to copepodites or nauplii. Messick et al. (2004) reported that protrusions were more prevalent in nauplii than in copepodites or adults.

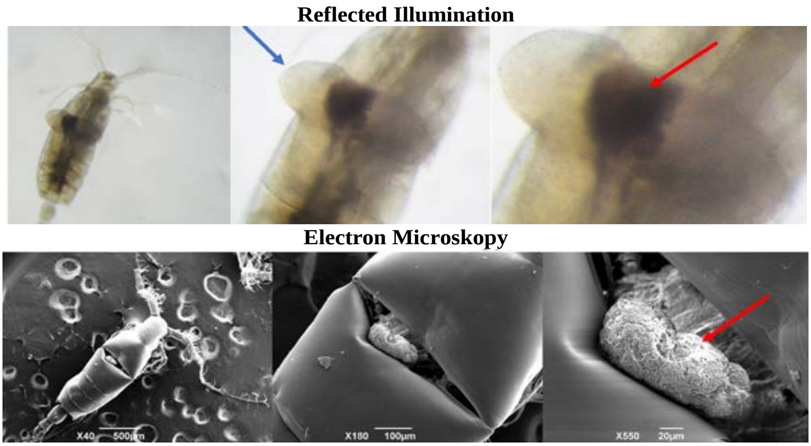


Figure 16. Images of abnormal protrusions on the prosome of *Labidocera fluviatilis* observed under illumination and electron microscopy (De Souza et al., 2024).

Specimens of *Labidocera fluviatilis* Dahl, 1894 exhibiting prosomal abnormalities and *Centropages typicus* displaying urosomal abnormalities were analysed using a scanning electron microscope (SEM), with the corresponding images shown in Figures 16 and 17 (De Souza et al., 2024).

Figure 17. Images of abnormal protrusions in the urosome of *Centropages tipicus* observed under illumination and electron microscopy (De Souza et al., 2024).

The reflected images (Figure 16) show a protrusion of light-coloured, translucent tissue (blue arrow) surrounding a darker substance at the centre (red arrow). The lighter tissue appears to be an extension of the longitudinal musculature, while the darker central region is reportedly associated with the organism's digestive system (De Souza et al., 2024).

2.5.4. Common TLA conditions in nauplii

Tumour-like abnormalities, with a frequency ranging from 0% to 70%, have been documented in copepods from a small lake in Michigan (Bridgeman et al., 2000), Lake Maggiore in Italy (Manca et al., 1996), the Mediterranean Sea (Crisafi and Crescenti, 1975), and the Gulf of Finland (Silina and Khudolei, 1994). Tumour-like abnormalities occur more frequently in nauplii than in adults and copepodites. The anomaly in Lake Michigan has predominantly been detected in three species: *Leptodiaptomus ashlandi*, *L. sicilis* (Forbes, 1882), and *L. minutus* (Lilljeborg, 1889), with a significantly higher prevalence in nauplii (Messick et al., 2004).

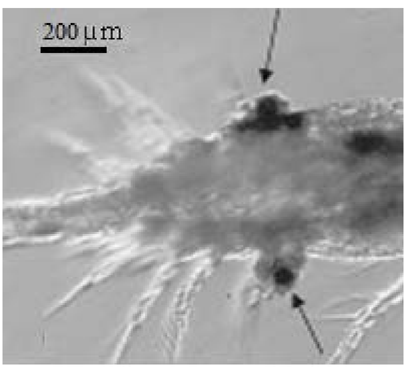


Figure 18. Anomalous bilateral protrusions extending in opposing directions between the cephalosome and metasome (Bridgeman et al. 2000).

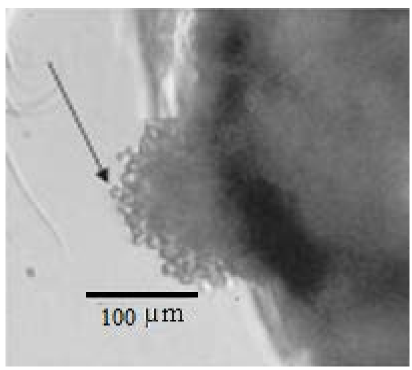


Figure 19. Nauplii with abnormally protruding nodes consisting of numerous nodular or bud-like protrusions on the outer periphery (Bridgeman et al. 2000).

A substantial proportion of the protrusions (56%) emerged from the prosome on the lateral surfaces, located between the cephalosome and metasome. Bilateral protrusions frequently appeared on opposite sides of the same metasome (Figure 18) (Messick et al., 2004).

Protrusions (Figure 19), characterised by numerous elevated, nodular, or bud-like formations along their outer perimeter, were observed in 45% of affected copepods. Nauplii exhibited a greater number of lateral and nodular protrusions compared to copepodites or adults (Messick et al., 2004).

The appendages, smooth in 27% of copepods, often have a translucent, rounded exterior, with contents sometimes encased in a membrane or smooth, rounded covering (Figure 20). Some appendages appear to have burst previously, discharging their contents and creating a smooth surface (Figure 21) (Bridgeman et al., 2000).

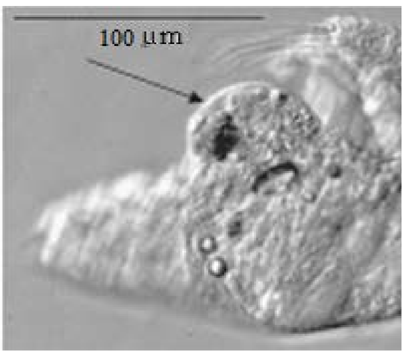


Figure 20. Nauplii with abnormally smooth protrusions (arrow) with a semi-transparent and rounded outer surface (Bridgeman et al. 2000).

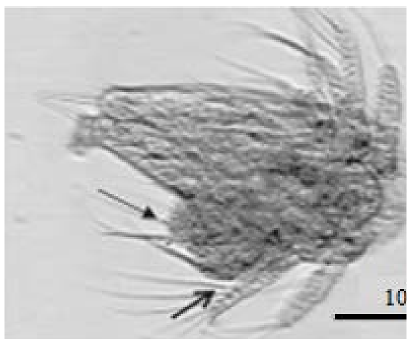


Figure 21. Nauplii with a smooth cover and a knobby protrusion that appears to have released its contents and formed a knobby surface (Bridgeman et al. 2000).

Transparent, elongated extensions, sometimes containing spherical formations of varying sizes, have been documented in 3% of copepods. These protrusions closely resemble those produced by ellobiopsid parasites, which often contain rounded bodies with spores at different developmental stages (Fig. 22) (Bridgeman et al. 2000). Occasionally, glassy or rod-like structures were observed on the surface of the protrusions. These structures appear to be attached to and clustered on the protrusion, rather than on other areas of the copepod body (Fig. 23) (Bridgeman et al. 2000).

Figure 22. Copepod nauplii exhibiting elongated, translucent dorsal appendages (arrow). Highly analogous to ellobiopsid parasites (Bridgeman et al. 2000).

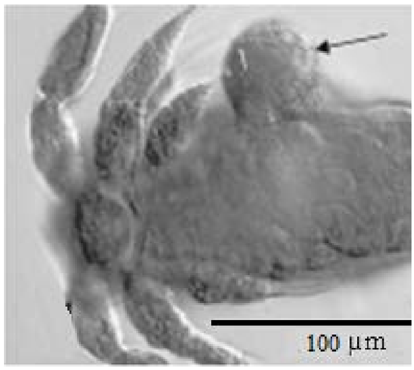


Figure 23. Laterally rounded copepod with glassy or rod-like features affixed to its surface (arrow) (Bridgeman et al. 2000).

The herniated tissue is a projecting structure composed of finely granular, non-cellular material emerging from the copepod's body, as shown in Figure 24. However, uncoloured, spherical, glassy formations have been documented as embedded within the body, as shown in Figure 25 (Bridgeman et al. 2000).

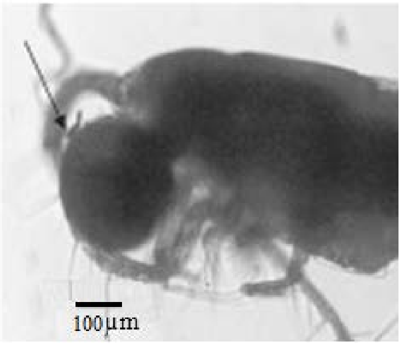


Figure 24. Morphology of the anterior projection of a copepod (Bridgeman et al. 2000).

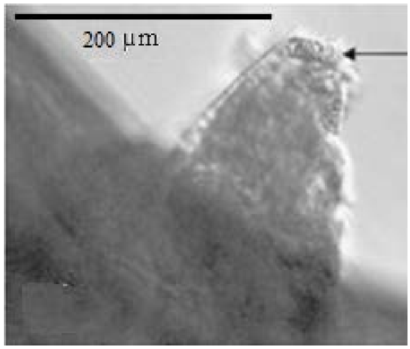


Figure 25. Morphology of a glassy, rod-like protrusion on a copepod (Bridgeman et al. 2000).

2.5.5. TLA caused by hydrothermal vents

Hydrothermal vents, such as those on the eastern side of Kueishantao Island, release various gases and hydrothermal fluids, resulting in distinct ecosystems (Chen et al. 2005; Lee et al. 2008). Hydrothermal vent fluids contain elevated levels of nutrients, gases, and metals in dissolved or particulate forms, which may be harmful to many organisms (Amaral et al. 2006; Peng et al. 2011). The high temperatures (reaching 116°C) produced by hydrothermal vents affect daily tides, leading to rapid circulation of hydrothermal fluids (Manthaa et al. 2013).

Hydrothermal vent fluids significantly influence the diversity, abundance, biology, and ecology of phytoplankton and zooplankton (Chan et al. 2012). Areas adjacent to shallow hydrothermal vents are important biodiversity hotspots for eukaryotes (Tarasov 2006; Hwang et al. 2008). Abnormal protrusions (TLAs) have been observed in many copepod specimens from these hydrothermal vents and surrounding areas. Protrusions are defined as extensions of the body surface with minimal internal tissue or shell expansion (Bridgeman et al. 2000).

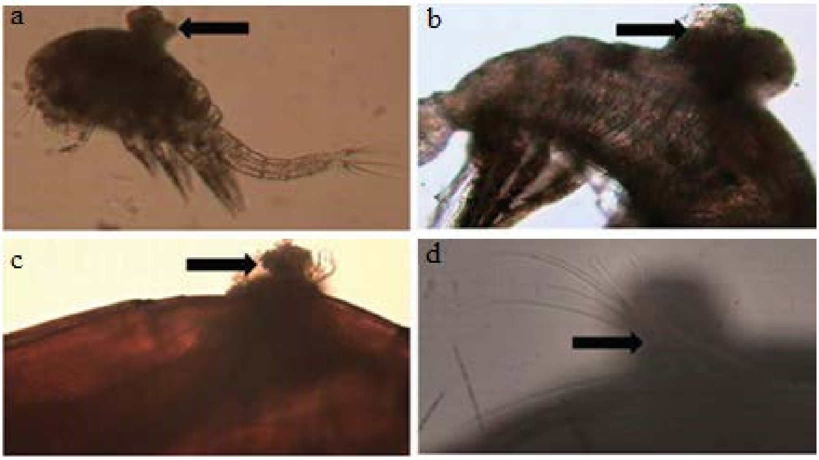


Figure 26. TLAs on the body surface of cyclopoid copepods from Kueshintao Island, off the coast of northeastern Taiwan.

a, b) *Oncaea* species with external protrusions,

c, d) *Corycaeus* species with epibionts attached to the cephalothorax (probably representing tantulocarid infection).

TLAs were observed on the ventral and dorsal body surfaces of species within the cyclopoid copepod family Corycaeidae (Figure 26). TLAs were predominantly found at stations with hydrothermal vents, occurring in 83.3% of adult copepods and 16.7% of juvenile individuals (Manthaa et al., 2013).

Active shallow hydrothermal vents on Kueishantao Island emit mineral-laden, hazardous chemical-rich vent fluids. These vents may negatively affect the health of species inhabiting or passing through the vent fluids (Burd et al., 1992). The impacts of hydrothermal vents extend beyond the benthic environment and are evident throughout the vent fluids (Peng et al., 2011). Abiotic variables, including temperature and chemical composition, play a crucial role in shaping vent community structures (Cuvelier et al., 2009; Chan et al., 2012).

These pelagic copepods are opportunistic feeders, ingesting vent microorganisms and organic carbon near hydrothermal vents. They are also thought to be influenced by potentially harmful chemicals, gases (Chen et al., 2005; Peng et al., 2011), and metals (Rozan et al., 2000). Under elevated temperatures and low pH, these toxic compounds compromise the exoskeletons of pelagic copepods (Omair et al., 1999; Bhandare and Ingole, 2008), increasing vulnerability to ectoparasite infestation and resulting in the development of TLAs (Savchenko and Kolbasov, 2009).

2.5.6. Large TLA structures in zooplankton

A tumour-like anomaly has been detected in the dominant predatory copepod *Limnocalanus macrurus* Sars, 1863 (Vanderploeg et al., 1998) in zooplankton samples from the hypolimnion and nearshore regions of Lake Michigan (Figure 27) (Omair et al., 1999).

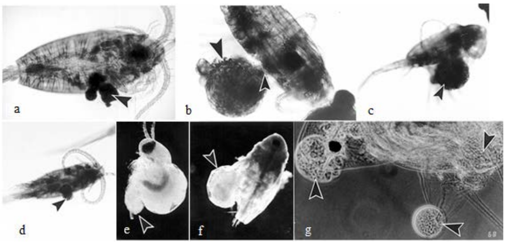


Figure 27. Appearance of tumour-like abnormalities in zooplankton. a) A large, multilobed tumor on the ventral surface of the prosome between the swimming legs and mouthparts of *Limnocalanus*, b) Dorsal view of *Limnocalanus*, with a large, spherical abnormality (large arrowhead) attached to the right side of the prosome by a stalk-like structure (small arrowhead), c, d) Tumour-like abnormalities on the ventral prosome of *Diaptomus* spp., e) *Polyphemus pediculus*, f) Dorsal view of *Diaphanosoma* sp., g) Abnormalities on the helmet near the compound eye, the ventral claw, and the body shell of *Daphnia galeata mendotae* (Omair et al., 1999).

Certain anomalies in *Limnocalanus* have multilobed characteristics (Figure 27a), are substantial, nearly spherical, and are attached by a stalk-like structure (Figure 27b). Young adult copepods have been documented as affected by these anomalies (Vanderploeg et al., 1998). Anomalies in *Diaptomus* (Figures 27c, d) vary in size, with some reported to be proportionately as large as those observed in *Limnocalanus*. Three cladoceran species – *Polyphemus pediculus* (Linnaeus, 1761), *Diaphanosoma* sp., and *Daphnia galeata mendotae* – exhibited TLAs at multiple sites on the carapace and on the ventral claw (Figures 27e, f, g) (Omair et al., 1999).

2.5.7. Round, dark, granular, non-granular and transparent TLA types

Jagadeesan and Jyothibabu (2016) documented the occurrence of TLA in 24 copepod species, comprising 20 from Calanoida, two from Poecilostomatoida, and one each from Harpacticoida and Cyclopoida, predominantly among dominant copepods (Figure 29). In coastal waters, the TLA-carrying species generally included *Paracalanus parvus*, *Temora turbinata*, *Acartia danae*, *Acartia erythraea*, *Undinula vulgaris*, *Clausocalanus arcuicornis*, *Corycaeus danae*, *Oncaea venusta*, *Pseudodiaptomus serricaudatus,* and *Acrocalanus gracilis*. Conversely, *Acrocalanus gracilis*, *Paracalanus parvus*, *Pa. aculeatus*, *Ps. serricaudatus*, *T. turbinata*, *Acartiella gracilis*, *Heliodiaptomus cinctus,* and *Allodiaptomus* sp. were identified as TLA-bearing pelagic copepods (Jagadeesan and Jyothibabu, 2016).

TLAs are predominantly found on the dorsal and lateral surfaces of the prosome and urosome of copepods (Figures 28, 29, 30, 31, and 32). Research indicates that of the two prevalent types of TLAs, the round and granular type (Figure 28) is more common than the non-granular type (Jagadeesan and Jyothibabu, 2016). TLAs in the urosome have mainly been documented in *Aca. erythraea*, *Aca. danae*, *T. turbinata*, *Pa. parvus*, and *Ps. serricaudatus*. Two varieties of TLAs have been recorded as prevalent in the prosomal region: (Figures 28a, b) round, dark, and granular, and (28c, d) round, non-granular, and transparent (Jagadeesan and Jyothibabu, 2016).

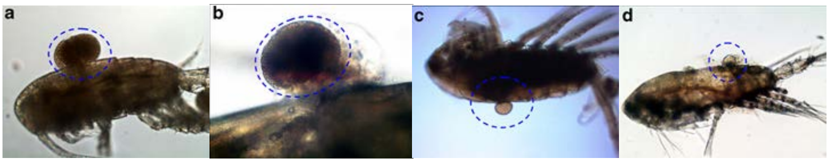


Figure 28. Two types of TLAs in the copepod prosome, a, b) round, granular and dark, c, d) round, non-granular and transparent (Jagadeesan and Jyothibabu, 2016).

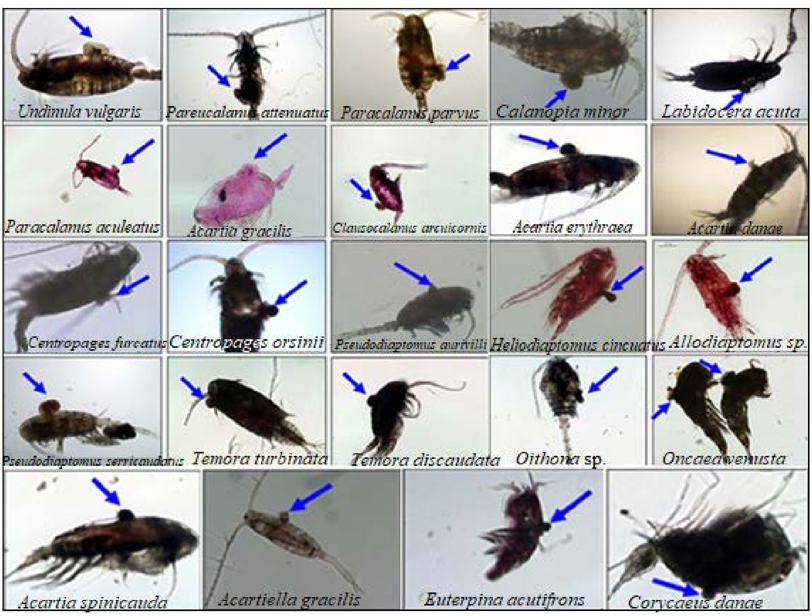


Figure 29. TLA observed in the prosome of copepod. Dark granular TLA was mostly seen between the cephalosome and metasome of copepods (Jagadeesan and Jyothibabu, 2016).

Reports indicate that TLAs observed in the urosome typically exhibit a round, granular morphology, but others display a multi-lobed, elongated, transparent, small-granulated form, characterised by elongated, black clot-like formations with extensions (Figures 30 and 31) (Jagadeesan and Jyothibabu, 2016).

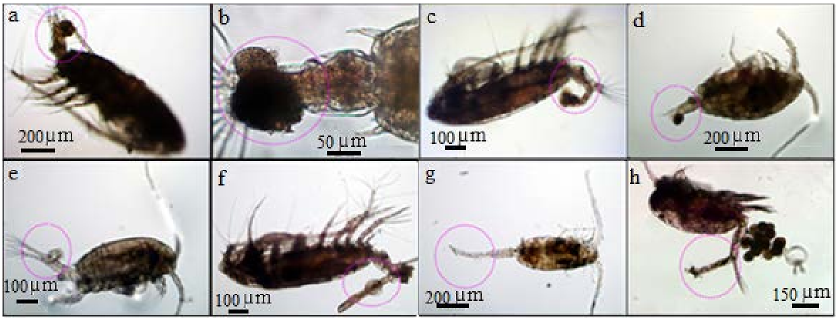


Figure 30. Various types of TLA in copepod urosome. a) *Acartia erythraea*, b) *Acartia danae*, c) *Temora turbinata*, d) *Paracalanus parvus*, e) *Pseudodiaptomus serricaudatus*, Anal TLA types: a, d dark granular, b multilobed, c, f stalked, sleeve-shaped, e small and slightly curved, g transparent and long, and h stalk-like extension. (Jagadeesan and Jyothibabu, 2016).

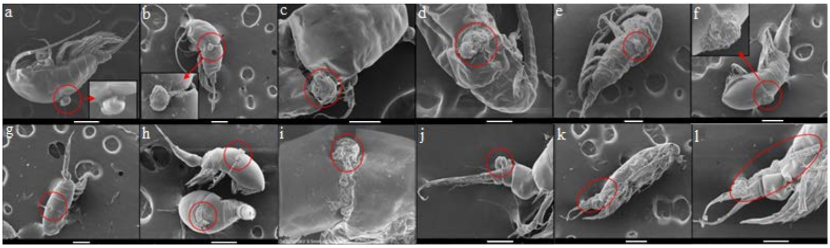


Figure 31. SEM images of TLA in copepods. Red circles represent TLA on the prosome (a–i) and urosome (j–l) of copepods (Scale bars: a, b, e, f, g, h, k 200 µm; c, d, j, l 100 µm) (Jagadeesan and Jyothibabu, 2016).

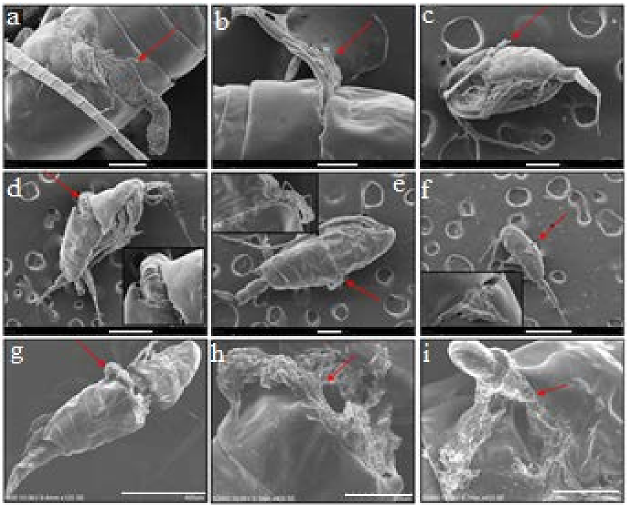


Figure 32. SEM images of shedding of internal body segments associated with the TLA in copepods. Shedding occurred mostly in the intersomital regions between the last prosome and the first metasomal segment (Scale bars: a, b, h, i, 100 µm; c, e, 200 µm; g, 400 µm; d, f, 500 µm) (Jagadeesan and Jyothibabu, 2016).

2.5.8. Endoparasites and TLA

Blastodinium was identified in the digestive systems of various copepod species, including *U. vulgaris*, *Cl. arcuicornis*, *Pa. parvus*, *Pa. aculeatus*, *Oithona* sp., and *Co. danae*; however, its prevalence was significantly lower compared to TLAs (Figure 33) (Jagadeesan and Jyothibabu, 2016).

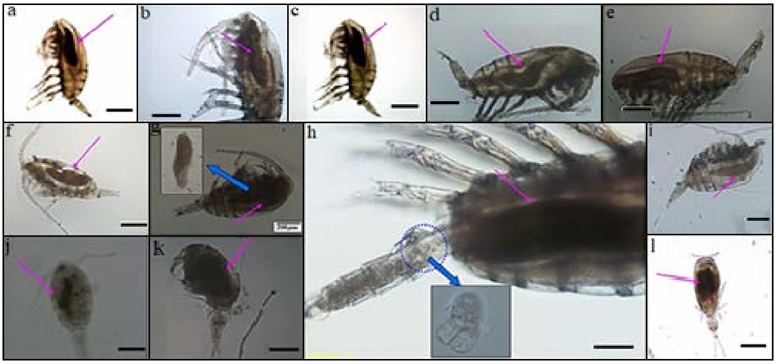


Figure 33. Endo-parasitic *Blastodinium* infection within the digestive system of copepods, denoted by purple arrows. a–e) *Undinula vulgaris*, f–i) *Paracalanus parvus*, j) *Oithona* sp., k) *Corycaeus danae*, and l) *Corycaeus catus*. g) Internal parasite structure post-dissection (thick blue arrow), h) The expulsion pathway of the mature gonocyte of *Blastodinium* (blue circle) from the anus (Scale bars a, b, c, d, e, f, 200 µm; j, k, l, 100 µm) (Jagadeesan and Jyothibabu, 2016).

2.5.9. Ectoparasites and TLA

The ectoparasite *Ellobiopsis* sp. was observed attached to the cephalic processes of the copepod *U. vulgaris* by its stalks (Figures 34 and 35), with infection density reported to fluctuate between 0.08% and 0.31% of the total *U. vulgaris* population. Reports indicated that none of the *Ellobiopsis* sp.-infected copepods collected from the field had TLA, and similarly, those incubated in the laboratory showed no signs of TLA development (Jagadeesan and Jyothibabu, 2016).

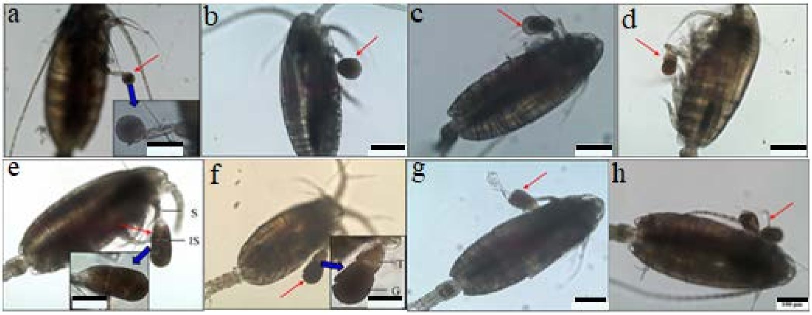


Figure 34. Ectoparasitic *Ellobiopsis* infection in the copepod *Undinula vulgaris*. a–g) Various life stages of *Ellobiopsis* infection in copepods: a) initiation stage, b, c) trophomere development, d) formation of internal septa, e) distinct separation of trophomere and gonome, f) maturation of gonome, g) post-spore release, h) attachment of two parasites to the host. S: stalk, T: trophomere, G: gonome (Scale bars: b, c, d, g, h 100 µm; a, e, f, 50 µm) (Jagadeesan and Jyothibabu, 2016).

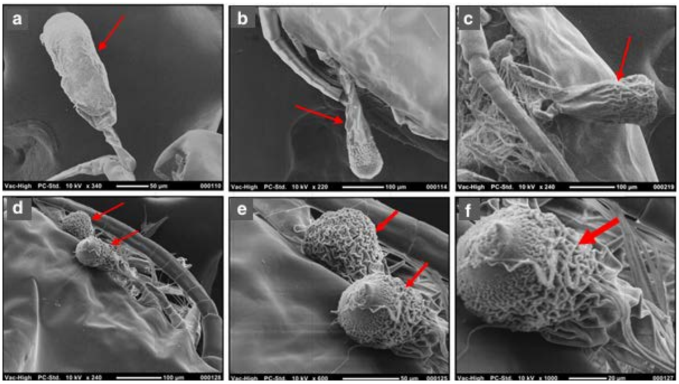


Figure 35. SEM images of *Ellobiopsis* infection on copepods.

a–c) Single *Ellobiopsis* attached to feeding appendages.

d) Two *Ellobiopsis* attached to the copepod.

e–f) Detailed morphology at higher magnifications (Jagadeesan and Jyothibabu

2.5.10. Epibionts and TLA

Infection by the peritrichous ciliate *Zoothamnium* sp. has been documented on the surfaces of *Aca. erythraea* and *Aca. danae*, with infection rates reported between 0.28% and 1.14% of the total copepod population (Jagadeesan and Jyothibabu, 2016). The number of attachments on an individual host ranged from 0 to 60, predominantly on the lateral surfaces of the prosome (Figure 36a, b). *Acineta* infection has been recorded on the lateral surfaces (prosome and urosome) of the harpacticoid species *Microsetella rosea*, *Macrosetella gracilis*, *Macrosetella oculata*, and *Euterpina acutifrons* (Figure 36c, d), with infection rates reported between 0.15% and 0.46% (Jagadeesan and Jyothibabu, 2016). The infestation density on individual hosts ranged from 0 to 140, although the host copepods showed no signs of TLA formation attributable to epibiont attachment. The epibionts use the copepod body solely as an attachment substrate without causing injury to the host (Jagadeesan and Jyothibabu, 2016).

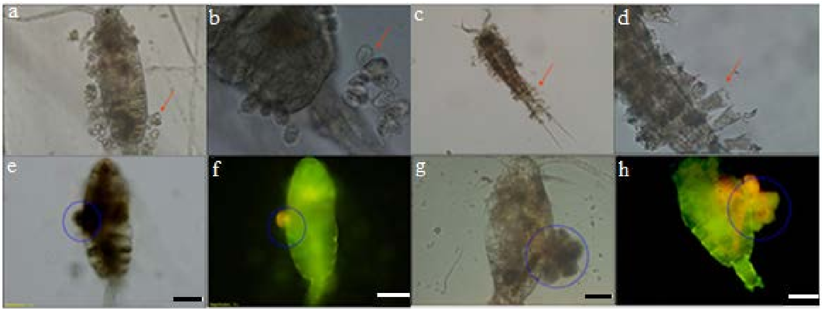


Figure 36. Attachment of the epibiont Zoothamnium to the copepod *Acartia danae* (a, b), and attachment of *Acineta tuberosa* to *Macrosetella gracilis* (c, d). Photomicrographs from light (e, g) and fluorescence microscopes (f, h) demonstrate that the TLA is an extension of the digestive system (Scale bars: 200 µm) (Jagadeesan and Jyothibabu, 2016).

2.5.11. Hunting and TLA

The post-contact predator avoidance behaviour of copepods was documented in two individuals that became ensnared in the nematocysts of a hydromedusa and attempted to extricate themselves (Figure 37). However, their urosomes (caudal rami) were injured. This damage resulted in an unusual swimming pattern in both copepods. In a separate observation, the nematocysts of the hydromedusa were dislodged from the copepod's body due to the copepod's evasive manoeuvres, and subsequently, TLA formation was observed at the site of nematocyst contact in the same specimen (Figure 37) (Jagadeesan and Jyothibabu, 2016).

Marine plankton exhibit epibiosis, characterised by the attachment of bacteria, algae, protozoa, or rotifers to their surface. Numerous protozoan species from the flagellates, suctorians, and peritrichid groups can inhabit zooplankton organisms (Skovgaard, 2014). Crustaceans display epibiosis and host dinoflagellates, ciliates, acanthocephalans, nematodes, tantulocarids, and ellobiopsids (Boxshall, 1983; Savchenko and Kolbasov, 2009), while also promoting the development of TLA in their shells (Messick et al., 2004; Skovgaard, 2004).

Several hairy diatoms and peritrichous ciliates are epibionts that inhabit the surface of copepod bodies (Skovgaard et al., 2012), causing lesions that penetrate deeply into the body. Abnormal protrusions in copepods arise from infection, oedema, rupture, and similar causes, leading to the growth of body tissue and the ballooning of small amounts of the zooplankton's internal tissue (Bridgeman et al., 2000).

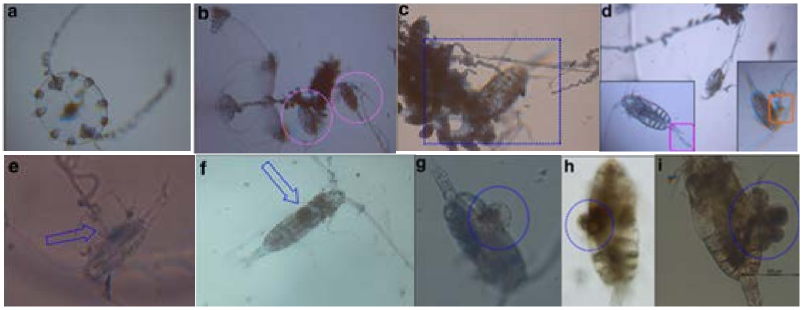


Figure 37. Sequential snapshots of hydromedusae predation on copepods. a) Hydromedusae, b) Copepods captured by hydromedusae with their nematocysts (in pink circles), c) Close-up of the capture (shown in blue rectangles), d) Copepods trying to escape from nematocyst contact, e) Nematocysts attached to the dorsal side of the copepod, f) TLA development in a copepod escaping from nematocyst contact, g–i) Other TLAs observed during the predation experiment using hydromedusae (highlighted in blue circles) (Jagadeesan and Jyothibabu, 2016).

Reports indicate that TLAs in copepods are located on multiple appendages, particularly on the antennae of calanoid copepods, across the dorsal, lateral, ventral, dorso-lateral, and dorso-ventral body surfaces (Figure 38a). The most notable instances are found in the calanoid *Labidocera* sp. (Figures 38b, d, e; 39a, b) (Al-Aidaroos and Mantha, 2018).

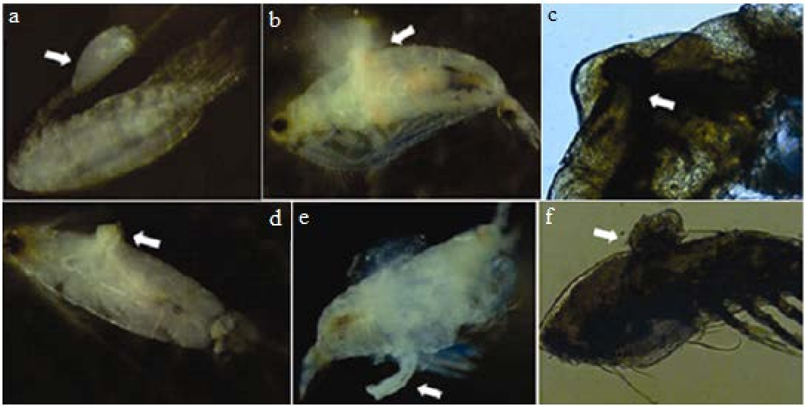


Figure 38. Different tumor-like anomalies in copepods. a) Ellobiopsid infection on the antennal of a calanoid copepod; b) Infectious protrusion with its internal mass protruding from the dorsal side of a *Labidocera* sp.; c) Protrusion from the dorsal side of a calanoid copepod; d) Infectious protrusion from the lateral side of a *Labidocera* sp.; e) Protruding parasitic infection; f) Protrusion from the dorsal side of a calanoid copepod (Al-Aidaroos and Mantha, 2018).

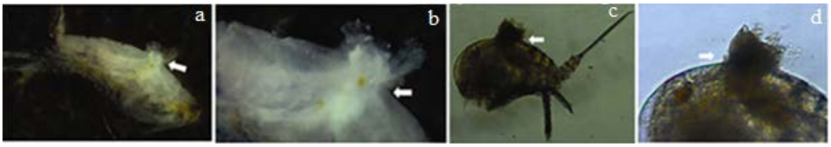


Figure 39. Tumor-like anomalies in copepods. a, b) A protrusion with an internal mass protruding from the dorsal side of the calanoid copepod (white arrow); c,d) A protrusion from the dorsal surface of the cyclopoid copepod (Al-Aidaroos and Mantha, 2018).

2.6. Factors causing copepod anomaly

Abnormal protrusions in copepods are a significant issue reported across various aquatic environments worldwide, with no consensus on the underlying factors that induce their formation. Although the precise aetiology remains unconfirmed, research suggests this anomaly is more common in urban coastal regions

(Vanderploeg, 1998), oil refineries, areas experiencing substantial fluctuations in water temperature or salinity (Crisafi and Crescenti, 1977), locations with high pollution levels, carcinogenic substances, ultraviolet radiation, injuries, viral or bacterial infections, parasitism, and environmental changes (Bhandare and Ingole, 2008; Mantha et al., 2013).

Parasitism is a frequent cause of malformations; specifically, infections by endoparasites such as the dinoflagellate *Blastodinium* sp. and the ectoparasitic alveolate *Ellobiopsis* sp. have been documented to induce tissue protrusions in copepods (Bridgeman et al., 2000; Skovgaard, 2004). Furthermore, Mantha et al. (2013) suggested that fluctuating climatic conditions may increase harmful mineral concentrations from hydrothermal vents on Kueishantao Island, Taiwan, thereby compromising the exoskeleton of these crustaceans and heightening their susceptibility to infection. Additional research indicates that shallower habitats exhibit higher rates of abnormalities compared to deeper waters (Silina and Khudolei, 1994).

Abnormal protrusions in copepods are histologically diverse structures, including necrotic tissue, which may result from impaired blood flow, environmental exposure, disease lesions, or other localised injuries. Protrusions containing granular material may have undergone autolysis, rendering the cells unrecognisable. Other studies, after examining multiple individuals, have found that the protrusions consist of apparently necrotic or degenerative tissue (Omair et al., 2001).

The transitional moulting stages of nauplii may make them susceptible to damage, developmental problems, or parasitism. The presence of many protrusions between the somites suggests that intersomite regions are more vulnerable to penetration or rupture than other areas (Omair et al., 2001). Puncture wounds caused by external predators or parasites are likely to provoke herniation (Bridgeman et al., 2000; Omair et al., 2001).

Some protrusions clearly indicate ellobiopsid parasites, with early life stages of these infestations shown to attach to the antennae and mouthparts of copepods (Jepps, 1937); however, the infection mechanisms and histological features of early infections remain to be clarified. One hypothesis is that the parasite's root-like connection penetrates the skin but does not anchor securely, resulting in herniated swollen tissue (Jepps, 1937).

Research indicates that cuts, punctures, or damage to the exoskeleton of copepods are the main factors contributing to TLA production in these organisms (Messick et al. 2004; Omair et al. 2001). This was confirmed by perforating the copepod exoskeleton with a sterile needle, which revealed that TLA appeared in the injured region within one day. In controlled laboratory studies, a predation experiment was conducted on copepods using medusae as predators, showing that TLA developed in the area where medusae tentacles were attached (Jagadeesan and Jyothibabu, 2016). Previous research indicates that ectoparasitism, endoparasitism, epibionts, and predation are likely factors responsible for wounds in copepods (Manca et al. 2004; Bhandare and Ingole 2008).

Endoparasites (*Blastodinium*), ectoparasites (*Ellobiopsis* sp.), epibionts, and other factors have been documented as sources of TLA infection in copepods (Messick et al. 2004). Additionally, like all living organisms, copepods may display abnormal development in their body structures at any stage of their life cycle (Souissi and Souissi, 2020), and related anomalies may occur.

Regarding the development of TLA, Skovgaard (2004) reported that the ectoparasite *Ellobiopsis* sp. typically penetrates the anterior region of the body, piercing copepods with fragile exoskeletons and consuming their bodily fluids. Alternatively, the root-like attachment of *Ellobiopsis* may detach upon skin penetration without secure adherence, resulting in an opening where the engorged tissue herniates. Chatton (1920) observed that certain dinoflagellate endoparasites, such as *Blastodinium* sp., which infect marine copepods, generate protrusions that remain even after the parasite has separated from its host.

3. CONCLUSION

The consequences of aberrant protrusion in copepods can be substantial. The malformation may increase copepods' susceptibility to predation, diminish population size and lifespan, and affect food web dynamics in aquatic habitats (Souissi and Souissi, 2020). Moreover, diminished swimming capability, vertical migration, and nutrient cycling in copepods exhibiting this anomaly may result in decreased primary productivity, hence affecting the overall health and resilience of the ecosystem (Al-Aidaroos and Mantha, 2018; De Souza et al., 2024). Rectal prolapse in copepods is a disease characterized by the protrusion of a copepod's rectum beyond its body. This anomaly, however very uncommon, signifies a deterioration of the rectal musculature. Rectal prolapse can adversely affect copepods by impairing their capacity to feed, reproduce, or execute other vital duties. It also heightens their susceptibility to predation and other environmental stressors (De Souza et al., 2024).

Epibiosis and similar conditions are common in aquatic microorganisms, and it has been documented that both the host (basibiont) and the epibiont face various disadvantages (Wahl, 1989). The primary issues include diminished fertility (Threlkeld and Willey, 1993), challenges in the mating process (Souissi et al., 2013), reduced survivability (Allen et al., 1993), heightened mortality, and decreased body size (Burris and Dam, 2014), lesions and diseases (Nagasawa, 1987), movement disorders (Henebry and Ridgeway, 1979), competition for resources, increased vulnerability to predation (Willey et al., 1993), elevated energy requirements, accelerated sinking rates (Allen et al., 1993), and physiological upregulation of stress-related genes (Petkeviciute et al., 2015). in addition to these TLA in copepods is seen as a possible hazard to the integrity of the aquatic food web and should be included in future aquatic management strategies (Al-Aidaroos and Mantha, 2018).

Although anomalies may not directly harm bodily tissues, the substantial size of tumors in certain species poses a significant risk to the integrity of food webs (Messick et al., 2004), since they can influence swimming and eating behaviors. Regardless of whether abnormalities are neoplastic or non-neoplastic, induced by an environmental carcinogen, or attributable to an infectious agent, their influence on the food web can be substantial (Omair et al., 1999).

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YAPAY ZEKÂ'NIN SU ÜRÜNLERİ YETİŞTİRİCİLİĞİ İLE ENTEGRASYONU

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1. GİRİŞ

Yapay zekâ (YZ) uygulamaları, günümüzde su ürünleri yetiştiriciliği sistemlerinin sürdürülebilirliğinin artırılmasına yönelik köklü bir dönüşüm potansiyeline sahiptir. YZ tabanlı modelleme, izleme ve öngörü araçları, üretim süreçlerinin daha kesin, hızlı ve düşük maliyetli bir şekilde yönetilmesine imkân tanıyarak geleneksel yöntemlerin ötesine geçen yenilikçi yaklaşımlar sunmaktadır. Bu kapsamda, YZ destekli su ürünleri yetiştiriciliği; çevresel etkilerin minimize edilmesi, kaynak kullanım verimliliğinin artırılması ve balık refahı standartlarının yükseltilmesi gibi çok boyutlu katkılar sağlayabilmektedir. Özellikle su kalitesine ilişkin parametrelerin erken tespiti, hastalıkların öngörülmesi, besleme stratejilerinin optimize edilmesi ve çevresel değişkenlere otomatik uyum sağlayan kontrol mekanizmalarının geliştirilmesi, YZ'nin sektöre entegrasyonunun en kritik avantajları arasında yer almaktadır. YZ'nin karar verme destek sistemlerine entegre edilmesi, sadece operasyonel verimliliği artırmakla kalmamakta; aynı zamanda

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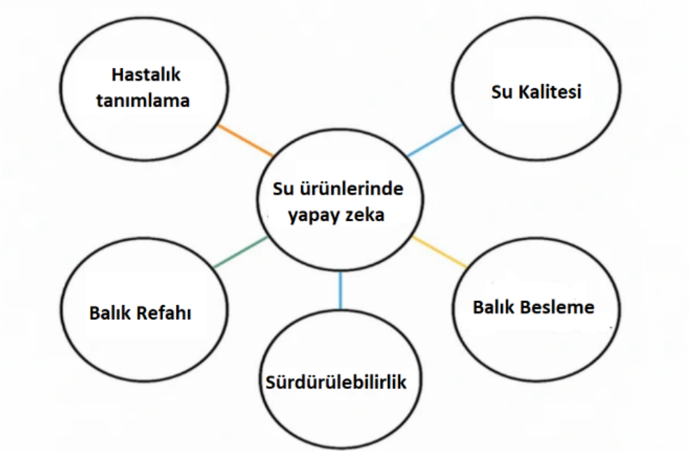
sürdürülebilir çevresel yönetim ilkeleriyle uyumlu, ekonomik açıdan sürdürülebilir ve iklim değişikliğine dirençli üretim modellerinin geliştirilmesine de katkıda bulunmaktadır. Böylece su ürünleri yetiştiriciliği, daha öngörülebilir, izlenebilir ve çevresel risklere karşı adaptif bir yapıya kavuşmaktadır. Bu doğrultuda, bu çalışmada yapay zekânın su ürünleri yetiştiriciliğine entegrasyonunun temel gerekçeleri, uygulama alanları, sektöre sağladığı kazanımlar, karşılaşılan teknik ve operasyonel zorluklar ile geleceğe yönelik potansiyel gelişim fırsatları kapsamlı bir şekilde ele alınacaktır.

Su ürünleri yetiştiriciliği (akuakültür), dünya genelinde artan gıda talebi, doğal stokların baskı altında olması ve sürdürülebilirlik gereksinimi nedeniyle giderek daha kritik bir üretim biçimi hâline gelmiştir. Bu bağlamda, verimliliğin artırılması, maliyetlerin düşürülmesi, çevresel etkilerin minimize edilmesi ve hayvan refahının iyileştirilmesi gibi hedefler ön plana çıkmaktadır. Bu hedeflere ulaşabilmek için geleneksel yöntemlerin ötesine geçilmesi, dijitalleşme, otomasyon, veri-analitiği gibi yaklaşımların benimsenmesi kaçınılmazdır. Burada devreye giren önemli bir teknoloji kümesi de **yapay zekâ (YZ)**dır. YZ, büyük veri-setleri, sensörlerden gelen çoklu değişkenli veriler, görüntü ve ses analitiği gibi kaynakları işleyerek alınan kararları destekleyebilir, öngörüler sunabilir ve süreçleri optimize edebilir.



Şekil 1. Su ürünlerinde yapay zekâ.

Yapay zekâ (YZ) da dahil olmak üzere yeni teknolojilerin entegre kullanımı, bu alandaki faaliyetlerin verimliliğini artırmak için yeni fırsatlar sunmaktadır. YZ'dan su ürünleri yetiştiriciliği için beklenti; ı) besleme stratejileri, ıı) üretim modellemesi ve ııı) çiftliğin genel işleyişinde karar alma, optimizasyon ve otomasyon için bir katalizör görevi görmesidir. Ayrıca, YZ, balık çiftliklerindeki koşulların izlenmesinde ve su ortamının uygun şekilde yönetilmesini kolaylaştırmak için erken hastalık teşhisinde kullanılmaktadır (Aung vd., 2025; Yang vd., 2025; Aung vd., 2025; Roy vd., 2025; Ma vd., 2025; Rizzi vd., 2025; Baena-Navarro vd., 2025; Roy vd., 2025).

2. YAPAY ZEKÂNIN AKUAKÜLTÜRDEKİ BAŞLICA UYGULAMA ALANLARI

2.1. Su kalite ve çevresel izleme

Su ürünleri yetiştiriciliğinde su kalitesi (örn. sıcaklık, çözünmüş oksijen, pH, amonyak, nitrit, tuzluluk), hayvan sağlığı ve büyümesi açısından kritik öneme sahiptir. YZ ve sensör-veri entegrasyonu, bu parametrelerin gerçek zamanlı takibini ve anomalilerin erken tespitini mümkün kılar. Örneğin bir çalışmada "smart aquaponics" sistemlerinde IoT + YZ kullanımı incelenmiş olup, sensörlerden gelen verilerle hem izleme hem de kontrol amacıyla karar destek sistemleri oluşturulabileceği vurgulanmıştır (Anila and Daramola, 2024). Bu tür izleme sistemleri sayesinde aşırı yüklenme, oksijen düşüşü, toksik gaz birikimi gibi riskler önceden saptanabilir ve operatör müdahalesi erkene alınabilir.

2.2. Besleme optimizasyonu ve biyokütle tahmini

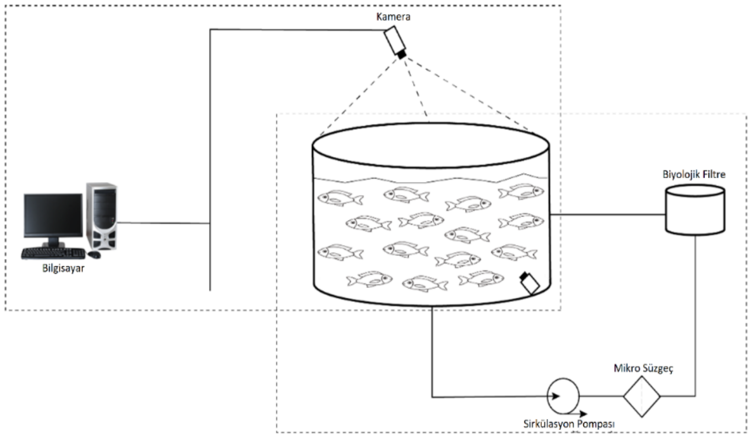
Besleme, işletme maliyetlerinin yüksek olduğu ve çevresel yük oluşturabileceği bir alandır (örneğin aşırı yemleme → atık artışı → su kalitesi bozulması). YZ sistemleri, yemleme zamanlarını, miktarlarını, yemleme sıklığını optimize ederek yem verimliliğini artırabilir. Ayrıca biyokütle tahmini (yetişen balık miktarı) ve büyüme modelleri de YZ ile geliştirilmektedir. YZ'nın su ürünleri yetiştiriciliği endüstrisindeki olası uygulamalarının araştırıldığı çalışmada, veri algoritmalarının potansiyel patojen enfeksiyonlarını ve hastalık salgınlarını erken tespit ederek, su ürünleri yetiştiriciliği paydaşlarının zamanında önleyici tedbirler almasını ve ardından uygun zamanda doğru kararı vermesini sağlayabileceği bunun yanısıra su ürünleri yetiştiricilerinin balık çiftlikleri üzerindeki olumsuz etkileri önlemek ve balık üretimi için kolay ve güvenli bir ortam yaratmak üzere strateji / planlar benimsemelerine yardımcı olması gereken ekolojik koşulları tahmin edebileceği rapor edilmiştir (Ragab vd., 2025). Ayrıca, besin gereksinimleri, besin bulunabilirliği ve fiyatla ilgili verileri analiz etmek ve toplamak için YZ yardımcılarının kullanılması, çiftçilerin yem formülasyonlarını optimize etmek için diyetlerini ayarlamalarına ve değiştirmelerine yardımcı olabilir. Dolayısıyla, YZ kullanımı çiftçilerin işçilik maliyetlerini azaltmalarına, aquatik organizmaların büyümesini ve sağlığını izlemelerine, yem formülasyonlarını optimize etmelerine, atık üretimini azaltmalarına yardımcı olabilir. Genel olarak bu inceleme, su ürünleri yetiştiriciliğinde sürdürülebilirliği sağlamak ve çiftçilerin net kârlarını artırmak için yapay zekânın kullanılmasının önemini vurgulamaktadır.

2.3. Hastalık tespiti ve hayvan refahı

Hastalıklar ve stres koşulları, üretim verimini düşüren, ölüm oranlarını artıran önemli risklerdir. YZ, görüntü işleme (örneğin balığın davranışı, yüzeyi, solungaç durumu vs.), ses verisi, fiziksel aktivite analizi yoluyla erken hastalık tespiti için kullanılabilir. Su ürünleri yetiştiriciliğinin şu anda karşı karşıya olduğu temel zorluklar, hem su ortamı hem de balık davranışları, sağlığı ve refahının değerlendirilmesi için en iyi yönetim uygulamalarının iyileştirilmesine ve izleme sistemlerinin geliştirilmesine dayanmaktadır. Balıkların temel ihtiyaçlarının daha iyi anlaşılması, stres faktörlerinin ve stres tepkilerinin azaltılması ve nihayetinde verimliliğin ve ürün kalitesinin artırılması için, tüm üretim döngüsünü kesime kadar kapsayan sistematik ve entegre bir refah değerlendirme çerçevesinin uygulanması esastır. Sistem modelleme ve makine öğrenimini içeren 'Hassas Balık Çiftçiliği' sistemlerinin geliştirilmesi, su ürünleri yetiştiriciliği teknolojisinde önemli bir ilerlemeyi temsil etmektedir (Burke vd., 2025). Bu yaklaşım, mevcut çalışmada ele alınanlar da dahil olmak üzere refahla ilgili zorluklara umut verici çözümler sunmaktadır. Bu sayede zamanında müdahale edilebilir, ilaç ya da başka tedavi stratejileri planlanabilir, hayvan refahı iyileştirilebilir.

2.4. Balık tanımlama, sayma ve davranış analizi

Görüntü işleme ve bilgisayarlı görü teknikleri sayesinde balıkların hareketlerini, sürüleşme durumlarını, konumlarını ve sayımlarını otomatik olarak yapmak mümkündür. Bu, hem stok kontrolü hem de üretim yönetimi açısından değerlidir.



Şekil 2. Balık verisi toplama deney düzeneği (Iqbal vd., 2022).

Mevcut sınırlamaların üstesinden gelmek için, entegre balık izleme sistemlerinin doğruluğunu, sağlamlığını ve verimliliğini artırmak amacıyla çok modlu veri birleştirme ve derin öğrenme gibi yeni teknolojilerin kullanım potansiyelinin araştırıldığı çalışmada balık takibi, sayımı ve davranış analizi için mevcut veri kümelerinin bir özeti sunulmuştur. Bu bütünsel bakış açısı, teknolojiler arasında anlamlı karşılaştırmaları kolaylaştırmak ve gerçek dünya ortamlarında pratik uygulamalarını desteklemek için kapsamlı veri kümelerine ve değerlendirme standartlarına olan ihtiyacı vurgulayarak, gelecekteki araştırmalar için bir yol haritası sunması planlanmaktadır (Cui vd., 2025). Bu tür otomasyon, insan hatasını azaltır ve veriyi gerçek zamanlı kullanılabilir hale getirir.

2.5. Üretim planlaması ve karar destek sistemleri

YZ modelleri, geçmiş verilerden öğrenerek üretim süreçlerini, besleme planlarını, hasat zamanlarını, su değişim ihtiyaçlarını ve maliyet-getiri analizlerini destekleyebilir. Bu karar destek sistemleri sayesinde işletmeler daha stratejik hareket edebilir, riskleri daha iyi yönetebilir.

3. YZ ENTEGRASYONUNUN SAĞLADIĞI FAYDALAR

YZ'nin su ürünleri yetiştiriciliğine entegrasyonunun başlıca faydaları şunlardır:

- **Verimlilik artışı**: Örneğin yemleme optimizasyonu sayesinde yemden gelen verim artar, yem israfı azalır.
- **Maliyetlerin düşürülmesi**: Otomasyon ve gerçek zamanlı izleme ile işgücü, su/enerji atığı, hastalık kontrolü gibi maliyet kalemleri azaltılabilir.
- **Çevresel sürdürülebilirlik**: Daha az atık, daha az bozulan su kalitesi, daha iyi hayvan refahı sayesinde çevresel baskılar azalabilir. YZ, su kalite bozulmadan önceden uyarı verebilir.
- **Hayvan sağlığı ve refahı iyileşmesi**: Erken hastalık tespiti, davranış izleme gibi uygulamalar sayesinde balıkların sağlığı daha yakından takip edilebilir.
- **Veriye dayalı karar alma**: Geleneksel sezgisel veya tecrübeye dayalı kararların yerine, büyük veri ve YZ algoritmalarına dayalı daha nesnel karar alma mekanizmaları kurulur.

Karşılaşılan Zorluklar ve Kısıtlar

- **Veri eksikliği, kaliteli veri toplama**: YZ algoritmalarının iyi çalışması için büyük ve kaliteli veri setlerine ihtiyaç vardır. Akuakültürde bu tür verilerin toplanması, etiketlenmesi ve standartlaştırılması genellikle zor.
- **Çeşitli yetiştiricilik koşulları ve ölçek farkları**: Farklı alt sistemler (örneğin havuz, göl, açık deniz kafesleri), farklı koşullar (iklim, tür, su kalitesi) için genellenebilir. YZ modelleri geliştirmek ve pratiğe uyarlanması zaman alabilir.

- **Altyapı ve teknoloji maliyeti**: Sensör ağları, görüntü sistemleri, veri işleme altyapısı gibi unsurlar başlangıçta yüksek maliyetli olabilir; küçük ölçekli üreticiler için erişilebilir olmayabilir (Aung vd., 2025)
- **Veri güvenliği ve etik kaygılar**: Verilerin gizliliği, yönetimi ve algoritmaların karar süreçlerinin şeffaflığı konusunda belirsizlikler vardır (Bagde vd., 2024).
- **İnsan kaynağı ve beceri**: YZ sistemlerini kuracak, kullanacak ve yorumlayacak kalifiye insan kaynağı her yerde yeterli düzeyde olmayabilir. Eğitim, değişim yönetimi süreçleri önemlidir.
- **Model geçerliliği ve sürdürülebilirliği**: Bir modelin bir sistemde başarılı olması, başka sistemde aynı başarıyı göstereceğini garanti etmez. Model güncellemesi, yeniden eğitim, uzun vadeli bakım gerekir.

4. GELECEĞE YÖNELİK PERSPEKTİFLER

YZ'nin su ürünleri yetiştiriciliğinde ilerlemesini sağlayacak ve sektörü dönüştürecek bazı önemli yönelimler şunlardır: Sensörler, görüntü sistemleri, haberleşme altyapısı ve YZ modellerinin birleşimiyle "akıllı çiftlikler" konsepti güçlenecektir. Multimodal veri kullanımı (Görüntü, akustik, sensör, çevresel data) farklı modalitelerden gelen verilerin birleşik analizi ile zenginleştirerek bireylerin davranışlarını, stres düzeylerini, hastalık risklerini belirleyebilir hâle gelecektir. Küçük ölçekli üreticiler için düşük maliyetli, kolay uygulanabilir YZ sistemleri geliştirilerek sektörde kapsayıcılık artabilir. Ayrıca her tür ve coğrafi bölge için optimize edilmiş YZ modelleri geliştirilebilecektir.

5. TÜRKİYE VE BÖLGESEL UYARLAMA AÇISINDAN DÜŞÜNCELER

Türkiye gibi su ürünleri yetiştiriciliği açısından potansiyel taşıyan ülkelerde, YZ teknolojilerinin entegrasyonu şu hususlara dikkat edilerek planlanmalıdır:

1. Yerel altyapı koşulları (internet erişimi, sensör maliyeti, operatör eğitimi) dikkate alınmalı.
2. Gökkuşağı alabalığı, çipura, levrek gibi yetiştiricilikte önemli olan türler için için veri setleri oluşturulmalı, YZ modelleri bu türlere özel uyarlanmalı.
3. Üreticilerle iş birliği içinde pilot uygulamalar başlatılmalı; ilk adımda otomasyon düzeyi daha düşük ama etkisi yüksek alanlar (örneğin yemleme optimizasyonu) tercih edilebilir.
4. Sürdürülebilirlik açısından çevresel izlemenin (özellikle açık deniz kafeslerinde) YZ ile desteklenmesi Türkiye-koşulları için büyük kazanç sağlayabilir.
5. Eğitim ve kapasite geliştirme faaliyetleri önemli; YZ teknolojisini uygulayacak insan kaynağı oluşturulmalıdır.

6. SONUÇ

Yapay zekâ (YZ) teknolojilerinin su ürünleri yetiştiriciliğine entegrasyonu, sektörün üretim verimliliğini artırma, operasyonel maliyetleri azaltma, çevresel etkileri en aza indirme ve hayvan refahını iyileştirme açısından önemli potansiyel taşımaktadır. Özellikle karar destek sistemleri, görüntü işleme temelli davranış izleme uygulamaları, otomatik yemleme algoritmaları ve çevresel parametrelerin gerçek zamanlı analizi gibi YZ tabanlı yaklaşımlar, yetiştiricilik süreçlerinin daha öngörülebilir ve optimize edilebilir hâle gelmesini sağlamaktadır.

Bu teknolojilerin etkin kullanımı, sadece üretim performansını artırmakla kalmayıp aynı zamanda kaynak kullanım etkinliğini yükselterek sektörün ekonomik ve ekolojik sürdürülebilirliğine katkı sunmaktadır.

Bununla birlikte, yapay zekâ uygulamalarının akuakültür sektöründe geniş çaplı olarak benimsenebilmesi için çeşitli yapısal gerekliliklerin karşılanması önem taşımaktadır. Veri toplama altyapısının yetersizliği, sensör teknolojilerine erişimdeki maliyetler, algoritmaların tür ve yetiştirme yöntemine özgü olarak doğrulanması, model performansının sahaya uyarlanabilirliği ve yetiştiricilerin teknoloji okuryazarlığı gibi unsurlar, YZ temelli uygulamaların yaygınlaştırılmasında kritik rol oynamaktadır. Özellikle model geçerliliğinin farklı yetiştirme koşullarında sınanması ve veri güvenilirliğinin sağlanması, teknolojinin operasyonel başarısını doğrudan etkilemektedir. Bu nedenle, disiplinler arası iş birlikleri, pilot uygulama çalışmaları ve sürdürülebilir dijital altyapı yatırımları sürecin temel bileşenleri olarak öne çıkmaktadır. Türkiye gibi hızla büyüyen ancak dijitalleşme süreci henüz erken aşamada olan akuakültür sektörlerinde, YZ'nin stratejik olarak konumlandırılması gelecekteki rekabet gücünün belirleyicilerinden biri olabilir. Sektörün güçlü üretim kapasitesi, genç teknoloji girişimcileri ve artan Ar-Ge faaliyetleri dikkate alındığında, yapay zekâ tabanlı çözümler sayesinde hem üretim verimliliğinin hem de çevresel sürdürülebilirliğin geliştirilmesi mümkündür. Bu doğrultuda kamu destekleri, üniversite-sanayi iş birlikleri ve veri paylaşım ekosistemlerinin güçlendirilmesi, YZ'nin gerçek potansiyelinin açığa çıkarılmasına katkı sağlayacaktır. Sonuç olarak, yapay zekâ uygulamaları su ürünleri yetiştiriciliğinde dönüşüm yaratma kapasitesine sahip olmakla birlikte, bu dönüşümün başarıya ulaşması sistematik planlama, güçlü veri altyapısı ve sektör paydaşlarının aktif katılımını gerektirmektedir. Bu unsurların sağlanması hâlinde, YZ'nin Türkiye akuakültür sektörüne sürdürülebilir, verimli ve rekabetçi bir üretim modeli sunması beklenmektedir.

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ENTEGRE TROFİK SU ÜRÜNLERİ YETİŞTİRİCİLİĞİ (IMTA): AKUAKÜLTÜR İÇİN STRATEJİK MODEL ÖRNEĞİ

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1. GİRİŞ

Dünyanın en hızlı büyüyen endüstrilerinden biri olan su ürünleri yetiştiriciliği ve artan dünya nüfusuna gıda sağlamadaki önemli rolü "mavi devrim" olarak adlandırılmıştır. Sektörün geleceği, uzun vadeli sürdürülebilirliğini korumak, tek kültür sistemlerinin çevre üzerindeki yükünü ve daha da önemlisi su temini, balık unu ve arazi üzerindeki mevcut kısıtlamaların üstesinden gelmek gibi zorluklarla karşı karşıya kalacaktır (Khanjani vd., 2022). Son zamanlarda, ötrofikasyona neden olan kirleticileri/fazla besinleri gidermek için çevre dostu bir su ürünleri yetiştirme sistemi ve özel bir arıtma tesisi geliştirilmesi araştırılmaktadır. Su ürünleri yetiştiriciliğinin gelişmesi, teknolojilerin, sorumlu ve sürdürülebilir yaklaşımların, kültür sistemlerinin geliştirilmesini gerektirmektedir. Bu durum çevresel sürdürülebilirliğe ve su ürünleri yetiştiriciliğinin sosyal kabulüne (daha iyi yönetim uygulamalarını duyurmak yoluyla)

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katkıda bulunacaktır (Cutajar vd. 2022). Entegre Trofik Su Ürünleri Yetiştiriciliği (IMTA) sistemi bazı su ürünleri türlerinin eş zamanlı üretimi için tüm gıda seviyelerinin kullanılması prensibine dayanmaktadır. Aynı zamanda farklı trofik seviyelerdeki sucul organizmaların bir arada yetiştirilmesi esasına da dayanan bu sistemde, beslenen türler (örneğin, balıklar) tarafından bırakılan atıklar, diğer türler (örneğin algler, midyeler, deniz salyangozları) tarafından besin kaynağı olarak kullanılır. Bu sayede, sistemin verimliliği artırılırken çevresel etkiler azaltılır. Yoğun monokültür uygulamaları (özellikle balık yetiştiriciliği) giderek daha ciddi çevresel dışsallıklar yaratarak sürdürülebilir çözümlere olan talebi artırmıştır. Besin maddelerini geri dönüştürmek için tür sinerjisinden yararlanan Entegre Trofik Su Ürünleri Yetiştiriciliği (IMTA), umut verici bir strateji olarak ortaya çıkmaktadır.

Su ürünleri yetiştiriciliğinin entegrasyonunu temsil eden IMTA: a) yem (balık), b) organik ekstraktif (filtre beslemeli ve süspansiyon beslemeli omurgasızlar), c) inorganik ekstraktif (makroalgler) ve d) tortu ekstraktif (süspansiyon beslemeli ve tortu beslemeli omurgasızlar) bileşenlerinden oluşmaktadır. Entegrasyonu sağlamak için türler arasındaki oranı, özel rolleri ve ekosistemin abiyotik koşullarını belirlemek gerekir. Bu yaklaşım, farklı trofik seviyelerin faydalarını en üst düzeye çıkarmayı, faaliyetleri çeşitlendirmeyi, çevresel sürdürülebilirliği ve ekonomik uygulanabilirliği sağlamayı ve aynı zamanda toplum genelinde su ürünleri yetiştiriciliği imajını iyileştirmeyi hedefler (Loayza-Aguilar vd., 2023).

2. IMTA SİSTEMİNİN BİLEŞENLERİ

Kavramsal olarak IMTA, iki veya daha fazla organizmanın birlikte yetiştirilmesini, türlerin trofik seviyelerini, beslenme alışkanlıklarını ve bir türün yan ürünlerinin farklı bir tür için girdi olarak geri dönüştürülmesini dikkate alan, gelişen bir tarım tekniğidir.

Beslenen Türler (Fed Species): Genellikle balıklar (örneğin, çipura, levrek) bu kategoride yer alır. **Filtrasyon Türleri (Extractive Species):** Algler, midyeler ve deniz salyangozları gibi organizmalar, suyun besin maddelerini alarak su kalitesini iyileştirir. **Çürütücüler (Decomposers):** Bakteriler ve diğer mikroorganizmalar, organik atıkları ayrıştırarak besin döngüsüne katkı sağlar.

Sinerji için çeşitli kültür türlerinin seçilmesinde aşağıdaki kriterler dikkate alınmaktadır: **Türlerin entegrasyonu:** Çeşitli türler seçilirken, farklı trofik seviyeler dikkate alınmalıdır. Daha iyi su kalitesi için bir türün atığının diğeri tarafından tüketilmesi tercih edilir. **Habitat adaptasyonu:** Sistem kurulumunda adaptasyon seviyesi yüksek ve yerel türlerin seçilmesine dikkat edilmelidir. **Etkili biyolojik azaltma:** Seçilen türler, sudaki besin yükünü azaltmak için çok miktarda atığı geri dönüştürebilmelidir. **Pazar talebi ve müşteri tercihi:** ekonomik değeri yüksek ve tüketici tarafından tercih edilen türlerin kullanılması gereklidir. Yatırım yapmadan önce sistemin SWOT analizinin detaylandırılması önem taşımaktadır (Shinde vd.,. 2024). **Çevresel sürdürülebilirlik:** Her ne kadar bir IMTA çiftliğinin konfigürasyonu büyük ölçüde değişiklik gösterse de, literatürde üç ana ekstraktif türü dikkate alınmıştır: deniz yosunlarının (su kolonundaki çözünmüş besin yükünü azalttığı için), çift kabukluların (çiftliklerinin filtrasyon kapasitesi, partikül organik maddenin etkilerini olumlu yönde azalttığı için) ve dip besleyicilerin (partikül organik yükü azalttığı için) IMTA sistemine dahil edilebileceği rapor edilmiştir (Zhang vd., 2019). Bu nedenle, bu ekstraktif türlerden herhangi birini kullanan bir somon çiftliği teorik olarak en azından bir dereceye kadar çözünmüş inorganik besinleri ve/veya partikül organik maddeyi azaltarak olumsuz çevresel etkileri minimum düzeye taşıyabilir.

IMTA sistemlerinin geliştirilmesi ve uygulanması için minimum çevresel etki temel argüman olsa da (Alexander vd., 2016), IMTA operasyonel riskleri en aza indirmek ve ürünleri çeşitlendirmek için bir tarım stratejisi olarak da tanıtılmıştır (Carras vd., 2020). Bu sebeple, IMTA uygulamasının yalnızca çevreye değil, aynı zamanda kamu algısına da fayda sağlama potansiyeli vardır. besin özümseme kapasitesini artıran asimilatif biyofiltrasyon algler tarafından gerçekleştirilir. Antropojenik besinleri emebildikleri için biyoremediasyon için etkili bir araç olan makroalglerdir (Marinho-Soriano vd., 2011), Deniz yosunları ise tüm bitkiler arasında en yüksek verimliliğe ve yüksek ekonomik potansiyele sahip oldukları için biyofiltrasyon için en uygun olanlardır. Alglerle (Rhodophyta) birlikte balıklara (levrek balığı *Dicentrarchus labrax* ve kalkan balığı *Scophthalmus maximus*) odaklanan bir IMTA çalışması da algleri biyofiltrasyon ve atık su azaltımı için mükemmel adaylar olarak belirlemiştir (Barrington vd., 2009). *Gracilaria bursa-pastoris, Gracilaria gracilis, Chondrus crispus, Palmaria palmata, Porphyra dioica, Asparagopsis armata*, *Gracilariopsis longissima, Ulva rotundata* (Rhodophyta) ve *Ulva intestinalis* (Chlorophyta) türleride IMTA yaklaşımlarında biyofiltrasyon amaçlı kullanılması üzerinde de araştırmalar yürütülmüştür. Kalkan balığı ve deniz levreği ile alglerin entegrasyonu üzerine deneysel çalışmalar devam etmiştir. *Gracilaria bursa pastoris*, incelenen üç tür arasında (*Gracilaria bursa pastoris, Chondrus crispus ve Palmaria palmata*) en iyi verime ve azot emilim verimliliğine sahip olduğundan deniz levreği veya kalkan balığı ile entegrasyon için en iyi seçenek olarak önerilmiştir (Matos vd., 2006).

Çevresel sürdürülebilirlik, doğal kaynakların akıllıca ve etkili kullanımı ile birlikte ekosistem bütünlüğünün ve doğal çevrenin korunması ile ilgili bir durumdur. Su ürünleri yetiştiriciliğinin çevresel etkilerinden en önemlileri tüketilmeyen yem ve dışkı içeren kirli atıkların ortama salınması sonucunda özellikle azot ve fosforun artmasıdır. IMTA, su kolonundan azot ve fosforu uzaklaştırarak ötrofikasyonu hafifletebilir, biyolojik bozunma risklerini düşürebilir ve böylece su ürünleri yetiştiriciliğini daha sürdürülebilir hale getirebilir (Hossain vd., 2022).

Ekonomik Verimlilik: Ekonomik sürdürülebilirlik, iş gücü ve maddi kaynakların uzun vadede sürdürülebilir değerler yaratacak şekilde kullanılmasını, geri dönüştürülmesini ve korunmasını gerektirir. Ekonomik sürdürülebilirlik ayrıca, gelecekteki gereksinimleri tehlikeye atmadan tüketim ihtiyaçlarını karşılayan bir üretim sistemini de gerektirir. Sürdürülebilirliğin kâr bileşeni, ekonomik büyüme, kaynak verimliliği ve işletmelerin finansal sürdürülebilirliği ile ilgilidir (Biswass vd., 2019). IMTA sistemlerinin uygulanmasından kaynaklanan yetiştiriciler, tüketiciler ve toplum için çeşitli faydalara odaklanan ekonomik araştırmalarda, Güney Afrika deniz kulağı (*Haliotis tuberculata*) çiftçiliği üzerine yapılan bir çalışma, IMTA'nın ürün çeşitliliğini artırarak ve fiyat dalgalanmalarından kaynaklanan piyasa risklerini azaltarak deniz ürünleri arzını dengeleyebileceğini ve ayrıca eğitimli personele yüksek ücretli işler sağlarken, çevre bölgelerdeki eğitimsiz kişilere düşük ücretli işler sunarak iş çeşitliliğini artırabileceğini göstermektedir (Hannah vd., 2013). Deniz yosunları Omurgasızlar ve detritivor balıklar, yerel tüketim ihtiyaçlarını karşılama açısından ekonomik olarak faydalı olabilirken, yüksek değerli balık ve karideslerın ihracat potansiyeli bulunmaktadır. IMTA'nın uygulanması, çiftlik düzeyinde ve daha geniş çevrede atık asimilasyon yeteneklerini iyileştirebileceği bildirilmiştir (Rusco vd., 2024).

Yemlerde bileşen olarak kullanılmak üzere yüksek besin değerine sahip biyokütle üretimi, IMTA sistemlerinin ticari ölçekte daha geniş ve daha hızlı bir şekilde uygulanmasını teşvik etmek için önemli bir ekonomik teşvik teşkil etmektedir. Nitekim, SDG (Sürdürülebilir Kalkınma Amaçları) 14' ün IMTA yan ürünlerinin değerlendirilmesi yoluyla döngüsel ekonomiyle ilgili parametrelerle bütünleştirilmesi, maliyetlerden ve çevresel faydalardan tasarruf etmemizi sağlamakta ve sektörü, hem yatay kesitte hem de deniz ürünleri üretimi boyunca dikey olarak ESG parametreleriyle uyumlu daha sürdürülebilir uygulamalar ve değerlendirmeler benimsemeye teşvik etmektedir. Uygun besin bileşimine sahip yemlerin maliyet artışı ve bulunabilirliği FAO'nun gündeminde olup, IMTA gibi modellerin benimsenmesi ve süreç boyunca teknoloji kullanımının artırılması gerekmektedir (Rusco vd., 2024).

Biyolojik Çeşitlilik: IMTA sistemlerinin organik atıkların etkisini azaltmak için biyolojik kirletici organizmalardan yararlanarak deniz kültürü ortamlarının iyileştirilmesine ve biyolojik çeşitliliğin artırılmasına yardımcı olabileceğini gösteren çalışmalar öncelikli olarak organik madde dinamiklerine odaklanmış ve IMTA sistemlerinin su kalitesinin korunmasına katkıda bulunduğunu kanıtlamıştır. Aynı zamanda, IMTA'nın ekosistem sağlığını ve direncini artırma açısından yumuşak tabanlı bentik topluluklar üzerindeki önemli etkisi olduğu bilinmektedir. IMTA sistemine geçişin, ekosistemin genellikle "biyolojik hafızası" olarak adlandırılan yumuşak tabanlı makro-zoobentik topluluklarda önemli değişikliklere neden olabileceği saha araştırmalarında belirlenmiştir. IMTA sistemleri içerisinde bentik biyolojik endekslerin değerlendirilmesi, zenginleştirilmiş tür kompozisyonu ve daha yüksek ekolojik kalite durumu dahil olmak üzere çevresel koşullarda belirgin iyileştirmeler göstermiştir (Trani vd., 2025).

Sosyal Sürdürülebilirlik: Sosyal sürdürülebilirlik, eşitlik, güçlendirme, erişim, katılım, kültürel kimlik ve kurumsal istikrarı kapsayacak şekilde kavramsallaştırılmıştır ve dünya çapında sağlıklı sağlık hizmeti, beslenme, eğitim, barış ve istikrara odaklanarak anlamlı bir yaşam elde etmeye yardımcı olmak için elzem görülmüştür. Tarım, ormancılık, balıkçılık ve su ürünleri yetiştiriciliğinde sürdürülebilir kalkınma, arazi, su, bitki ve hayvan kaynaklarını korurken çevresel olarak bozulmayan, teknik olarak uygulanabilir, ekonomik olarak başarılı, sosyal olarak adil, iyi huylu ve sosyal olarak kabul edilebilir kalır. Su ürünleri yetiştiriciliği çeşitlendirilmiş bir sektördür ve özellikle çevre üzerindeki etkileri türlere, çiftçilik yöntemlerine, yerel çevre koşullarına ve sosyoekonomik bağlama göre değişir (Hossain vd., 2022).

IMTA sistemi, yalnızca iklim değişikliğinin azaltılmasına yönelik sürdürülebilirlik açısından üretilen ürün ve yan ürünlerin büyüme performanslarını ve kalite özelliklerini iyileştirmek için değil, çevresel biyoremediasyona değerli bir yaklaşım olarak aynı zamanda bir yöntem olarak tanımlanmaktadır. Bu bağlamda, son yirmi yılda, özellikle üretkenliği ve daha az ölçüde yetiştirilen türlerin refahını ve kalitesini artırırken atık yüklerini ve çevresel etkileri azaltma konusunda çeşitli IMTA kurulumlarının potansiyelini bilimsel olarak kanıtlamayı amaçlayan çok sayıda araştırma bulunmaktadır.

Hayvan stresi ve refahının, IMTA sistemleri tarafından üretilen hayvan refahının ve deniz ürünlerinin beslenme ve duyusal kalitesinin iyileştirilmesini destekleyen çalışmaların sınırlı sayıda olması, bugüne kadar elde edilen sonuçları pekiştirmeyi amaçlayan üniversiteler ve endüstriler arasında daha fazla ortak uygulamalı araştırma ve proje geliştirilmesini önermemize yol açmaktadır. Bu bağlamda, başka bir "omik" yaklaşımıyla entegre edilmiş proteomik, balık refahını daha iyi anlamak, refah durumu değerlendirmesini iyileştirmek, balıkların kaçınılmaz zorluklar/stresle başa çıkma kapasitesini optimize etmek ve olası stres biyobelirteçlerini bulmak için su ürünleri refah çalışmalarında son derece değerli bir araç olarak ortaya çıkmıştır (Raposo de Magalhães vd., 2020).

IMTA konsepti AB balıkçılık politikasının gerekliliklerini tam olarak karşılasa da, daha geniş uygulama alanı için araştırmacıların sonuçlarının pilot ölçekten ticari ölçek geliştirme çalışmaları ve söz konusu türlerin biyogüvenliğini de hesaba katması zorunludur. Bu bağlamda, kalitelerini ve güvenliklerini daha da artırmak için açık sistemlerden, IMTA ve RAS (Resirküle Akuatik Sistem)'den oluşan çiftler halinde yenilikçi entegre çok trofik geridönüşümlü su ürünleri yetiştirme sistemlerine (IMTRAS) geçmek iyi bir stratejidir (Huo vd., 2024). Dahası, ticari ölçekli IMTA sistemlerine geçişin farklı sektörlerden paydaşların sosyal kabulünden de geçmesi gerektiğini anlamak gereklidir. Bu amaçla, bir dizi üretim standardı ve sertifikasyonunun geliştirilmesi hem tüketicilerin bu sisteme olan güvenini artırabilir hem de üreticilerin yatırımlarını koruyabilir. Hassas su ürünleri yetiştiriciliği, özellikle açık deniz ve açık su IMTA sistemleri için, çevresel ve hayvansal değişkenlerin (balıkların davranışsal veya fizyolojik durumuyla ilgili parametreler) otonom ve sürekli izlenmesi yoluyla standartlaştırılmış üretim yöntemlerinin elde edilmesine yönelik olası bir çözüm olabilir. Özellikle, bu yaklaşım daha etkili, hassas, doğru ve tekrarlanabilir çiftlik yönetimine olanak tanıyan daha güvenilir karar desteği sağlamak, izlemek, analiz etmek, yorumlamak, tahmin etmek ve sağlamak için çeşitli teknolojileri ve uyarlanabilir araçlarını kullanmaya imkân sağlamaktadır (O’Donncha and Grant, 2019).

Gelecekteki çalışmalar, sucul ortamda iklim değişikliğinin azaltılmasıyla bağlantılı, verimliliği, ürünlerin genel kalitesini ve sucul çevresel sürdürülebilirliğini optimize etmek amacıyla hassas tarım ve IMTA'nın olası kombinasyonunu değerlendirmeye odaklanabilir. Burada değerlendirilen çalışmalar, IMTA uygulamasının, su ürünleri tedarik zinciri boyunca elde edilen yan ürünlerin sürdürülebilir bileşenler olarak kullanılmasıyla piyasa değerini artırmamızı ve su ürünleri yetiştiriciliğinin balık unu ve yağına olan bağımlılığını azaltmamızı veya ortadan kaldırmamızı sağlayan çok değişkenli bir protokol olduğunu vurgulamaktadır. Ekonomik açıdan değerlendirildiğinde, yüksek nitel - nicel lipit ve proteinlere sahip poliketlerin ve deniz yosunlarının su ürünleri yetiştiriciliği ve karasal türler için yem endüstriyel işleme süreçlerine dahil edilmesi, IMTA sisteminin kârlılığını artırmak ve şirketleri ve politika yapıcıları bunu uygulamaya teşvik etmek için umut verici bir entegre faaliyet olabilir (Rusco vd., 2024).

3. SONUÇ

Küresel anlamda önemi artan su ürünleri yetiştiriciliğinin daha sürdürülebilir tarım yaklaşımları ile entegrasyonu ihtiyaç ortaya çıkmaktadır. Farklı trofik seviyedeki türlerin dengesi aracılığıyla olumsuz çevresel etkileri azaltma amaçlı olan IMTA'nın temel amaçlarından biri sürdürülebilir akuakültür için umut verici bir model sunmaktadır. Bunun yanısıra, ekonomik olarak çok daha kârlı bir faaliyet olma potansiyeline sahiptir; ancak dengeli bir ekosistemde, bu yeni üretim modelinin ekolojik mühendislik yaklaşımıyla benimsenmesi gerekmektedir. Farklı trofik seviyelerden türlerin entegrasyonu, adaptasyonları için temel kavramdır. Bu model, türlerin üretimlerinin çeşitlendirilmesine, ekonomik ve sosyal kârlılıklarını artırmalarına ve sürdürülebilirliklerini garanti altına almalarına olanak tanıyacaktır. Ancak, başarılı bir uygulama için dikkatli planlama, uygun tür seçimi ve etkili yönetim gereklidir. Gelecekte, IMTA'nın daha geniş alanlarda uygulanabilmesi için araştırmalar ve politikaların geliştirme süreçlerine ihtiyaç duyulmaktadır.

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GIDALARDA VE SU ÜRÜNLERİNDE NANOTEKNOLOJİ UYGULAMALARI

Nermin KARATON KUZGUN[1]

1. GİRİŞ

Nano ölçüsündeki maddeler, artmış re-aktivite, yüksek yüzey alanı, üstün mekanik özellikler ve gelişmiş çözünürlük gibi avantajlara sahip olan ve özellikler sayesinde nanoteknoloji, gıdalaştırma (food design), besin bileşenlerinin stabilizasyonu, kontaminasyon ve akıllı ambalajlamanın belirlenmesi gibi pek çok kritik alanlarda çözümler sağlar (Chaudhry et al., 2008). Yirmi birinci yüzyılda gıda teknolojisi; güvenlik, fonksiyonellik ve kalite konularında artan beklentilere karşılık vermeyi amaçlamaktadır. Küreselleşen Dünya'da, gıda tedarik zincirleri, uzun raf ömrüne sahip ürünleri ve tüketici tercihlerinin çeşitlenmesi gibi ve ayrıca gıda güvenliği problemlerinden dolayı bu alanda yeni teknolojilerin kullanımını zorunlu hâle getirmiştir. Bu yeni teknolojiler arasında en önemli olanlardan biri de nanoteknolojidir. Nanoteknoloji, 1–100 nanometre büyüklüğündeki yapıların kullanılması ve gıdaların işlenmesi, korunması, tüketiciye ulaştırılması ve taşınmasında devrim niteliğinde yenilikler sunan en yeni teknolojidir (Sekhon, 2010).

Nanoteknolojik gıdaların uygulamasında, biyopolimerik ve inorganik nanopartiküller kullanılabilirler. Bu sayede oksijen bariyerli ambalajlar, antimikrobiyal kaplamalar, besin taşıma sistemleri ya da akıllı sensör sistemlerinin geliştirilebilmesi söz

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konusu olabilmektedir (Duncan, 2011; Polat & Fenercioğlu, 2014).

"Nanosistem" ifadesi, nano boyutlu yapılar da (1–100 nm aralığında ki boyutlarda) kullanımı için nanopartiküller, nanoemülsiyonlar, nanokapsüller, nanokompozitler, nanolifler gibi sistemlerin kullanımını kapsar. Ancak bu sistemler, makroskobik maddelerin klasik özelliklerinden farklı davranışlar ortaya koyabilirler (Sürengil & Kılınç, 2011; Polat & Fenercioğlu, 2014).

2. NANOTEKNOLOJİ'NİN SU ÜRÜNLERİ VE GIDA SEKTÖRÜNDE VEREBİLECEĞİ HİZMETLER

Nanoteknoloji, su ürünleri ve gıda sektöründe hem üretim verimliliğinin artırılmasında hem de ürün güvenliğinin geliştirilmesinde giderek daha fazla tercih edilen yeni bir teknolojik araç olmuştur. Özellikle gıda güvenliğinin, raf ömrünün uzatılmasında ve hastalıkların erken tespitinde temel ihtiyaçları karşılamak amacıyla, nanoteknoloji tabanlı çözümlerin kullanılması önem arzetmektedir. Örneğin nanosensörler gıdalarda ambalajlama materyali olarak kullanılır ve içerisindeki mevcut ürünün bozluması hakkında bize bilgi verebilmek adına pozitif bir etkiye sahiptir ve ayrıca ürünlerde ki mikrobiyal kontaminasyonu daha hızlı ve yüksek hassasiyetle tespit edebilmesi sektör adına kritik sorunların doğrudan yanıt vermesi adına önem taşımaktadır (Kumar & Yadav, 2021; Üçüncü, 2011).

Su ürünleri sektöründe antibiyotik kullanımında azaltma ve hastalıkların erken teşhisi gibi izlenebilirlik gereksinimleri nanoteknolojiyle daha etkin şekilde karşılanabilmektedir. Nano-kapsülleme teknikleri, balık yemlerinde besin maddelerinin biyoyararlanım oranını artırarak daha sürdürülebilir üretim süreci olrak devam etmesini sağlar (Hoseinifar et al., 2020). Bununla birlikte nanokompozit ambalajlar, hem oksijen geçirgenliğini azaltarak raf ömrünü ve gıda israfını azaltabilmektedir (Silva & Cerqueira, 2022).

Gıda işleme teknolojisinde kullanılan nanomalzemeler, ısıl işlem gereksinimini azaltan ve dolayısıyla besin kaybını en aza indiren alternatif yöntemlerin geliştirilmesini sağlamaktadır. Böylece hem enerji tüketimi azaltılır hem de tüketiciye daha kaliteli ürünler sunulur. Tüm bu özelliklerinden dolayı nanoteknoloji, su ürünleri ve gıda sektörlerinde kritik ihtiyaçların karşılaması için yenilikçi ve güçlü bir araç olarak görülürler (Joseph & Morrison, 2020).

3. NANOPARTİKÜLLER

Bu başlık altında polimerik, metal, lipid, biyopolimerik nanopartiküller vb. özellikteki parçacıklardan bahsedilecektir.

2.1. Polimerik Nanopartiküller

Polimerik nanopartiküller, genel olarak sentetik polimerlerden (PLGA, PLA, PCL vb.) üretilir ve kontrollü salınım yeteneklerinden dolayı özellikle ilaç taşıma sistemlerinde önemli bir yere sahiptir. PLGA nanopartikülleri biyobozunur özelliğe sahiptir. Bu sayede farmasötik ürünlerde yaygın olarak kullanılır. Aktif maddelerin kontrollü olarak serbest bırakılması bu özelliğinden kaynaklanır (Danhier vd., 2012). Gıda sektöründe ise polimerik nanopartiküller, aroma bileşenleri yada vitaminlerin kapsüllenmesinde kullanılır ve stabilite ile biyoyararlanım oranını yükseltir (Acosta, 2009).

3.1. Metal Nanopartiküller

Metal nanopartiküller (altın, gümüş, titanyum dioksit, bakır, çinko oksit gibi) yüksek yüzey alanına sahip elektriksel iletkenliği olan plazmonik özellikleri ve güçlü antimikrobiyal aktivitelerinden dolayı yaygın kullanıma sahiptir. Özellikle gümüş nanopartiküller (AgNP), bakteriler ve mantarların hücre zarını parçalayarak güçlü bir antimikrobiyal etki sergiler (Rai et al., 2021). Ayrıca titanyum dioksit (TiO_2) ve çinko oksit (ZnO) nanopartiküller UV soğurma kapasitelerine sahip olmaları nedeniyle gıda ambalajlarında oksidatif bozulmayı en aza indirgemek amacıyla yaygın bir şekilde kullanılmaktadır (Sirelkhatim et al., 2015). Metal nanopartiküller, sensör platformlarında, yüzey plazmon rezonansı özelliği göstermesi nedeniyle yüksek hassasiyetli biyosensör geliştirilmesinde tercihlerin en önemli olanlarındandır (Dreaden et al., 2012).

3.2. Biyopolimerik Nanopartiküller

Biyopolimerik nanopartiküller; kitosan, kitin, alginat, nişasta ve jelatin gibi doğal biyopolimerlerden üretilirler. Bu nedenle biyouyum gösteren, toksik olmayan ve biyobozunur karaktere sahip özellikleri vardır. Özellikle kitosan nanopartikülleri, pozitif yüzey yüküne sahip olmaları nedeni ile bakteri hücre zarına kolayca bağlanırlar ve güçlü antimikrobiyal etki göstermeleri ile karakterizedirler (Kumar et al., 2018). Biyopolimerik nanopartiküller, su ürünlerinde ve gıda sektöründe; antimikrobiyal filmler, besin maddelerinin enkapsülasyonu, probiyotiklerin korunması ve geliştirilmesi gibi alanlarda kullanılmaktadır (Perinelli et al., 2020).

3.3. Lipid Nanopartiküller

Lipid nanopartiküller (katı lipid nanopartikülleri=SLN, nanoyapılı lipid taşıyıcılar=NLC) hem farmasötik hem de gıda alanında yaygın kullanılan biyouyumlu sistemlerdir. Katı lipid nanopartikülleri ve nanoyapılı lipid taşıyıcılar, lipofilik bileşiklerin biyoyararlanımını ve çözünürlüğünü artırır. Ayrıca oksidatif bozulmayı en aza indirgeyerek gıdalarda duyusal kaliteyi arttırır (Mehnert & Mäder, 2012). Lipid nanopartikülleri su ürünlerinde balık yemlerine vitamin veya nükleotid eklemek, gıda sektöründe ise antioksidan veya aromaların kontrollü salımı için kullanılmaktadır (McClements, 2020).

4. NANOENKAPSÜLASYON TEKNOLOJİLERİ

Nanoenkapsülasyon, biyolojik olarak aktif olan bileşenlerin yani; probiyotikler, vitaminler, mineraller, polifenoller, omega-3 yağ asitleri vb. yüzlerce nanometre çapında olan kapsüllerin içine alınması işlemidir ki bu kapsüller genellikle lipit, protein ya da polisakkarit temelli nanokapsüller şeklinde üretimleri gerçekleşir (Augustin & Sanguansri, 2009). Yağda çözünen vitaminler (A, D, E ve K) ışık, oksijen ve sıcaklığa karşı oldukça hassas olan vitaminlerdir. Nanoenkapsülasyon bu bileşenleri çevresel etkenlere karşı koruyarak ürünün raf ömrünün ve besin değerinin artırılmasını sağlar (Mozafari, 2006).

Nanoenkapsüller, bileşenlerin sindirim sisteminde kontrollü bir şekilde salınmasını sağlar ve bu sayede; enerji içeceklerinde, probiyotik içeceklerde, bebek mamalarında, medikal gıdalarda, yaygın bir şekilde kullanılmaktadır (McClements, 2012).

Nanoenkapsüller, kötü tat ve kokuların maskelenmesinde, balık yağı gibi hoş olmayan tat ve kokulara sahip bileşenler nano kapsüller ile kaplanarak gıdalarda kullanılır ve duyusal bakımdan hoş olmayan durumları engellerler (Solans & Solé, 2012).

5. NANOEMÜLSİYON TEKNOLOJİLERİ

Nanoemülsiyonlar, 20–200 nm çapında olan çok küçük yağ ya da su damlacıklarından oluşan kararlı yapılardır. Nanoemülsiyonlar özellikle içecek sektöründe yaygın kullanım alanı bulmaktadır. Nanoemülsiyonların biyoyararlanımı artırılması açısından önemi büyüktür. Yağda çözünen bileşenlerin emülsiyon fazında daha iyi çözünmesini sağlar. Örneğin;

koenzim Q10, karotenoidler, kurkumin, omega-3 yağ asitleri gibi bileşenlerin biyoyararlanımı nanoemülsiyonlar sayesinde önemli ölçüde artmaktadır (McClements, 2011). Ayrıca, nanoemülsiyonlar çok küçük damlacık boyutunda olmaları nedeniyle içeceklerde bulanıklık oluşturmazlar ve vitaminli sular, aroma takviyeli ürünler ve fonksiyonel içecekler de bu teknik yaygın bir şekilde kullanılmaktadır (Chaudhry et al., 2008). Nanoemülsiyonların Stabilite avantajlarıda bulunmaktadır. Çökelme, köpüklenme faz ayrılması gibi istenmeyen fiziksel değişimleri en aza indirgeyerek stabilitenin korunmasını sağlar.

Nanokompozitler, nano boyutlu malzemeler oldukları için nanokompozit ve nanolif uygulamaları ile gıda ambalajlarında dayanıklılığı artırma, gaz geçirgenliğini azaltmak ve ısıya dayanıklılığı artırmak için kullanılır (Duncan, 2011). Nanokil (nanoclay) içeren polimerler ambalaj dayanımının artırır ve oksijen geçirgenliğini %40–80 oaranında azaltır, paketlerin delinme direncini artırır ve raf ömrünün uzamasına katkı sağlar. Nanolif yapılar özellikle gıdalarda kullanımı et ürünleri, balık, peynir, sporcular için özel gıdalar gibi yüksek protein içeren ürünlerde yapı iyileştirmek için kullanılmaktadırlar.

6. ANTİMİKROBİYAL ALANLARDA NANOTEKNOLOJİ UYGULAMALARI

Gıdalarda mikroorganizmaların gelişimini engelleyen nanopartiküller özellikle ambalajlama açısından devrim niteliğinde değişimler yapmıştır. Bu açıdan kullanılan üç faklı nano partikül en güncel çalışmalarda bulunmaktadır. Bunlar;

Gümüş nanopartikülleri (AgNP): Bakterilere karşı en etkili nano yapılar arasında sayılır ve bakteri hücre zarını bozup hücre ölümüne sebep olur (Emamifar et al., 2010).

Çinko oksit (ZnO) nanopartikülleri: UV ışığı absorbe eder, bakterisidal etki gösterir, süt ürünlerinde ve içecek ambalajlarında makbuldür (Mlalila et al., 2016).

Nano-Kitosan: Nano boyuttaki kitosanın kullanımı antimikrobiyal gücü artırır. Özellikle maya-küf gelişimini en aza indirmede etkendir (Suyatma et al., 2004).

7. AKILLI AMBALAJ SİSTEMLERİ

Akıllı ambalajların gıdalarda kullanımı çok yeni bir teknolojidir. Gıdanın durumu ve tüketici ile üretici arasında iletişimi daha net sağlayabilen sensör kaynaklı olan bir paket türüdür.

a) Tazelik göstergeleri olarak;Ambalaj içerisine yerleştirilen nanosensörler sayesinde bozulma ile ilgili bilgiler tüketiciye ambalaj vasıtası ile aktarılır. Bu göstergeleri sıralamamız gerekirse;

- CO_2 seviyesi,
- pH,
- Amonyak ve sülfür oluşumu,
- Uçucu organik bileşikler.

b) Sıcaklık göstergeleri ise, Soğuk zincirde herhangi bir kırılma söz konusu olduğunda renk değiştiren nano boyuta sahip sensörleri olan, önceliklede et ve süt ürünlerinde kritik önem taşıyan akıllı ambalaj sistemleridir (Duncan, 2011; Üçüncü, 2011).

8. AKTİF AMBALAJ SİSTEMLERİ

Aktif ambalajlar ürünün raf ömrünü uzatabilmek ve ambalaj içerisinde ürünün etkileşimini sağlayan sistemlerdir. Antimikrobiyal salım ile Nano kapsüllere hapsedilen, karvakrol, timol, nisin, nanogümüş gibi bileşikler zamanla ambalajdan salınır ve ürünü korurlar. Oksijen tutucu nano-filmler ile nanokompozit oksijen ayırıcı filmler ve yağ oksidasyonunu önleyerek özellikle; kuruyemiş, et ve balık ürünleri, tütsü yapılmış besinler için önemlidir (Üçüncü, 2011).

9. SONUÇ

Nanoteknoloji, gıda ve su ürünlerinde endüstriyel anlamda raf ömrü, duyusal özellikleri, kalite, güvenlik ve verimlilik açısından önemli avantajlar sağlamaktadır. Özellikle aktif-akıllı ambalajlar, nanoemülsiyonlar, nanoenkapsülasyon, antimikrobiyal nanopartiküller ve nano-biyosensörler günümüzde gıda ve su ürünleri sektöründe en yaygın kullanılan nanoteknolojik yaklaşımlar olup gelecekte bu uygulamaların daha da yaygınlaşması beklenmektedir.

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NEW TECHNOLOGIES RESHAPING MARINE AQUACULTURE: INSIGHTS FROM GLOBAL RESEARCH (2018–2025)

Ercüment GENÇ[1]

1. INTRODUCTION

Marine aquaculture has gained increasing importance in recent decades as countries search for stable and sustainable sources of marine-based protein. Population growth and the rising global demand for seafood have drawn attention to the limits of wild capture fisheries and the need to diversify production strategies. As pressures on natural stocks continue to grow, aquaculture has come to be viewed not only as a complementary source of food but also as a field in which scientific research, engineering solutions and digital technologies intersect. Recent studies underline that the structure of marine fish farming has changed considerably during the past ten years, with developments in digital tools, biotechnology and environmentally oriented engineering shaping new production practices (Araujo et al., 2022: 1598). Complementary reviews similarly emphasise the emergence of new techniques that integrate biological, engineering and digital components within marine aquaculture systems (Ma & Qin, 2023: 2239).

Advances in technology have influenced many stages of marine aquaculture. In this sense, the mechanisation-oriented perspective discussed by Genc et al. (2020: 254) can be seen as

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an important foundation rather than a comprehensive framework. Subsequent advances have built on this foundation by integrating automation with data-driven monitoring and management practices, allowing production systems to respond more dynamically to environmental and biological variability.

Recirculating systems allow water to be reused and help reduce environmental pressures, while sensor platforms linked to the Internet of Things enable continuous tracking of critical water-quality parameters (Aich et al., 2020: 17; Prapti et al., 2022: 979; Rastegari et al., 2023: 100187). Within this context, the precision aquaculture paradigm highlights how IoT-based sensing and uninterrupted data capture form the basis of real-time operational decision-making (O'donncha & Grant, 2019: 26). Broader assessments of IoT applications further demonstrate how networked sensors enhance environmental observation capacity across marine ecosystems (Xu et al., 2019: 1711). Together, these tools have shifted monitoring practices from periodic observation toward continuous system awareness. In parallel, unmanned aerial and surface vehicles have become increasingly relevant as complementary systems for remote monitoring and spatial data acquisition in farm operations (Ubina & Cheng, 2022: 12). These sensor-driven developments intersect with the expanding use of artificial intelligence, which supports behavioural interpretation, optimised feeding and early disease detection (Liu et al., 2023: 867; Bhalla et al., 2025: 20339). Recent evaluations also show that cloud-integrated monitoring platforms, intelligent control tools and automated decision-support systems are reshaping digital production processes (Zhang & Gui, 2023: 401). Precision aquaculture frameworks therefore emphasise the importance of harmonising AI-enhanced analytics with IoT infrastructures to enable adaptive and automated farm management (O'donncha & Grant, 2019: 26). These technological progressions are consistent with the intelligent fish farm concept, wherein digital tools are embedded into unified platforms that govern feeding, environmental regulation and real-time decision-making (Wang et al., 2021: 2681). Moreover, advances in deep learning frameworks have further expanded analytical capabilities, particularly in behavioural tracking, biomass estimation and anomaly detection (Kaur et al., 2023: 4399512). Together, these developments illustrate a sector-wide shift driven not only by scientific progress but also by market conditions, cost-efficiency requirements and environmental responsibilities (Asche & Smith, 2018: 1).

Other areas of innovation include genetic and biotechnological methods designed to improve growth, strengthen disease resistance and support the farming of new species (Gratacap et al., 2019: 672; Bohara et al., 2024: 836). Offshore farming systems, which operate in more demanding marine environments, rely on engineering designs that prioritise operational safety, structural durability and welfare considerations (Bjelland et al., 2025: e12964). Importantly, these technological trends are not confined to a small group of highly industrialised producers. They can be observed in long-established producing countries such as Norway and China, as well as in rapidly expanding producers like Türkiye (Li et al., 2025: 191; Aydın et al., 2025: e70010). The growth of Türkiye's aquaculture sector demonstrates how increased research capacity and the progressive adoption of new technologies shape production performance. In the literature, such wider changes are frequently described through concepts related to technological disruption or transformation, and they align with trends identified in recent studies (Yue & Shen, 2022: 111).

A substantial body of research also shows that innovation in marine aquaculture contributes to environmental objectives and to broader blue-economy goals (Carballeira Braña et al., 2021: 666662; Føre et al., 2022: 101115). Technologies that reduce emissions, improve energy performance or strengthen welfare monitoring help align aquaculture operations with international sustainability commitments. Smart aquaculture farm models that integrate automation, energy optimisation and environmental monitoring further illustrate how engineering-driven approaches facilitate transitions toward more sustainable production systems (Kassem et al., 2021: 10685). These insights underline the need to evaluate technological innovation not only in terms of production outcomes but also with respect to natural-resource management. Some authors nevertheless caution that capture fisheries alone cannot meet future food requirements, emphasising the necessity of parallel technological and managerial innovations to secure long-term supply (Belton et al., 2020: 5804).

Despite the rapid expansion of research in this field, relatively few reviews provide a broad synthesis of the multiple forms of innovation being applied in marine aquaculture. Recent contributions outline technological advances across various domains and highlight the expanding diversity of techniques used in the sector (Ma & Qin, 2023: 2239). However, many studies continue to focus on a single technological area—such as IoT systems, recirculating technologies or biotechnological tools—without adequately addressing their interactions (Prapti et al., 2022: 979; Aich et al., 2020: 17; Gratacap et al., 2019: 672). Furthermore, much of the literature centres on Asia and Europe, while findings from emerging producer countries remain comparatively limited (Aydın et al., 2025: e70010). The present study therefore aims to provide a thematic and regional assessment of technological developments between 2018 and 2025 and to examine their implications for production, sustainability and welfare. A further aim is to outline a reference framework that may guide future research and help identify priority areas for continued development within marine aquaculture.

2. METHODS

2.1. Databases and Search Strategy

This study reviewed scientific papers published between 2018 and 2025 to understand the main technological developments in marine aquaculture. The review followed basic principles of a systematic literature review and used the PRISMA approach as a general guide. Several academic databases were searched, including Web of Science, Scopus, ScienceDirect, SpringerLink, Wiley Online Library, MDPI, Taylor and Francis, IEEE Xplore and ResearchGate. TR Dizin and DergiPark were also included to make sure that studies from Türkiye were not overlooked.

The search strategy focused on key terms related to technology in marine fish farming. These terms included marine aquaculture, recirculating aquaculture systems, precision aquaculture, Internet of Things, artificial intelligence, machine learning, genome editing, automation, fish welfare, sustainability, digital transformation, disease diagnosis, One Health and Türkiye aquaculture. The study by Öz et al. (2025: 652), which examined artificial intelligence in disease diagnosis, was noted as a recent example of digital health applications in aquaculture.

The search was limited to peer-reviewed journal articles and conference papers. At the beginning, 512 publications were found. First, titles, abstracts and keywords were checked. Then full texts were reviewed. Once these criteria were applied, the final set of studies was established.

2.2. Inclusion and Exclusion Criteria

Studies were included if they were published between 2018 and 2025 and focused on marine or brackish water aquaculture. The review included full-text, peer-reviewed articles that met the scope of the study. After applying these criteria, 25 studies remained.

2.3. Data Analysis and Thematic Coding

The selected studies were examined using qualitative content analysis. The analysis had three steps: open coding, axial coding and selective coding. In the open coding step, each paper was grouped according to the type of technology, the purpose of the technology, the species involved, the environmental effects and the type of innovation. For example, studies working on artificial intelligence in disease detection were placed under digital health management.

In the axial coding step, links between the codes were identified. These links helped form larger thematic groups. In the last step, four main themes were created. They represented the major directions of technological development: digitalisation and automation, biotechnological innovation, engineering and energy efficiency and sustainability-oriented governance.

2.4. Methodological Synthesis and Analytical Approach

The findings were brought together through thematic analysis. For each theme, the level of technological use, regional differences, environmental effects and economic importance were compared. Case studies from Türkiye, China and Norway were used to understand how different regions adopt new technologies. Studies on artificial intelligence–supported diagnosis helped show how digital tools, environmental management and aquatic health are connected. This approach made it possible to understand technological progress during 2018–2025 from several angles. Repeated cross-checking helped maintain both methodological and conceptual coherence.

2.5. Regional Distribution and Comparative Analysis

The studies were also examined by region. Research from Norway and Northern Europe focused mainly on sustainability and fish welfare (Føre et al., 2022: 101115; Bjelland et al., 2025: e12964). In contrast, research from Asia, particularly China tended to centre on digitalisation, artificial intelligence and genetic innovation (Li et al., 2025: 191; Gratacap et al., 2019: 101115). Studies from Türkiye highlighted the growing interest in digital transformation and recirculating aquaculture systems (Aydın et al., 2025: e70010). This comparison helped show how regional priorities shape technological choices.

2.6. Reliability and Validation Process

To ensure reliability, the studies were cross checked at different stages, and the consistency of the thematic groups was reviewed several times. This process supported both methodological and conceptual coherence. Taken together, the findings indicate a shift toward more digital, biotechnological and sustainability-oriented production models.

2.7. Quality Assessment

A quality assessment was carried out to evaluate the methodological strength of each study. The assessment followed general ideas from well-known appraisal tools. Each study was examined for clarity of aims, suitability of methods, transparency of data collection, strength of analysis, reporting of limitations and relevance to technological development in marine aquaculture.

Most studies showed moderate or high methodological clarity. However, many were based on pilot or laboratory scale experiments, which limits how well the findings can be applied to commercial systems. Some studies did not clearly report sample size, environmental variation or long-term outcomes. Only a few papers discussed possible biases or uncertainties. Even so, all studies met the minimum quality standards for inclusion. Studies with weaker methods were kept because they provided useful thematic information, but their results were interpreted with caution. These studies collectively form the evidence base for the review and correspond directly to the citations presented in the reference list.

2.8. Limitations

This review has several limitations. The studies considered here represent only a portion of the expanding literature and therefore do not offer a complete picture of global practices. The search included only English and Turkish publications, so relevant work published in other languages may not have been captured. Grey literature, including technical reports and theses, was excluded, which inevitably narrows the range of perspectives.

There was also considerable variation in methodological design and reporting style, limiting the extent to which direct comparisons could be made. Regional representation was uneven: China and Northern Europe were well documented, whereas emerging producer countries such as Türkiye appeared far less frequently. Publication bias may have influenced the evidence base, as studies reporting novel or positive outcomes tend to be overrepresented in peer-reviewed sources. For these reasons, the results should be viewed as indicative trends rather than definitive statements about the sector.

3. RESULTS

The analysis of the 25 studies shows that research on technological change in marine aquaculture between 2018 and 2025 mainly focuses on four areas: digital tools, biotechnological applications, engineering and system design and practices linked to environmental sustainability. Although the studies differ in scope and detail, several shared patterns appear.

Many papers describe the use of digital technologies such as sensor-based monitoring, artificial intelligence for interpreting environmental and behavioural data and online information platforms. These developments are consistent with recent analyses showing a rapid expansion of intelligent sensing, automated environmental control and cloud-based data management systems in marine aquaculture (Zhang & Gui, 2023: 401). These developments align with the precision aquaculture model, which positions coordinated sensing, automated responses and data-driven control as central pillars of modern marine farming (O'donncha & Grant, 2019: 26). These developments align with the intelligent fish farm framework, which integrates monitoring, feeding automation and environmental regulation into coordinated digital platforms (Wang et al., 2021: 2681). In addition, unmanned systems are highlighted as valuable tools for enhancing monitoring efficiency, particularly in large-scale or offshore operations where manual data collection is limited (Ubina & Cheng, 2022: 12). Deep learning-based systems have also been highlighted as promising tools for improving accuracy in behaviour detection and environmental interpretation, which aligns with the recent findings summarised by Kaur et al. (2023: 4399512). These studies generally report better access to real-time data and more organised monitoring routines. However, only a small number include results from commercial production, and most concentrate on testing or developing digital tools instead of evaluating their longer-term performance.

Biotechnological approaches include selective breeding, genome-related methods and microbiome research. These technological categories are consistent with broader mappings of emerging techniques in marine aquaculture, which describe parallel growth in biological, digital and engineering innovations (Ma & Qin, 2023: 2239). These studies point to growing interest in using genetic and molecular techniques to improve fish health, resilience and growth. Most results, however, come from laboratory or pilot-scale work, and their practical use in commercial farms is not always clear.

Engineering and system design studies mostly focus on recirculating aquaculture systems, offshore cage structures and water-quality control technologies. These contributions suggest that engineering solutions can help stabilise production conditions and reduce external inputs. Integrated smart farm architectures further demonstrate how engineering-driven digitalisation enhances resource efficiency and strengthens sustainability outcomes in marine aquaculture (Kassem et al., 2021: 10685). Only a few studies evaluate operational feasibility or economic considerations.

Research related to sustainability examines issues such as welfare monitoring, energy use, carbon emissions and environmental data tracking. These studies show that technology can support more environmentally responsible practices, but the evidence is scattered and direct comparisons across systems or regions are limited.

4. RECOMMENDATIONS

Taken together, the findings show growing interest in digitalisation, biotechnology and engineering solutions that support environmental goals. However, the strength of the evidence varies, and many studies do not include large-scale or long-term results. For this reason, the trends identified here should be viewed as early signals rather than complete descriptions of sector-wide change.

At the policy level, the studies point to the need for clearer data systems. Many digital tools depend on regular and structured data flow, but standard reporting rules are often missing. As noted in IoT-focused reviews, the effectiveness of marine monitoring networks depends heavily on interoperability and stable data transmission infrastructures (Xu et al., 2019: 1711). Recent work underscores that emerging digital platforms in marine aquaculture rely heavily on structured data pipelines, interoperable architectures and unified monitoring frameworks to function effectively (Zhang & Gui, 2023: 401). Policies that encourage the use of compatible data formats and shared monitoring platforms may improve data quality. Support for gradual adoption of energy-efficient and environmentally focused technologies may also help long-term sustainability, provided that economic limits are carefully assessed. Concepts emerging from smart and sustainable aquaculture farm models offer policy-relevant insights into how technological integration can support more structured, efficient and environmentally responsible governance frameworks (Kassem et al., 2021: 10685).

At the research level, more integrated studies are needed. Many papers examine a single technology, which makes it difficult to understand how different tools work together. For example, deep learning frameworks offer substantial potential for combining behavioural, environmental and visual data streams, as emphasised by recent reviews on precision fish farming (Kaur et al., 2023: 4399512). IoT-based monitoring frameworks have been particularly influential in expanding the precision and temporal resolution of environmental measurements in marine farms (Xu et al., 2019: 1711). Studies, that combine biological, environmental and digital data would offer a more complete picture. Research should also include more commercial-scale trials and more comparisons between countries with different environmental and regulatory conditions.

At the industry level, digital and engineering-oriented tools appear useful for routine monitoring and farm management, but adoption is uneven. A precision aquaculture perspective further illustrates how coordinated IoT infrastructures and automated feedback systems can enhance operational reliability and support scalable digital transformation across the sector (O'donncha & Grant, 2019: 26). Intelligent farm architectures offer a practical illustration of how such tools can be operationalised to improve coordination across feeding, monitoring and welfare management functions (Wang et al., 2021: 2681). Unmanned monitoring platforms can further support operational decision-making by providing spatially resolved environmental and structural information, which is particularly relevant for large marine farms (Ubina & Cheng, 2022: 12). Training programs that bring together biologists, engineers and data specialists may support more effective use of new technologies. Pilot projects under real farming conditions may also help producers understand benefits and constraints before investing. Collaboration among industry, researchers and public agencies may help identify practical barriers and opportunities for gradual technology uptake.

Overall, the findings suggest that marine aquaculture is moving toward more data-informed, biologically informed and environmentally attentive models of production. The recommendations presented here support incremental and evidence-based improvement rather than broad or prescriptive strategies.

5. CONCLUSION

This review examined 25 studies published between 2018 and 2025 to identify emerging technological trends in marine aquaculture. The findings show increasing attention to digital tools, biotechnological approaches, engineering-based system design and sustainability-oriented practices. However, many developments remain at early or experimental stages, and long-term commercial evidence is limited. Therefore, the conclusions presented here reflect general tendencies rather than complete descriptions of the sector.

Future work will benefit from clearer methodological reporting, broader regional comparisons and studies that combine technological, ecological and economic perspectives. Cooperation among researchers, policymakers and industry actors will be important for supporting informed and realistic adoption of new technologies. While the current evidence base has limits, this review provides a structured foundation for further studies and for guiding sustainable and data-informed development in marine aquaculture.

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EMERGING AND INNOVATIVE TECHNOLOGIES IN FISH FEED SYSTEMS

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1. INTRODUCTION

Aquaculture is playing an increasingly decisive role in ensuring global food security. However, as is well known, the sustainability of this production model largely depends on the structure, origin and technological characteristics of the feeds used. Today, feeds are no longer seen only as inputs that determine growth performance; they are increasingly considered strategic components that directly influence environmental footprint, animal welfare, production costs and consumer perception. In this context, feed technologies in aquaculture have entered a multidimensional transformation process that goes beyond the classical formulation approach (Nathanailides, 2025: 2601). For many years, fishmeal and fish oil have been used as the main protein and lipid sources in the nutrition of aquatic species due to their high biological value and balanced amino acid profiles. However, the strong dependence of these raw materials on capture fisheries has increased pressure on natural stocks. Supply fluctuations and price instability have made feed costs a critical issue, especially in intensive production systems. In

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current production models, the fact that feed expenses can reach 50–60% of total costs has positioned feed technologies at the centre of economic sustainability considerations (Fregene et al., 2020: 69). These structural limitations have accelerated research and development activities related to feed technologies in aquaculture. Along with the industrial-scale growth of the sector, studies on alternative protein sources, feed processing techniques and functional additives have increased significantly. Research published in recent years shows that innovations in feed technologies are not limited to fishmeal replacement alone; they also address the digestibility and bioavailability of nutrients, as well as their effects on animal health, in a more holistic manner (Davis, 2022: 1; Midhun & Arun, 2023: 291; Solomon et al., 2025: 183).

In the development and commercialisation of new feed technologies, food and feed safety, regulatory frameworks and social acceptance dynamics have become as decisive as technical and biological parameters. In many countries, particularly within the European Union, the safety assessment of new feed sources and production technologies is carried out within scientific, evidence-based approaches. These processes are supported by comprehensive risk assessment frameworks that aim to balance performance gains with consumer safety (European Food Safety Authority [EFSA], 2025: 9558E). At the same time, consumer perception and attitudes towards innovation are becoming increasingly important factors in the market integration of new feed technologies. Especially when new protein sources, advanced processing techniques and technology-based feed components are involved, social acceptance and perceptual barriers are as important as technological feasibility (Protano et al., 2025: 2825). This situation makes it necessary to evaluate feed technologies not only from a biological and economic perspective, but also within a broader socio-economic framework (van der Poel et al., 2020: 114692; Nathanailides, 2025: 2601). Within this framework, contemporary feed technologies no longer seek answers only to the question “what should be fed?”, but also to “how, for what purpose and within which production system should feeding be carried out?”. Across a wide spectrum ranging from alternative protein sources to nano-scale additives, and from advanced feed processing and formulation techniques to integration with digital feeding systems, feeds are increasingly seen as strategic tools that shape the performance and sustainability of aquaculture production systems (Bu et al., 2024: 759; Nwankwo et al., 2025: 263).

In this review book chapter, the transformation of feed technologies in aquaculture is addressed from a holistic perspective, considering driving factors, next-generation protein sources, functional and advanced additives, production and processing technologies, as well as regulatory and market dynamics. The aim is to synthesise the existing literature and to provide a structural framework for future directions in feed technologies.

2. INNOVATION DRIVERS IN FISH FEED TECHNOLOGIES

Innovations in fish feed technologies within aquaculture are shaped by the combined effects of several factors, including structural limitations in raw material supply, increasing environmental pressures, the intensification of production systems and the gradual tightening of regulations. In this context, it is increasingly recognised that developments in aquaculture feed technologies need to be addressed through a holistic sustainability perspective (van der Poel et al., 2020: 114692).

Historically, fishmeal and fish oil have been considered indispensable in the nutrition of aquatic species due to their high biological value and balanced amino acid profiles. However, the limited nature of these raw materials and uncertainties related to supply security have forced the feed industry to develop alternative solutions. This situation has brought not only substitute raw materials, but also new production, processing and formulation approaches to the forefront of feed technologies (Davis, 2022: 1; Midhun & Arun, 2023: 291).

Economic factors stand out as a key determinant shaping the direction of feed technologies, particularly in intensive aquaculture systems. Feed costs represent the largest share of total operational expenses in many production models, directly linking feed efficiency, digestibility and waste generation to overall economic performance (Fregene et al., 2020: 69). In recent years, environmental sustainability has also become an important driver of innovation in feed technologies. In intensive systems, nitrogen and phosphorus inputs originating from feeds increase the risk of eutrophication in aquatic environments, making environmental licensing processes more complex. This has accelerated the shift towards feed formulations that are highly digestible, have lower environmental loads and are compatible with circular economy principles (Midhun & Arun, 2023: 291). In particular, alternative protein sources and the use of agricultural or industrial by-products are increasingly seen as strategic tools to reduce the environmental impacts of feed technologies (Nwankwo et al., 2025: 263).

Regulations and food–feed safety approaches also play a decisive role in shaping innovations in feed technologies. New feed sources and production technologies must be evaluated not only in terms of performance gains, but also with regard to safety, traceability and risk management. This has increased the importance of science-based, transparent and standardised approaches in feed technology development (Nathanailides, 2025: 2601). At the same time, it is emphasised that consumer perception and social acceptance are critical factors that cannot be overlooked in the adoption of feed innovations (Protano et al., 2025: 2825). During the shift towards plant-based alternatives, important limitations related to nutrient balance, digestibility and anti-nutritional factors have been identified (Bu et al., 2024: 759). Within this framework, next-generation sources such as microalgae, insect meals and microbial-derived proteins have begun to be considered as core components of feed technologies that are aligned with circular economy concepts, system integration and environmental sustainability goals.

3. NOVEL PROTEIN SOURCES IN FISH FEEDS

During the transformation process of feed technologies in aquaculture, protein sources clearly emerge as one of the most critical components. In the initial phase, plant-based protein sources were considered the most accessible options for fishmeal replacement. However, over time, it became evident that these sources have important limitations in terms of amino acid profile, digestibility and the presence of anti-nutritional components. This situation has made it necessary to explore protein sources that are more compatible with the physiological requirements of aquatic species and that also have a lower environmental footprint (Davis, 2022: 1; Midhun & Arun, 2023: 291). Within this framework, the concept of “novel protein sources” has moved beyond a narrow focus on fishmeal substitution and has evolved into a broader perspective that includes circular bioeconomy principles, waste valorisation and integrated approaches linked to production systems.

In the current literature, next-generation protein sources are generally discussed under three main categories: microalgae-based proteins, insect-derived meals, and microbial or single-cell proteins. The common characteristics of these protein groups include high production potential, lower land and water requirements compared to conventional agricultural resources, and the ability to be integrated into aquaculture production systems (Bu et al., 2024: 759). Especially in the context of recirculating systems, biofloc technology (BFT) and aquaponic applications, these protein sources are considered not only as feed ingredients but also as functional components of the production system itself. The reuse of microalgae as feed raw materials through the treatment of RAS effluent waters, the production of microbial proteins via waste-based bioprocesses, and the capacity of insect-derived proteins to convert organic by-products into biomass all support the system-based sustainability of this approach (Genc et al., 2024a: e13086; b: e13041; Santillan et al., 2024: 2620; Vázquez-Romero et al., 2024: 104904). In this context, next-generation protein sources are positioned not only as nutritional inputs, but also as strategic tools for reducing environmental loads, increasing resource efficiency and supporting circular production models. Within the scope of Novel Protein Sources in Fish Feeds, microalgae-based protein sources will be examined first, followed by insect-derived proteins and microbial proteins, which will be discussed under separate subheadings.

3.1. Microalgae-Based Protein Sources

Microalgae have begun to attract considerable attention as next-generation protein sources in aquaculture, from both scientific and technological perspectives. This interest is mainly driven by their high protein content, balanced amino acid profiles and richness in long-chain polyunsaturated fatty acids. Compared with conventional agricultural protein sources, the fact that microalgae do not require arable land and can be produced using saline or wastewater places these organisms in a strategic position for sustainable feed technologies (Bu et al., 2024: 759).

In early studies, microalgae were mostly evaluated as alternative lipid sources to fish oil, with particular emphasis on their positive effects on pigmentation and fatty acid profiles. However, subsequent research has shown that some microalgal species can reach protein levels comparable to fishmeal and can be incorporated into feed formulations at meaningful inclusion rates when appropriate processing techniques are applied (Davis, 2022: 1; Midhun & Arun, 2023: 291). In the current literature, species belonging to genera such as *Chlorella*, *Scenedesmus*, *Tetraselmis* and *Nannochloropsis* are extensively studied as protein sources in aquaculture feeds. Depending on production conditions, protein contents reaching 40–60% offer significant potential for fishmeal replacement. However, the cell wall structure and digestibility characteristics of microalgae represent key limitations that must be carefully considered from a feed technology perspective. To overcome these constraints, mechanical, enzymatic or thermal pre-treatments are identified as critical steps to improve the effectiveness of microalgae-based feeds (Albaqami, 2025: 741404).

Microalgae-based protein sources can be integrated into aquaculture production systems. For example, water discharged from recirculating aquaculture systems (RAS) can serve as an environmental treatment medium, allowing microalgae to remove nutrients such as nitrogen and phosphorus from the water. Moreover, the use of RAS effluents for microalgae cultivation and the subsequent reuse of the resulting biomass as a feed raw material provide a concrete example of the circular bioeconomy approach (Vázquez-Romero et al., 2024: 104904). The economic dimension remains one of the main factors determining the wider adoption of microalgae-based proteins. Current studies indicate that production costs are still higher than those of fishmeal and plant-based protein sources. Nevertheless, it is anticipated that these costs can be significantly reduced through scale-up, the expansion of wastewater-based production systems and the adoption of multi-product strategies (Solomon et al., 2025: 183). Overall, microalgae-based protein sources are regarded as a holistic solution that brings together environmental sustainability, system integration and circular production objectives in the transformation of feed technologies in aquaculture.

3.2. Insect-Based Protein Sources

Insect-derived proteins are among the alternative protein sources that have gained momentum most rapidly during the transformation of feed technologies in aquaculture. This growing interest is mainly based on the high protein content of insects, their favourable amino acid profiles and their capacity to convert organic by-products into biomass. Compared with conventional protein sources, insect farming requires less land and water and is considered to be highly compatible with circular economy and sustainable production approaches (Bu et al., 2024: 759). Initially, insect-based proteins were primarily used in poultry and pig nutrition, while their application in aquaculture remained limited. However, recent studies have demonstrated that meals obtained from certain insect species can reach protein levels and amino acid profiles comparable to those of fishmeal. These findings indicate that insect-based proteins represent a technically feasible and biologically effective option for the nutrition of aquatic species (Midhun & Arun, 2023: 291). In the current literature, the most widely studied insect species include *Hermetia illucens*, *Tenebrio molitor* and *Musca domestica*. These species are considered suitable for industrial-scale production due to their rapid growth rates, high protein yields and ability to feed on a wide range of organic substrates (Bu et al., 2024: 759).

One of the main discussion points regarding the use of insect-derived proteins in aquaculture feeds relates to their lipid content and fatty acid profiles. Many insect species are rich in saturated fatty acids, which may require adjustments in dietary formulation for certain aquatic species. This limitation is being addressed through partial replacement strategies and the development of insect meals with improved fatty acid profiles. In addition, the chitin content of insects is known to have potential positive and negative effects on digestibility and gut health (Davis, 2022: 1). From a system integration perspective, the compatibility of insect-based proteins with aquaponic and recirculating production systems has attracted increasing interest. The conversion of organic wastes into insect biomass and the use of the resulting products as feed ingredients are considered important for waste valorisation in aquaculture (Pinho et al., 2024: e0295811). Consumer perception and regulatory frameworks play a decisive role in the wider adoption of insect-based proteins. In many countries, legal frameworks governing insect-derived feed ingredients are being gradually implemented (Protano et al., 2025: 2825). In general, insect-based proteins contribute to the diversification of feed technologies in aquaculture.

3.3. Microbial and Single-Cell Protein Sources

Microbial and single-cell proteins are also gaining a strategic position in the development of feed technologies in aquaculture. Proteins derived from bacteria, yeasts and certain filamentous microorganisms are considered sustainable alternatives with strong potential to reduce dependence on conventional sources, due to their ability to generate biomass rapidly (van der Poel et al., 2020: 114692). In early applications, the use of microbial proteins in aquaculture remained limited. However, advances in modern fermentation technologies and bioprocess control have significantly improved both the nutritional quality and production capacity of these proteins (Davis, 2022: 1). Recent studies indicate that microbial proteins can exhibit characteristics comparable to fishmeal in terms of amino acid profile, digestibility and functional properties (Solomon et al., 2025: 183).

One of the most notable features of microbial proteins is their strong compatibility with circular economy approaches. Industrial by-products, agricultural residues and even wastewater can be used as substrates for microbial biomass production (Santillan et al., 2024: 2620). Recirculating production systems and biofloc technology (BFT) provide an important basis for integrating microbial proteins into aquaculture. In these systems, microbial communities are utilised as feed components while simultaneously playing functional roles in water quality regulation. This shifts microbial proteins beyond the traditional definition of a "raw material" and positions them as active components of the production system itself (Bu et al., 2024: 759; Genc et al., 2024a: e13086; b: e13041). Despite their potential, several technical and perceptual constraints still limit the widespread use of microbial proteins. Production costs, process complexity and regulatory compliance requirements restrict their commercial-scale adoption. In addition, consumer perception and safety assessments related to microbial-derived feed ingredients are important aspects that must be considered during market integration (EFSA, 2025: 9558E; Protano et al., 2025: 2825). Nevertheless, opportunities related to circular production models, waste valorisation and integration with closed systems may position these protein sources as core components of sustainable and innovative feed strategies (Midhun & Arun, 2023: 291). In summary, microbial and single-cell proteins have significant potential to play an important role in the future of feed technologies in aquaculture.

4. ADVANCED FEED PROCESSING AND FORMULATION TECHNOLOGIES

The effectiveness of next-generation feed technologies in aquaculture does not depend solely on the type of protein and energy sources used. How these components are processed, the physical form in which they are presented, and their behaviour during digestion have become at least as decisive as their nutritional composition. For this reason, the transformation of feed technologies has made it necessary to reconsider processing and formulation approaches in parallel with the diversification of raw materials. Contemporary feed technologies are increasingly shaped as an integrated engineering field that aims to enhance nutrient bioavailability, reduce digestive losses and limit environmental loads.

For many years, pelleting has been the main method used in the production of aquaculture feeds. Its low investment requirements and simple process structure have supported its widespread adoption, particularly among small- and medium-scale enterprises (Fregene et al., 2020: 69). However, the limited thermal treatment and mechanical pressure applied during pelleting provide restricted control over starch gelatinisation and protein structure. This has led to technical constraints, especially in the incorporation of alternative protein sources and functional components into the feed matrix. As these limitations became more apparent, extrusion technologies have gained an increasingly dominant position in the aquaculture feed industry. During extrusion, the controlled application of temperature, pressure and shear forces significantly modifies the physical structure of the feed matrix, improving digestibility and water stability by enhancing starch gelatinisation. The structural advantages provided by this technology are particularly important in the production of floating and semi-floating feeds, as they support feed intake monitoring and the effectiveness of precision feeding practices (Midhun & Arun, 2023: 291). Despite these advantages, the high energy demand and investment costs associated with extrusion systems limit their application across all production scales. In response, hybrid processing systems that aim to combine the advantages of pelleting and extrusion have attracted increasing attention in recent years. Hybrid approaches allow more flexible adjustment of process parameters, with the goal of optimising energy use while improving consistency in feed quality. These systems are reported to offer more adaptable solutions, particularly for the processing of insect-, microalgae- and microbial-derived proteins. Beyond mechanical operations, advances in feed processing technologies also encompass mathematical modelling and process optimisation. Recently developed models enable more accurate characterisation of the mechanical, physical and operational parameters affecting pelleting and extrusion efficiency. In particular, basic models designed for hybrid processing systems highlight the growing importance of engineering-based decision-support approaches in feed technologies (Nnadi Daniel et al., 2025: 151).

Processing technologies also directly influence the interaction between feeds and digestive physiology. In this context, the behaviour of starch and fibre fractions during formulation has gained increasing importance. The effects of soluble non-starch polysaccharides (NSPs) on digestion, intestinal viscosity and metabolic responses in fish are among the key factors determining the nutritional outcomes of processing conditions. It has been shown that appropriate processing and formulation strategies can limit the negative effects associated with NSPs and improve feed utilisation efficiency (Wang et al., 2024: 1). Another important dimension of advanced feed technologies is the preservation of functional components throughout the chain from production to consumption. Microencapsulation, coating and controlled-release approaches aim to enhance the stability of vitamins, probiotics, prebiotics and biologically active compounds. By ensuring that these functional components remain effective in targeted regions of the digestive tract, such strategies can positively influence the immune status and performance of farmed species (Solomon et al., 2025: 183).

Nanotechnology-based applications are also emerging in the field of feed processing and formulation. Nano-scale carrier systems offer potential benefits by improving the solubility and bioavailability of nutrients, while also providing new options for toxin binders and protective components. However, the use of such applications in feeds requires careful consideration with respect to safety and toxicological assessments (Dube, 2024: 322).

Feed safety and quality control have become integral elements of advanced processing technologies. The increasing use of plant-based raw materials and alternative protein sources necessitates more comprehensive control mechanisms for mycotoxins and other contaminants. In this context, bio-based adsorbents and nanocomposite structures have shown promising results in binding harmful compounds such as aflatoxins (Ghobish et al., 2025: 2575; Boti et al., 2024: 118739). In addition, studies focusing on the economic and environmental optimisation of plant-based and mineral-supplemented diets suggest that low-cost formulations can be technically feasible (Sana et al., 2024: 1322; Fregene et al., 2020: 69).

Current trends point towards the integration of feed production processes with digital monitoring and control systems. Real-time monitoring of process parameters allows early detection of deviations in product quality, contributing both to the reduction of environmental footprint and to more effective management of production costs (Føre et al., 2023: 227). Overall, feed processing and formulation technologies are considered fundamental tools that jointly shape the physical, nutritional and functional performance of feeds in aquaculture. When pelleting, extrusion and hybrid systems are evaluated together with functional additives and advanced delivery technologies, it becomes clear that feed technologies should progress through context-specific and integrated approaches rather than isolated solutions. This holistic perspective represents a key prerequisite for the implementation of next-generation feed technologies in alignment with sustainable production objectives.

5. SMART FEEDING SYSTEMS AND DIGITAL INTEGRATION

The transformation of feed technologies in aquaculture has expanded beyond the development of feed composition and processing techniques to include feeding strategies that determine when, how much and under which conditions feeds should be delivered. At this point, smart feeding systems have become key tools that shift feed management from intuition-based practices to data-driven and dynamic decision-making processes. The integration of digital technologies into feeding operations represents a strategic transformation aimed at improving biological performance and reducing feed losses (van der Poel et al., 2020: 114692; Bu et al., 2024: 759).

The core components of smart feeding systems include sensor-based monitoring, automated feed delivery mechanisms and decision-support algorithms. These systems allow feeding decisions to be made with greater precision by simultaneously monitoring water quality parameters, fish behaviour and environmental conditions. For example, directly linking parameters such as dissolved oxygen, temperature and turbidity with feeding practices can help prevent overfeeding or underfeeding (Davis, 2022: 1; Føre et al., 2023: 227). Approaches based on monitoring fish behaviour are emerging as one of the most innovative aspects of smart feeding technologies. Image processing systems and behaviour-analysis algorithms can evaluate fish responses to feed intake in real time. This approach can contribute to improved feed utilisation efficiency and reduced environmental loads, particularly in intensive production systems (Midhun & Arun, 2023: 291).

In recent years, applications based on artificial intelligence and machine learning have further advanced the decision-making capacity of smart feeding systems. These technologies enable the combined analysis of historical production data and real-time sensor outputs, allowing feeding strategies to be optimised through predictive models. As a result, feeding is increasingly becoming an adaptive process that responds sensitively to environmental and biological conditions (Ahmad Dar et al., 2025: 123). Another important dimension of smart feeding systems is their integration with digital production platforms and farm management software. Cloud-based data management and remote access capabilities allow producers to continuously monitor feeding performance and manage production processes in a centralised manner. Through this integration, a more balanced relationship between production efficiency and cost control can be established. However, several technical and structural limitations still constrain the widespread adoption of smart feeding systems. The reliability of sensor systems, data quality, system maintenance requirements and initial investment costs can represent significant barriers, particularly for small- and medium-scale enterprises. Moreover, the effective use of digital systems is directly linked to the technical knowledge and digital literacy of producers (Fregene et al., 2020: 69). The smart feeding systems and digital integration are regarded as complementary elements that enhance the effectiveness of feed technologies in aquaculture, and these approaches are expected to play a key role in shaping the future of aquaculture production.

6. FEED SAFETY, QUALITY CONTROL AND EMERGING RISKS

For feed technologies in aquaculture, feed safety, consistency in quality and the minimisation of potential risks constitute an integral part of the ongoing transformation. In particular, the increasing use of next-generation protein sources, advanced processing techniques and functional additives has made it necessary to address feed safety assessments in a more comprehensive and multidimensional manner (van der Poel et al., 2020: 114692).

One of the most long-standing problem areas in feed safety relates to mycotoxins and other naturally occurring contaminants. The growing use of plant-based raw materials in feed formulations has increased the risk of various mycotoxins, especially aflatoxins, entering the feed chain. These toxins can reduce growth performance in aquatic organisms, suppress the immune system and pose long-term risks to product safety. As a result, toxin binders and adsorbent systems have begun to play a central role in quality control strategies within feed technologies (Davis, 2022: 1). In recent years, bio-based and nanocomposite adsorbents have offered promising solutions in the field of feed safety. Findings on the aflatoxin-binding capacity of chitosan-based nanocomposites suggest that such materials may represent effective and environmentally compatible alternatives to conventional binders (Ghobish et al., 2025: 2575). In addition, it is well recognised that zeolite-based minerals are also evaluated within this context (Kaya et al., 2022: 1284). Another risk area that has attracted increasing attention in the context of feed safety is the presence of emerging environmental contaminants.

Microplastics, heavy metals and various organic pollutants have been detected in fishmeal and commercial feeds. In particular, the detection of microplastics in commercial fishmeal and feeds indicates that these contaminants can be transferred into the food chain through aquaculture production systems (Jeyasanta et al., 2024: 142832). The identification and management of such complex risks require the use of advanced analytical techniques beyond conventional methods. High-resolution mass spectrometry (HRMS)-based target and suspect screening approaches enable the simultaneous assessment of both known and previously unidentified contaminants in feeds. These methods stand out as important tools that support a shift from reactive approaches towards proactive risk management in feed safety (Boti et al., 2024: 118739).

Regulatory frameworks play a key role in shaping feed safety and quality control processes, aiming to establish a balance between innovation in feed technologies and consumer safety (EFSA, 2025: 9558E). Processes extending from raw material acceptance to final product analysis make it possible not only to detect contamination, but also to identify deviations in production processes at an early stage. Digital monitoring systems and data-driven quality management approaches significantly enhance standardisation and traceability in feed production (Bu et al., 2024: 759). In this context, the successful implementation of next-generation feed technologies is considered to depend not only on performance and cost advantages, but also on the adoption of a holistic risk management approach based on safety, transparency and regulatory compliance.

7. SOCIO-ECONOMIC AND REGULATORY DIMENSIONS OF FEED INNOVATION

Next-generation feed ingredients and feeding systems have direct effects on production costs, market structures and competitiveness. In particular, the high share of feed costs within total production expenses makes it necessary to evaluate technological innovations together with their economic feasibility (Fregene et al., 2020: 69). From a socio-economic perspective, the rate at which new feed technologies are adopted may vary depending on factors such as production scale, access to capital and technical capacity. While smart feeding systems, advanced processing technologies and functional additives can be implemented more rapidly by large-scale and vertically integrated enterprises, investment costs and knowledge requirements can represent significant constraints for small- and medium-scale producers. As a result, feed innovation tends to generate a non-homogeneous transformation across the sector (Nwankwo et al., 2025: 263). New protein sources, nanotechnology-based additives and digital feeding applications are evaluated not only in terms of performance gains, but also with respect to safety, traceability and ethical considerations. In addition, consumer perception and social acceptance play an indirect yet critical role in the adoption of feed innovations.

8. CONCLUSION AND FUTURE PERSPECTIVES

The topics addressed in this chapter clearly demonstrate that feed technologies in aquaculture are undergoing a profound transformation. Traditional feeding practices based on fishmeal and fish oil are being replaced by a multidimensional approach that includes alternative protein sources, advanced processing and formulation techniques, and digital feeding systems. With this transformation, feed is no longer viewed merely as a nutritional input; it is increasingly recognised as a strategic tool that jointly shapes the environmental, economic and managerial performance of aquaculture production systems. Microalgae, insect-derived proteins and microbial proteins are being used more extensively as fishmeal substitutes, offering solutions that are aligned with circular economy principles and system integration goals. Pelleting, extrusion and hybrid systems, together with microencapsulation and controlled-release technologies, are expected to enhance the bioavailability and performance effects of these new raw materials. Digitalisation and smart feeding systems act as a critical interface between feed technologies and on-farm application. Sensors, data analytics and artificial intelligence-based decision-support systems are making feeding processes more precise, traceable and adaptable.

Looking ahead, the success of feed technologies in aquaculture will depend not on individual innovations alone, but on the system-based and holistic integration of these innovations. Feed safety, quality control and regulatory compliance should be treated as integral components of innovation. It is also essential to maintain a balance between performance improvement, risk management and ethical considerations. In this context, the support of feed technology innovations through interdisciplinary collaboration and evidence-based policy mechanisms should be regarded as a key factor in achieving the sustainability objectives of aquaculture.

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SU ÜRÜNLERİNDE KULLANILAN PAKETLEME YÖNTEMLERİ

Nermin KARATON KUZGUN[1]

1. GİRİŞ

Su ürünleri, insan beslenmesinde yüksek değerli biyolojik değere sahip proteinleri içermesinden ve çoklu doymamış yağ asitleri ile vitaminler ve mineraller açısından önemli bir yere sahiptir. Özellikle balık ve diğer deniz canlıları kardiyovasküler hastalıkların engellenmesinde rol oynayan omega-3 yağ asitleri bakımından zengin olmaları nedeniyle dünya genelinde tüketimi giderek artan gıda grupları arasında yer almaktadır. Ancak su ürünleri, yapısal özellikleri ve kimyasal bileşimlerinden dolayı en hızlı bozulan gıdalar arasında bulunmaktadır (FAO, 2022). Balık ve balık ürünleri, avlandıktan ve hasat edilmelerinden sonra ürün kalitesinin korunması ve raf ömrünün uzatılması bakımından mikrobiyal bozulmanın önlenmesi açısından uygun paketleme yöntemlerinin kullanılması büyük önem arz etmektedir. (Huss, 1995).

Su ürünlerinin yüksek su içeriği, kas yapısı, mikrobiyal florası ve serbest amino asit miktarının fazlalığı, bozulma sürecini hızlandırır. Avcılık ve hasat sonrası başlayan mikrobiyolojik, kimyasal (enzimatik ve oksidatif) reaksiyonlar, ürünlerin kısa sürede mikrobiyolojik, kimyasal ve duyusal açıdan tüketilemez olarak kabul edilmesine neden olmaktadır. Bu yüzden, su ürünlerinde tazeliğinin korunması, raf ömrünün uzatılabilmesi için etkili muhafaza ve paketleme metodlarının uygulanması

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gerekir (Huss, 1995). Ambalajlama, su ürünlerinde yalnızca ürünün fiziksel olarak korunabilmesini değil, aynı zamanda bozulma mekanizmalarının da kontrol altına alınabilmesini amaçlar. Uygun ambalajlama yöntemleri sayesinde oksijenle temas sınırlı hale getirilmekte, mikrobiyal gelişim en aza indirilmekte ve lipid oksidasyonu azaltılmaktadır. Buna ek olarak ambalajlama, ürünün taşınması, pazarlanması ve depolanması esnasında hijyenin sağlanması ve tüketici güveninin artırılması bakımından da önemli rol oynamaktadır (Ghaly et al., 2010; Üçüncü, 2011). Paketleme metotları yıllardan beri su ürünlerinde muhafazada kullanılmış olsa bile, bu metotlar muhafazayı sınırlı ölçüde uzatabilmiş ve özelliklede son zamanlarda tüketicilerin taleplerinin de farklılaşmasıyla katkısız ve taze ürünlerdeki ilginin artmasıyla ve gıda güvenliğine olan hassasiyetin artması, daha gelişmiş paketleme yöntemlerinin kullanımını zorunlu hale getirmiştir. Bu anlamda vakum, modifiye atmosfer (MAP), aktif ve akıllı paketleme sistemlerinin su ürünlerinde yaygın bir şekilde kullanımı artmıştır (Robertson, 2013). Bu araştırma, su ürünlerinde yaygın biçimde kullanılan paketleme yöntemlerini detaylı ve sistematik bir şekilde ele alınıp detaylı bilgiler verilecektir.

2. SU ÜRÜNLERİ AÇISINDAN PAKETLEMENİN TEMEL İLKELERİ

Su ürünlerinde paketlemedeki temel amaç ürünün kalitesinin korunması, raf ömrünün uzatılması ve gıda güvenliğinin sağlanması bakımından temel bir muhafaza uygulaması tekniğini içermektedir. Paketleme, sadece materyali dış etkenlerden korumak için değil; aynı zamanda uygun ambalajlama yöntem ve ambalaj materyali seçimi ile de bozulma mekanizmalarını kontrol altına alınmasında katkı sağlamaktadır (Üçüncü, 2011; Robertson, 2013).

2.1. Su Ürünlerinin Paketlemesindeki Temel Amaçlar

Su ürünlerinin paketlemesindeki temel amaçlar; mikrobial kontaminasyonun ve çoğalmanın azaltılmasını sağlamak, oksijen ile temas kesilerek oksidatif bozulmanın önlemesi, nem kaybınının ve damlama kaybınının azaltılması, fiziksel hasarların ve deformasyonların engellemesi, ürünün duyusal, besinsel ve teknolojik özelliklerinin koruması, ürünün taşıması, depolaması ve pazarlaması aşamalarında hijyenin sağlaması gibi temel amaçları sıralamamız mümkündür. Bu amaçların hepsi, seçilecek olan paketleme yönteminin ve ambalaj materyalinin üzerinde doğrudan etkili olabilmektedir (Huss, 1995).

2.2. Su Ürünlerinin Yapısal Özelliklerinin Ambalajlama Üzerindeki Etkisi

Su ürünlerinin ambalajlanmasında dikkate alınması gereken en önemli faktörlerden biri, ürünün kendine özgü fiziksel ve kimyasal yapısal özelliğidir. Balık etinin yüksek su içeriği ve gevşek kas dokusu ile düşük bağ dokusu yapısına sahip olması, paketleme esnasında sıvı kaybı ve doku bozulması riskini arttırır (Connell, 1995). Bunlara ek olarak su ürünlerinin yada balığın türüne bağlı olarak yağ içeriği büyük farklılıklar gösterebilmektedir. Yağlı balıklar (örneğin uskumru, sardalya, somon) oksidatif bozulmaya hassası olup, oksijen bariyeri ile yüksek ambalaj materyalleri kullanımına ihtiyaç göstermektedir. Buna karşın yağsız ve az yağlı balıklarda mikrobiyal bozulma daha baskın olamaktadır (Ghaly et al., 2010).

2.3. Oksijen Azaltılması ve Sonuçları

Oksijenin azalması su ürünlerinde hem mikrobiyal gelişim açısından hem de yağların oksidasyonu açısından önemli etmenlerden biridir. Bu yüzden paketlemenin en önemli ilkelerinden biride, ambalaj içerisindeki oksijen miktarının kontrol altında tutulmasıdır. Oksijen kontrolünü; vakum paketlemeyle ambalaj içerisindeki havanın uzaklaştırılmasını sağlayarak, modifiye atmosfer paketlemeyle oksijenin inert gazlarla değişiminin sağlanması ile ve oksijen geçirgenliği düşük paketleme materyallerinin kullanılmasıyla oksijeni ambalaj içerisinde en aza indirebilmesi sağlanabilir (Özogul et al., 2004; Üçüncü,2011). Bu uygulamalar vasıtasıyla aerobik mikroorganizmalarda gelişim sınırlanmakta ve yağların oksidasyonu önemli ölçüde yavaşlamaktadır (Robertson, 2013).

2.4. Sıcaklık Kontrolü ve Soğuk Zincir

Ambalajlama, soğuk muhafaza ile birlikte değerlendirilmelidir çünkü ancak bu şekilde etkili sonuçlar elde edilmektedir. Düşük sıcaklıklarda, mikroorganizmaların gelişimi ve enzimatik faaliyetleri yavaşlarken, uygun paketleme ile bu etkilerin sürdürülebilirliği beraber sağlamaktadır (Huss, 1995). Soğuk zincirde meydana gelebilecek kırılma, en gelişmiş paketleme yöntemini dahi kullansak bile hızlı bozulma kaçınılmaz olacaktır. Bu yüzden paketleme ilkeleri; Paketleme işlemleri düşük sıcaklıkta gerçekleştirilmeli, paketlenmiş ürünler +0–4 °C aralığında depolanmalı, taşıma ve dağıtım aşamaları süresince sıcaklık kontrolü sürdürülmeli şeklinde sıralanabilir. Bu maddelerin sağlanabilmesi özellikle vakum ve MAP uygulamaları için gıda güvenliği bakımından kritik öneme sahiptir (Gram & Dalgaard, 2002).

2.5. Su Aktivitesi ve Nemin Kontrolü

Su ürünlerinde yüksek su aktivitesi (aw) ile mikroorganizmaların gelişimi için uygun bir ortam oluşturmakta ve paketleme esnasında nem kaybının önlenmesi kadar, ambalaj içerisinde serbest su birikiminin kontrol altında tutulması önem arz eder (Connell, 1995). Uygun paketleme ile, damlama kaybı azalır, ürünün ağırlık ve görünüm kaybı önlenir, mikroorganizma gelişimi sınırlandırılır. Bu amaçla nem bariyeri yüksek olan ambalaj materyalleri ile sızdırma yapmayan paketleme sistemleri tercih edilmelidir.

2.6. Uygun Ambalaj Materyalinin Seçimi

Su ürünlerinde paketlemede, ürün için uygun ambalaj materyalinin özellikleri belirleyici rol oynar. İdeal bir ambalaj materyali; mekanik olarak dayanıklı olmalı, düşük su buharı ve oksijen geçirgenliğine sahip olmalı, gıda ile temasına uygun olmalı, kimyasal kimyasal tepkime vermeye yatkın olmamalı, şeffaflık ve ürünün görünümünü koruyacak yapıda olmalı. Su ürünleri paketlemesinde yaygın olarak kullanılan ambalaj materyalleri; Poliamid (PA), Polietilen (PE), polipropilen (PP) ve çok katmanlı kompozit filmlerdir (Robertson, 2013).

2.7. Kontaminasyonun Önlenmesi ve Hijyen

Paketleme yapılırken hijyen zincirinin sağlanması önemlidir. Paketleme esnasında hijyen koşullarının yetersiz olması, çapraz kontaminasyon riskini artırır ve ürünün güvenliği tehlikeye atılır. Bu yüzden paketleme ilkeleri kapsamında; personel hijyenine dikkat edilmeli, ekipman ve yüzeylerin düzenli aralıklarla dezenfekte edilmelidir (FAO, 2022).

2.8. Su Ürünlerinde Paketlemenin Amaçları

Su ürünlerinde paketleme işleminin temel olarak; mikrobiyal gelişimi yavaşlatmak, oksidatif bozulmayı ve lipid oksidasyonunu önlemek, fiziksel hasarları engellemek ,duyusal özellikleri (tat, koku, doku) korumak, raf ömrünü uzatmak tüketiciye hijyenik ve güvenilir ürün sunmak gibi amaçları vardır (Özogul & Özogul, 2006).

2.9. Paketleme Metotları Bakımından Bozulma Mekanizmalarının Önemi

Su ürünlerinde meydana gelen bozulma mekanizmalarının iyi bilinmesi, uygun paketleme yöntemlerinin seçimi bakımından temel oluşturmakta ve oksijenin varlığının yağların oksidasyonu ile aerobik mikrobiyal gelişimi üzerindeki etkisinin azaltılması için uygun olan tekniğin modifiye atmosfer yada vakum paketlemenin olması gerektiğini ortaya koyar. Aynı zamanda, nem kaybı ve fiziksel hasarların önlenebilmesi için uygun ambalaj materyallerinin seçilmesi gereklidir (Robertson, 2013). En etkili sonuçları elde etmek için, uygun paketleme metodunun yanı sıra soğuk muhafazayla hijyen uygulamaları ve ürünün kimyasal özellikleride dikkate alınarak bir bütün şekilde düşünülerek elde ambalaj materyali seçilmeli, ayrıca raf ömrünün de uzatılabilmesi ile ürün kalitesinin korunabilmesi bakımından büyük önem arz etmektedir (Huss, 1995).

3. SU ÜRÜNLERİ İÇİN KULLANILAN AMBALAJ MATERYALLERİ

Su ürünleri için kullanılan ambalajlama materyallerinin uygulanmasının etkinliği, kullanılan ambalaj materyallerinin özelliğine bağlı olarak değişim göstermektedir. Ambalajlama materyali, ürünü kimyasal, biyolojik ve fiziksel etmenlerden korumasının yanı sıra, paketleme yönteminin etkinliğini de direk etkileyebilmektedir. Bu yüzden su ürünleri için ambalaj materyalinin seçimi, ürünün türü, yağ içeriği, işleme yöntemi ve beklene raf ömrü de dikkate alınarak tercih edilmelidir (Üçüncü, 2011; Robertson, 2013).

3.1. Plastik Ambalaj Materyalleri

Günümüzde su ürünlerinde en çok kullanılan ambalaj materyalleri arasında olan plastik esaslı malzemelerdir. Bunun temel sebebi, plastiklerin ekonomik, hafif, kolay şekillendirilebilir ve farklı bariyer özelliklerine sahip olması nedeniyle tercih edilmektedir (Robertson, 2013).

3.1.1. Polietilen (PE): Su ürünlerinde paketlemede yaygın olarak kullanılan bir termo-plastiktir. Düşük yoğunluklu polietilen (LDPE) ile yüksek yoğunluklu polietilen (HDPE) türleri mevcuttur. **Avantajları;** Kolay işlenebilir, iyi bir nem bariyeri, ekonomiktir. **Dezavantajları;** Oksijen bariyerinin düşüktür ve yağlı balıklarda oksidatif bozulmaya karşı sınırlı koruma sağlar. Bu yüzden PE genellikle kısa süreli depolama için daha uygundur (Connell, 1995).

3.1.2. Polipropilen (PP): Polipropilen, polietilene oranla daha yüksek mekanik dayanıklılığa sahip olan ve sıcaklık direnci olan bir ambalaj materyalidir. Su ürünlerinde özellikle tepsi ve kap formunda yaygın olarak kullanılmaktadırlar. İyi kimyasal direnç gösterirler, orta düzeyde nem bariyeri sağlar, düşük yoğunluğa sahiptirler. Fakat PP'nin oksijen geçirgenliği, MAP ve vakum paketleme uygulamasında tek başına yeterli olmamaktadır (Robertson, 2013).

3.1.3. Poliamid (PA – Naylon): Poliamid, su ürünlerinde vakum ve modifiye atmosfer paketleme için tercih edilir. **Avantajları;** Yüksek mekanik dayanıklılığa sahiptir, düşük oksijen geçirgenliği vardır ve delinmeye karşı direnç gösterir. **Dezavantajları;** Nem bariyeri zayıftır, maliyeti PP ve PE'ne göre yüksektir. Bu yüzden PA genelde çok katmanlı ambalaj yapılarında kullanılması daha uygun görülmektedir (Özogul et al., 2004).

3.2. Çok Katmanlı Ambalaj Materyalleri (Kompozit)

Su ürünlerinde tek bir ambalaj materyali, tüm gereksinimleri karşılamadığı için genellikle çok katmanlı olan ambalaj materyalleri daha çok tercih edilmektedir. Bu nedenle çok katmanlı (lamine) ambalajlar yaygın olarak kullanılmaktadır. Bu yapılar sayesinde, oksijen ve nem bariyeri artırılır, vakum ve MAP uygulamalarına uygunluk elde edilmektedir. Örnek yapı: PET/PE, PA/PE, PA/EVOH/PE (Robertson, 2013).

3.3. Etilen-Vinil Alkol (EVOH) ve Bariyer Polimerler

Etilen-vinil alkol (EVOH), çok yüksek oksijen bariyerİ özelliği olan bir polimerdir. Su ürünlerinde özellikle yağlı balıklarda ambalajlanmada tercih edilmektedir. **Avantajları;** Çok düşük oksijen geçirgenliğine sahiptir ve lipid oksidasyonunu önemli ölçüde azaltır. **Dezavantajları;** Neme karşı hassastır, tek başına değil kompozit yapı halinde kullanılması gerekliliği. EVOH içeren materyaller, uzun raf ömrü sağlayan MAP ve vakum paketli ürünlerde yaygın bir şekilde kullanılmaktadır (Ghaly et al., 2010).

3.4. Kağıt ve Karton Ambalajlar

Kağıt ve karton ambalaj materyalleri, su ürünlerinde doğrudan temas eden birincil ambalaj olarak sınırlı kullanıma sahip oldukları için ikincil ambalaj olarak kullanım alanı bulmaktadır. Bunun sebebi, yağ ve nem bariyerinin zayıf olmasıdır (Connell, 1995). Ancak, İkincil ambalaj olarak, dondurulmuş ürünlerde dış ambalaj olarak ve kaplamalı (parafin, plastik film kaplı) formlarda kullanılmaktadır.

3.5. Metal Ambalajlar

Metal ambalajlar genellikle su ürünlerinde konserve ürünlerde yaygın kullanım alanı bulmaktadır. Teneke ve alüminyum kutular, yüksek mekanik dayanıklılığa ve tam bariyer özelliği olan bir ambalaj materyalidir. **Avantajları;** Işık, oksijen ve neme karşı tam bariyer oluşturur, uzun raf ömrü sağlar, ısıl işleme dayanıklıdır. **Dezavantajları;** Ağırlık, yüksek maliyet ve Korozyon riski bulunur. Metal ambalajlar genellikle sterilize edilen ürünlerde tercih edilmektedir (Huss, 1995).

3.6. Cam Ambalajlar

Su ürünlerinde en çok yarı konservelerin yapımında ve işlenmiş ürünlerin saklanmasında kullanılmaktadır. **Avantajları;** Nem ve gaz geçirgenliği yoktur. **Dezavantajları;** Taşıma zorlukları, kırılganlık, ağırlık. Bu yüzden taze su ürünlerinde için kullanımı sınırlıdır (Robertson, 2013).

3.7. Biyobozunur, Yenilikçi ve Yenilebilir Ambalaj Materyalleri

Son zamanlarda çevresel kaygılardan dolayı biyobozunur ambalaj materyalleri olan ilgi artmıştır. Nişasta bazlı olan filmler, kitosan ve protein esaslı yenilebilir filmler, su ürünleri paketlemesinde uygulama alanı bulmaya yönlendirmektedir (Kerry et al., 2006). Bu materyaller, özellikle aktif paketleme uygulamaları ile birlikte kullanılır.

3.8. Ambalaj Materyali Tercihinin Raf Ömrüne Etkisi

Ambalaj materyalinin uygun olarak seçilmesi; oksidatif bozulmaya, mikrobiyal gelişimi engelleyememesine ve fiziksel hasar riskini artırmasına sebep olur. Uygun materyal seçimi ise paketleme yönteminin etkinliğini artırarak raf ömrünün uzatılmasına katkı sağlamaktadır (Özogul et al., 2004).

4. SU ÜRÜNLERİNDE VAKUM PAKETLEME

Vakum paketleme, su ürünlerinde ürünün uygun bir ambalaj materyali seçilerek, içerisine yerleştirilmesi ve ardından ambalaj içerisindeki havanın mekanik yada otomatik sistemlerle uzaklaştırılması sonucu ambalajın sızdırmaz şekilde kapatılması esasına dayanan bir ambalajlama sistemidir. Bu işlem sonucu, ambalaj içindeki oksijen oranı %0,5'in altına düşebilmektedir (Üçüncü, 2011; Robertson, 2013). Vakum paketleme ile oksijen ortamdan uzaklaştırılır ve bu sayesinde aerobik mikroorganizmaların gelişimini önemli ölçüde sınırlandırılır (özellikle *Pseudomonas spp.*). Fakat vakum paketleme ile anaerobik ve fakültatif anaerobik mikroorganizmaların gelişimi tamamen engellenememektedir (*Shewanella putrefaciens* ve *Clostridium botulinum* gibi mikroorganizmalar). Bu yüzden vakum paketli su ürünlerinde soğuk muhafaza koşullarının sağlanması gerekmektedir (Huss, 1995; Gram & Dalgaard, 2002).

Vakum paketleme de oksijenin azaltılması ile yağlardaki oksidasyonu önemli ölçüde yavaşlatmaktadır. Özellikle yağlı balıklarda görülen acılaşma vakum paketleme ile geciktirilmektedir (Ghaly et al., 2010). Vakum paketleme ile su ürünlerinin renk, tat ve doku özelliklerinin korunmasında genel olarak olumlu etkilere sahiptir (Özogul et al., 2004). Bu amaçla en yaygın kullanılan materyaller şunlardır: Poliamid (PA) / Polietilen (PE) kompozit filmler, PA/EVOH/PE çok katmanlı yapılar, PET/PE lamine filmler (Robertson, 2013). Yapılan araştırmalar sonucunda, vakum paketleme uygulanan su ürünlerinin raf ömrünü geleneksel paketlemeye kıyasla 2–3 kat artırabildiğini göstermektedir (Özogul et al., 2004). Vakum paketlemenin su ürünleri sektöründe hangi ürünler için daha uygun olduğundan bahsedecek olursak, tütsülenmiş balıklar, taze balık filetoları, marine edilmiş su ürünleri, Dondurulmuş balık ürünleri gibi alanlarda kullanıma uygundur. (FAO, 2022).

5. SU ÜRÜNLERİNDE MODİFİYE ATMOSFER PAKETLEME (MAP)

MAP, ambalaj içerisindeki gaz bileşiminin ürünün bozulma mekanizmasını yavaşlatacak şekilde değiştirilmesi esasına dayanan bir sistemdir. İlk olarak et ve et ürünlerinde uygulanan modifiye atmosfer paketleme, 1980'li yıllardan sonra su ürünlerinde yaygın olarak kullanılmaya başlanmıştır. Su ürünlerinde modifiye atmosfer paketleme kullanımının temel nedenleri arasında, taze ürünlere olan tüketici talebinin artması, kimyasal koruyucu kullanımı azaltılmasını sağlamak ve raf ömrünün soğuk muhafaza ile birlikte uzatılabilmesi yer almaktadır (Ghaly et al., 2010; Üçüncü, 2011; Robertson, 2013). Aktif paketleme sistemleri su ürünlerinde mikroorganizma gelişimini doğrudan yada dolaylı olarak engellemektedir. Antimikrobiyal ajanlar ile gaz düzenleyiciler yardımıyla toplam bakteri yükünün artışında azalma meydana getirmektedir. Oksijen tutucular ve antioksidanlar, yağların oksidasyonunu yavaşlatır ve ürünün tat, koku özelliklerini koruma sağlamaktadır. Ayrıca nem düzenleyiciler ile ürünün görünümü iyileştirmekte, tüketici kabulünü artırmaktadır (Özogul et al., 2004; Robertson, 2013).

5.1. MAP Sistemlerinde Kullanılan Gazlar ve Özellikleri

Su ürünlerinde en çok kullanılan gazlar karbondioksit (CO_2), oksijen (O_2) ve azot (N_2)'dur.

- **Karbondioksit (CO_2);** MAP sistemlerinde mikrobiyal gelişimi baskılayıcı etkisi olan bir gazdır. Mikroorganizmaların hücre zarını etkiler ve çoğalmayı yavaşlatır. Özellikle *Pseudomonas spp.* ve *Shewanella putrefaciens* gibi bakteriler üzerinde etkilidir (Özogul et al., 2004).
- **Azot (N_2);** Azot, inert bir gaz olup kimyasal olarak ürünlerle reaksiyona girmez. Oksijenin yerini alır ve oksidatif bozulmayı önler ve ambalajın çökmesini engeller, CO_2'nin ambalaj içinde çözünmesi sonucu oluşabilecek hacim kaybını dengeler (Robertson, 2013).
- **Oksijen (O_2);** Su ürünlerinde MAP uygulamalarında oksijen genellikle sınırlı düzeyde kullanılması gerekmektedir. Çünkü bazı türlerde renk korunmasını sağlar (Huss, 1995).

MAP Gaz Kombinasyonları ve Uygulama Oranları aşağıdaki şekilde olmalıdır: %30–60 CO_2 / %40–70 N_2, %40 CO_2 / %60 N_2, %30 CO_2 / %70 N_2 (Özogul et al., 2004). Araştırmalar sonucunda, MAP uygulamalarının su ürünlerinde raf ömrünü geleneksel paketlemeye göre 2–4 kat uzatabilmektedir (Ghaly et al., 2010).

6. SU ÜRÜNLERİNDE AKTİF PAKETLEME

Aktif paketleme, ambalaj materyaline ve ambalajın içerisine yerleştirilen aktif bileşenler vasıtasıyla, ambalaj içi koşulların kontrol edilmesi esasına dayanan bir sistemdir. Bu aktif bileşenler; nem, oksijen yada karbondioksit gibi gazları absorbe edebilmekte, antimikrobiyal ve antioksidan maddeler salarak ürün kalitesini korumayı sağlayan bir sistemdir. Su ürünlerinde aktif paketlemenin esası, oksidatif bozulmayı azaltmak, mikrobiyal gelişimi sınırlandırmak ve duyusal özelliklerini daha uzun süre korunmasını sağlamaktır (Kerry et al., 2006; Üçüncü, 2011). Su ürünlerinde kullanılan aktif paketleme sistemleri, farklı gruplar altında incelenmektedir.

6.1. Oksijen Tutucular

Oksijen tutucular ile ambalaj içerisindeki serbest oksijen absorbe edilerek oksidatif bozulma ve aerobik mikroorganizma gelişimi yavaşlar. Genellikle demir bazlı bileşikler ile askorbik asit veya enzim sistemleri içeren oksijen tutucular tercih edilmektedir (Robertson, 2013). Su ürünlerinde oksijen tutucular: Vakum veya MAP ile kombine olarak ve yağlı balık ürünlerinde yaygın olarak tercih edilmektedir.

6.2. Karbondioksit Yayıcılar ve Tutucular

CO_2 yayıcı sistemlerde ambalaj içerisinde kontrollü miktarda karbondioksit salınarak mikrobiyal gelişimi baskılanır. CO_2 tutucular ise yüksek CO_2 seviyelerinin neden olabileceği ambalaj çökmesi ve doku yumuşamasını önlemek amacıyla kullanılır. Bu sistemler, özellikle MAP de ambalaj içi gaz dengesini korunma amaçlı katkı sağlamaktadır (Özogul et al., 2004).

6.3. Nem Düzenleyiciler

Su ürünlerinde yüksek oranda serbest su ve nem, mikrobiyal gelişim açısından hızlandırıcı bir etkisi olan önemli faktördür. Nem düzenleyiciler genellikle ambalaj içerisinde biriken sıvıyı absorbe eder ve damlama kaybını azaltır, görsel kaliteyi artırır, mikrobiyal gelişimi sınırlandırır. Bu sistemler genellikle yastık yada ped formunda ambalaj içerisine yerleştirilmektedir (Connell, 1995).

6.4. Antimikrobiyal Aktif Paketleme

Ambalaj materyalinden kontrollü bir şekilde salınan yada ambalaj yüzeyine verilen antimikrobiyal ajanlar aracılığıyla mikroorganizma gelişimini engellenir. Doğal Antimikrobiyal Maddeler den bahsedecek olursak; Bitkisel ekstraktlar, organik asitler, kitosan, esansiyel yağlar yer almaktadır. Bu maddeler, kimyasal koruyuculara alternatif olarak tüketici tarafından daha kabul görmektedir (Kerry et al., 2006).

6.5. Sentetik Antimikrobiyal Maddeler

Aktif paketleme sistemlerinde sorbatlar, benzoatlar ve gümüş iyonları gibi sentetik antimikrobiyal maddeler kullanılabilmektedir. Fakat bu maddelerin kullanımı, yasal düzenlemeler ve gıda güvenliği açısından dikkatlice kontrol edilmelidir (FAO, 2022).

6.6. Antioksidan İçeren Aktif Paketleme Sistemleri

Aktif paketleme sistemlerinde, serbest radikalleri bağlayarak oksidatif bozulmayı yavaşlatmak için, bu amaçla, Askorbik asit, tokoferoller ve bitkisel fenolik bileşikler ambalaj materyaline entegre edilebilmek suretiyle kullanılmaktadır (Ghaly et al., 2010).

7. SU ÜRÜNLERİNDE AKILLI PAKETLEME SİSTEMLERİ

Akıllı paketleme, ambalajın çevresel değişiklikleri yada ürün durumunu algılayıp bu bilgiyi dijital, görsel veya kimyasal göstergeler yardımıyla kullanıcıya ileten sistemleri kapsar. Temel olarak üç ana işlevi bulunur: Tazelik göstergesi (Freshness indicators), Sıcaklık göstergesi (Time–Temperature Indicators, TTI), Gaz sensörleri ve koku algılayıcılardır. Su ürünleri, bu sayede depolama esnasında kalite kaybını erken tespit etmeyi ve tüketiciye güvenli ürün sunmayı mümkün kılan bir sistemdir (Üçüncü, 2011; Robertson, 2013).

8. SONUÇ

Su ürünleri alanında paketleme ile yalnızca ürünün fiziksel korunmasını sağlamak amacıyla yapılmaz, aynı zamanda güvenlik, kalite ve tazeliğin yönetilmesi içinde önemli katkı sağlar ve genel olarak su ürünlerinde:

- Geleneksel paketleme ile düşük maliyetli ve kısa süreli uygulamalar için,
- Vakum paketleme, aerobik bozulmayı sınırlandırmak ve raf ömrünü orta düzeyde arttırmak için,
- MAP, raf ömrü ve kaliteyi uzun süre korumak ve yüksek değerli su ürünleri için,
- Aktif paketleme, oksidatif bozulmayı engelleme ve mikroorganizma kontrolü için,
- Akıllı paketleme ise güvenlik ve kalite takibini kolaylaştırmak için kullanılır

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TÜRKİYE VE DÜNYADA

SU ÜRÜNLERİ

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