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CONTENTS

Chapter 1

THE USE OF FISH PARASITES AS BIOINDICATORS OF HEAVY METAL POLLUTION IN AQUATIC ECOSYSTEM: A REVIEW

Özgür CANPOLAT[1]

1 Prof. Dr.

Introduction

While the European Economic Council classifies chemicals as green and black lists according to their hazard priority, the United States Environmental Protection Agency (U.S.EPA) has listed 129 pollutants that are considered to be most dangerous for living beings and ecosystems. This list includes both organic chemicals and heavy metals (HMs) (such as mercury, cadmium, silver, lead, copper, and zinc). Due to their physicochemical properties, most organic chemicals are abundant and persistent in the ecosystem. Metals, on the other hand, cause problems in the environment due to industrial and domestic use (Sofyan, 2004).

The environment is under great stress due to natural and anthropogenic pollution and regular monitoring of the environment is essential. In addition to water and air pollution, HM pollution has become a great risk for all organisms, including humans (Sures et al., 2017). HM pollution in the environment is caused by natural events (geological events and volcanic eruptions) and anthropogenic sources (amplified urbanization, domestic waste, agricultural activities, industrial waste, mining, etc.), (Fig. 1), (Aladaileh et al., 2020; Chandrasekhar et al., 2022). The most dangerous effect of HMs is that they enter the food chain and accumulate in all flora and fauna throughout the entire food chain, including fish and their parasites (Kawade, 2020). The biological accumulation of some pollutant sources (mining and industrial activities) that cause HM pollution in aquatic ecosystems and their effects on the aquatic food chain are illustrated in Fig. 2.

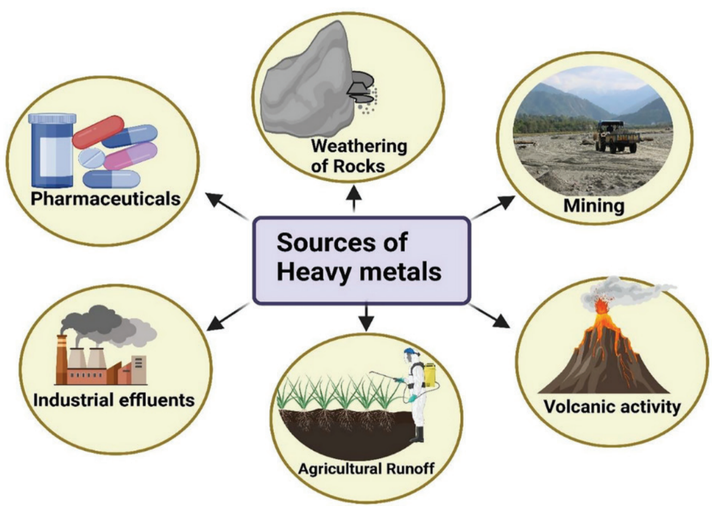

Figure 1. *Impact of HMs on aquatic ecology and biodiversity (Sharma et al., 2024)*

In this review, general information is given about the use of fish parasites as BIs of HM pollution in aquatic ecosystems.

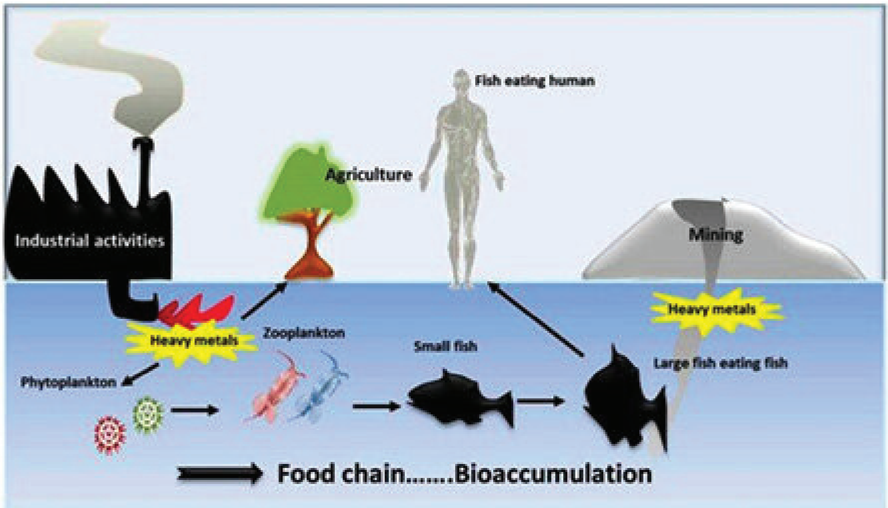

Figure 2. *The bioaccumulation of HMs due to mining and industrial activities, and its effect on the aquatic food chain (Mehana et al., 2020)*

What is Biomonitor and Bioindicator?

Both new global problems such as global climate change and the greenhouse effect and increased awareness of the complexity of ecosystems have led to the need for additional information on biological systems in environmental policies. In general, the majority of biomonitoring studies that started in the 1960s were related to chemical and physical parameters (Oertel and Salanki, 2003). The use of biological responses to assess environmental changes resulting from anthropogenic causes is called biological monitoring or biomonitoring (Rosenberg, 1998; Gerhardt, 1999). Biomonitoring programs can be qualitative, quantitative, or semi-quantitative (Oertel and Salanki, 2003).

Markert et al., (1999) define the word biomonitoring as "a method of observing the impact of external factors on ecosystems and their development over a period, or of ascertaining differences between one location and another."

Biomonitoring is a method of observing the The importance of aquatic biological monitoring is given below;

(a) to provide reliable and accurate information about the possible effects of chemicals found in water due to human activities,

(b) to ensure the protection of aquatic ecosystems,

(c) especially to provide scientific guidance for legislation and applications (Oertel and Salanki, 2003).

Biomonitoring is the use of bioindicators (BIs), that is, aquatic organisms, to determine the level of human impact on the ecological balance of aquatic ecosystems (Edegbene et al., 2020; Keke et al., 2020). HM biomonitors must meet certain specifications. The use of a suite of biomonitors allows the presence and relative magnitude of different metal sources to be recognized.

Some aquatic organisms are sensitive indicators of environmental changes and are widely used in the development of environmental regulations and the evaluation of dangerous developments in freshwater and marine ecosystems (Yan and Pan, 2002). Therefore, BIs can be used to monitor the uptake, excretion and bioavailability of HMs and to determine toxic effects. Since they are in direct contact with the aquatic environment, they can take in pollutants from the aquatic environment and accumulate them in their bodies, thus providing information about the pollution level of the environment (Kurt, 2000).

The importance of BIs is briefly explained below;

1. It can detect interactions between the chemicals that the organism is exposed to and enable the measurement of these effects sublethal level.

2. Chemical analysis methods can only be used to measure a certain number of contaminants; however, they do not provide information about the adverse effects of contaminants. However, BIs can provide information about the adverse effects of contaminants.

3. With BIs, it is possible to show the presence of both known and unknown contaminants.

4. Early diagnosis of effects sublethal levels is seen as a warning and helps to correct the situation or take protective measures.

5. With the help of BIs, biological detection of pollution can be done regionally or in the short term.

6. They provide information about the duration of exposure to environmental pollutants and the risks that may occur.

7. They can show the changes that occur in the ecosystem depending on the severity of pollution,

8. They are used as a guide, and can enable the development of biological correction strategies before ecological consequences due to irreversible environmental damage occur.

9. BIs can reveal the cumulative effects of many HMs resulting from toxicological interactions at a specific organ, tissue or molecular level.

10. It is suitable for both laboratory and field studies (Sarkar et al., 2006).

Today, developments in the field of biotechnology have increased the number of studies on the use of living organisms in solving problems and in the production of useful products. Accordingly, a new horizon has been opened for more effective steps to be taken in solving current global problems (Najm and Fakhar, 2015).

The use of living organisms as indicators to quantify environmental conditions, including environmental HM pollution, is called BI. BIs are divided into two groups: either effect indicators (they reflect changes in physiology, molecules, functions or organism numbers) or accumulation indicators (they can effectively accumulate substances with the ability to accumulate at concentrations significantly higher than those in the environment without producing harmful consequences), (Sures, 2003;Tellez and Merchant, 2015; Keke et al., 2020).

Accurate information on the stability of the ecosystem can be provided by BIs such as algae, microbial organisms and aquatic plants, including fish and their parasites (Vidal-Martínez, 2007). There are some difficulties in the use of free-living biota in water as BIs. These difficulties are characterized by several limitations, such as:

(1) Sampling processes are complex and costly;

(2) A large number of samples are required to obtain a reliable result;

(3) The composition of organisms changes depending on the seasons and time;

(4) The high inconsistency in the interpretation of the data obtained due to the use of complex analytical tools and methods (Wright, 2010; Vidal-Martínez and Wunderlich, 2017).

Fish Parasites As Bioindicator of Heavy Metal Pollution

Fish, which are at the top of the food chain in aquatic ecosystems and have a relatively long life span, contain a lot of pollutants. For this reason, fish are often used as BIs ((Rashed, 2001; Osama et al., 2023). Since the first studies on the effects of parasites on the tolerance of fish to environmental toxicants (Boyce and Yamada, 1977; Pascoe and Cram, 1977), several studies on the accumulation of parasitism and contaminants have been published (Osama et al., 2023).

Parasites are an important part of aquatic ecosystems, representing a significant portion of aquatic biomass. In the last two decades, the relationship between environmental pollution and parasitism among aquatic organisms, as well as the potential role of endoparasites as water quality indicators, has received increased attention (Sures, 2003, 2004; Nhi et al., 2013).

Parasite ecologists have begun to focus more on the study of parasites as potential indicators of environmental quality because of their responses to anthropogenic pollution. Some organisms provide valuable information about the chemical state of their environment in environmental impact studies not only by their presence or absence but also by their ability to concentrate environmental toxins in their tissues (Sures, 2003; Arimoro and Keke, 2017; Keke et al., 2020; Retief et al., 2006).

Some parasites, particularly intestinal Acanthocephalans and fish Cestodes, have the ability to accumulate HMs in concentrations much higher than those found in host tissues (liver, kidneys, gills, and muscles), ((life cycle of Acanthocephalan is illustrated in Fig. 3) or the environment (Sures et al., 1994; Turcekova and Hanzelova, 1997; Sures et al., 1999, 2001; Tenora et al., 2000; Sures, 2003, 2004; Barus et al., 2007; Jirsa et al., 2008; Nachev et al., 2010; Jankovska et al., 2011, 2012; Shahat et al., 2011; Brazova et al., 2012; Paller et al., 2016; Filipovic Marijic et al., 2013, 2014; Brazova et al., 2015; Paller et al., 2016; Nachev and Sures, 2016; Adewole et al., 2019; Mehana et al., 2020). The bio-filtration of HMs by intestinal parasites in fish is shown in Fig. 4.

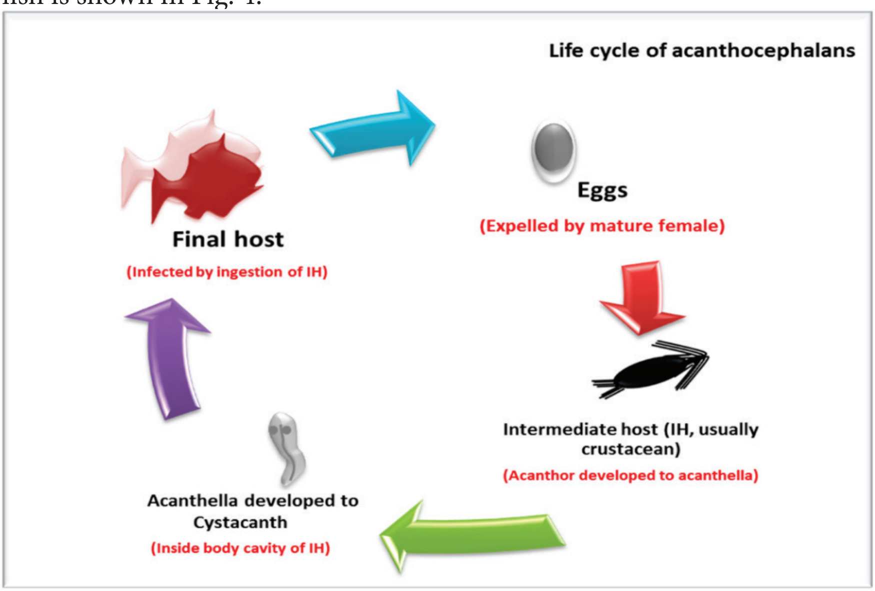

Figure 3. *Life cycle of Acanthocephalan (Mehana et al., 2020)*

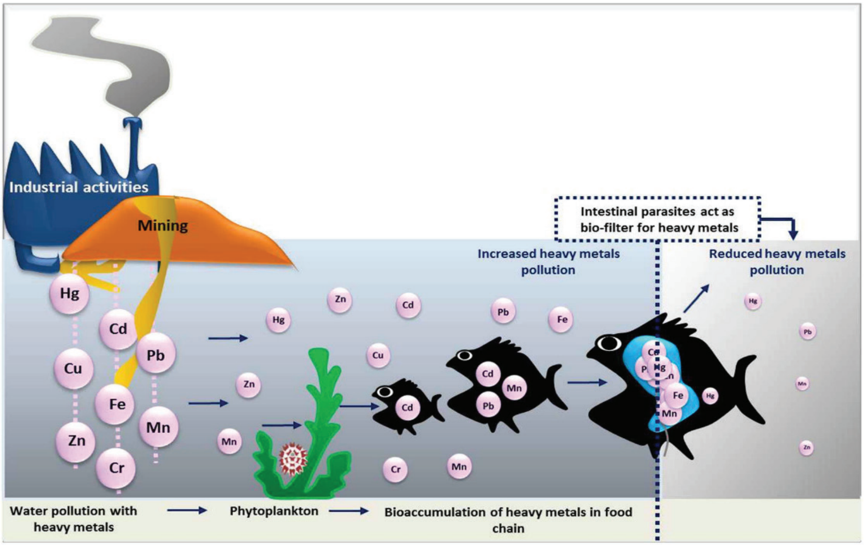

Figure 4. *Intestinal parasites in fish act as biofilters for HMs (Mehana et al., 2020)*

Researchers have used the terms "Sink" and "Sentinel" to describe fish parasites used in biomonitoring studies; Beeby (2001), defined "sentinel species" as biological monitors that accumulate contaminants in their tissues without suffering any serious consequences. Sentinel species are primarily used to measure the amount of a bioaccessible contaminant. In addition, they can increase the sensitivity of an analytical method and provide an indication of the presence of complex contamination (Osama et al., 2023). The European Environment Agency (2022) has defined the word Sink as a means of removing a chemical or gas from the atmosphere, ecosystems and oceans by absorbing the substance into a permanent or semi-permanent repository or converting it into another substance. The term "sink" was first used by Sures and Siddall (1999) to describe the Acanthocephalan species *Pomphorhynchus laevis*, which experimentally infects the grey mullet *Leuciscus cephalus* exposed to aqueous lead.

Laboratory and field studies have shown that fish with parasites have lower concentrations of HMs in their tissues than fish without parasites (Leite et al., 2021). Various fish endoparasites have been reported to be used as pollution sentinels in aquatic ecosystems, investigated the accumulation of HMs in Nematoda as well as Cestoda and Acanthocephala. The result of the study found that Nematodes have good capacity to accumulate HMs but less than Cestoda and Acanthocephala (Akinsanya and Kuton, 2016).

Research on fish parasites is of particular interest not only for fish health but also for understanding ecological problems. Although the majority of parasitological articles have addressed parasites as a threat to fish health (e.g. Roberts, 1989; Schaperclaus, 1990), a large number of articles have been published since the 1980s addressing the relationship between water pollution and parasites in the aquatic environment (Khan and Thulin, 1991; Poulin, 1992; Vethaak and Rheinallt, 1992; Overstreet, 1993; MacKenzie et al., 1995; Lafferty, 1997; Kennedy, 1997; Sures et al., 1997; Sures et al., 1999).

Helminth parasites found in fish, such as Trematodes, Nematodes, Cestodes and Acanthocephalans, are important BI species used in HM pollution in aquatic ecosystems (George-Nascimento, 1987; Bush et al., 2001; Sures, 2003; Biswal and Chatterjee, 2020). The uptake, transport, and excretion of HMs in fish and the route of HM uptake through the intestinal parasite such as acanthocephalans are illustrated in Fig. 5.

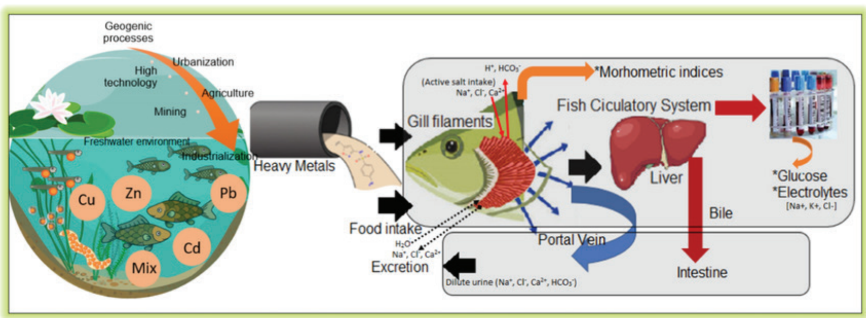

Figure 5. *The uptake, transport and excretion of HMs in fish, and the route of HM uptake through the intestinal parasite such as Acanthocephalans (Yeşilbudak, 2024)*

Conclusion

Because of their wide abundance and distribution, many researchers have begun to focus on the use of parasites as indicators of environmental quality. Parasites are also receiving increasing attention as environmental indicators because of the diversity of ways they respond to anthropogenic pollution.

Various parasite species (such as Cestodes and Acanthocephala) found in the gut of fish are widely used as BIs to detect the quality of aquatic ecosystem due to their higher response to different types of anthropogenic pollutants in water. As reported in many studies on fish parasites in aquatic ecosystems, fish parasites can accumulate HMs in much higher concentrations than their host tissues. Therefore, fish parasites can potentially provide useful information about the chemical status of the habitat they live in.

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Chapter 2

USE OF FUZZY LOGIC IN WATER QUALITY CLASSIFICATION

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Introduction

Water pollution, one of the most critical issues among environmental problems, causes significant problems in both artificial and natural aquatic environments created by humans. Moreover, the quality of surface waters is generally negatively affected by industrial centres and population growth (Buckley et al., 1995; Tessier & Campbell, 1987). Environmental management tools can be used as a control mechanism in water resources close to regions with intense industry and industrialisation. Environmental management tools evaluate the information and data obtained and ensure that the results are conveyed to the public, managers, decision-making mechanisms and the business world (Erdmenger, 1998; Storksdieck & Otto-Zimmermann, 1994). Although ecological risk assessment is not the ultimate solution (Bartell, 1997), it is one of the most significant environmental management approaches that can be applied to different ecosystems (Serveiss 2002, Wenger et al., 2000). Despite the fact that there are opposing views on the reliability of risk assessment estimates (Power & Adams, 1997), most studies in this field agree that ecological risk assessment is a valuable tool (Adams & Power, 1997). It is defined as a process required for developing decisions regarding environmental management and collecting, organising and presenting scientific information (Serveiss, 2002).

Although many classical methods are used today as ecological risk assessment tools, the application of engineering models in terms of risk assessment in water resources is relatively new.

All numerical and verbal information that can be obtained in engineering approaches is included in the solution algorithm, and meaningful solutions are reached under the control of the examined event. In recent years, artificial intelligence techniques have been developed to convert people's verbal information into digital form, be perceived by computers and algorithms, and make calculations. Artificial intelligence techniques represent a solution algorithm that is independent of mathematical and axiomatic approaches (Şen, 2001). There are various definitions of artificial intelligence. Although there is no definition that all researchers agree on, artificial intelligence can be defined as "a branch of science that investigates human-specific intelligence behaviours and uses information processing methods such as data structures, algorithms, programming languages and technologies in the storage and processing of information" (Çetiner et al., 1998). There are many artificial intelligence techniques that scientists work on in the field of artificial intelligence, such as Robotics, Natural Interface Expert Systems, Genetic Algorithms, Fuzzy Logic and Artificial Neural Networks.

Quality assessment of polluted waters: It provides essential theoretical information for determining the effects of pollution elements in waters and the sustainability of limited water resources. Many pollution index methods are used in the assessment of water quality. These methods define precise limits that show the amount and difference of water pollution at different degrees. However, due to the instability of each water pollutant, there is an uncertainty related to risk in quality assessments. The presence of precise limits in uncertainty classification diagrams makes using these diagrams difficult. Due to this uncertainty, some environmental researchers have had to turn to work on advanced assessment methods based on fuzzy logic.

In studies up to the last 30 years, only the Aristotelian logic with two outputs was used (Kişi et al., 2003). According to Aristotelian logic, choosing only one of the outputs is necessary, black or white. However, it is possible to make different degrees of grey preferences in the human thought system in between. What will allow this is fuzzy logic and the systems that arise from it.

Fuzzy Logic Theory and Working Principle

Fuzzy logic is a reasoning method used to overcome the uncertainties of life. The basic idea underlying fuzzy logic is that many daily concepts are uncertain. For example, when the "the weather is hot" expression is used, everyone clearly understands the daily use of the word 'weather'. However, the meanings expressed by the word 'hot' may be relatively different from each other. While a person in the poles perceives hot as 15°C, a person near the equator may find it to be 35°C. In between, there are different degrees, according to many people's opinions. Thus, there is an uncertain situation due to the numerical understanding implied by people under the word 'hot'. In this way, the uncertainties implied by words are called fuzziness (Şen, 2001).

In this way, the use of fuzzy logic would be a more accurate approach in every area of human life where there is no certainty. Fuzzy logic differs from classical logic with this certainty phenomenon. In classical logic, classification involves certainty. An element is either in a set or outside. However, an element can be in more than one set in fuzzy logic.

When we look at Figure 1, according to the classical logic model, a person who is 1.60 m tall is not tall. In fact, a person who is 1.69 m tall is also in the short class. This is not a real approach. According to fuzzy logic, a person who is 1.60 m tall is not called short. Because he is partly in the tall people cluster. In fuzzy logic, a person who is 1.60 m tall can be tall with a membership degree of 0.6, a person who is 1.70 m tall with a membership degree of 0.7, and a person who is 1.80 m tall with a membership degree of 1.0 (Baba, 1995).

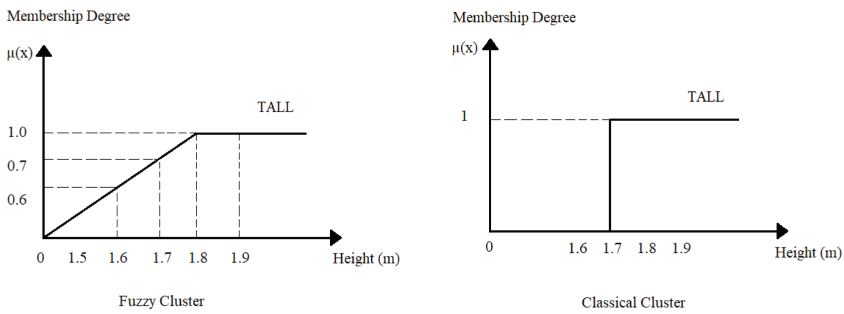

Figure 1. *Fuzzy Logic and Membership Degree (adapted from Baba, 1995)*

In fuzzy logic, the limit of inclusion is determined by the membership degree. In other words, while there is "true" or "false" in classical theory, there are degrees of truth in fuzzy logic. Figure 2 shows a triangular membership function that defines the young population and how much an observed individual belongs to this cluster or how young he is according to the fuzzy age value.

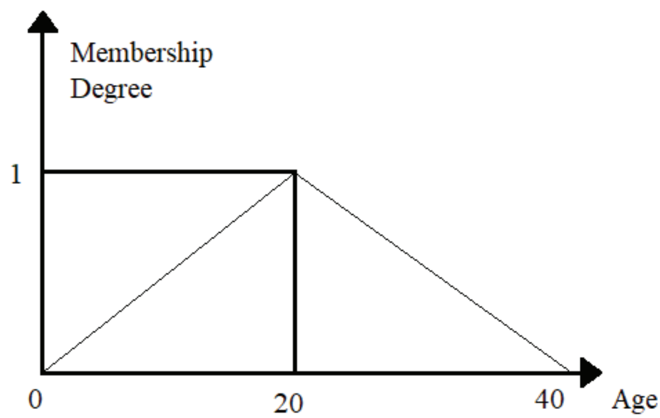

Figure 2. *Membership Function in Fuzzy Logic (adapted from Semiz & Genç, 2003).*

A 20-year-old individual is a member of this set of young people with probability 1. Individuals aged 10 or 30 fit the definition of young by 50%. As we move away from the age of 20, the definition of young becomes incorrect according to the definition here. Since fuzzy data must be defined with different membership functions due to its structure, there are many different membership functions, and the implementer himself can define a different fuzzy set function (Semiz & Genç, 2003).

When fuzzy logic is considered this way, it essentially includes classical logic.

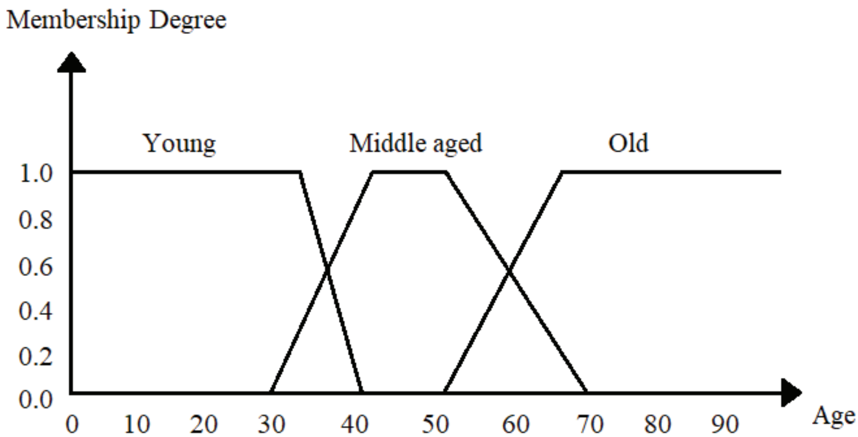

Figure 3. *Membership Functions That Show Ages of People in a Given Country (adapted from Şen, 2003)*

For example, when Figure 3 is examined, the ages of a country's old, middle aged and young populations are given. In this example, ages younger than 30 are entirely "young", ages between 40 and 50 are completely "middle aged", while age 36, for example, is partially included in both categories. In other words, the membership degree of the age of 36 to the "young" membership function is 0.4, the membership degree to the "middle aged" membership function is 0.6, and the membership degree to the "old" membership function is 0.0 (Şen, 2003).

If it were considered according to classical logic, an age would definitely have to be younger than 30 to be included in the young category. However, in fuzzy logic, ages younger than 30 belong to the "young" category with a membership degree of 1.0, while ages between 30 and 40 fall into the same category with membership degrees between 0.0 and 1.0. From here, it can be seen that fuzzy logic also includes classical logic.

The membership degrees of fuzzy variables can be determined using many different methods. Some of these methods are as follows: Heuristic, Inference, Arrangement of preferences, Angular fuzzy sets, Neural networks, Genetic algorithm-Artificial intelligence.

Fuzzy logic is composed of a fuzzy controller.

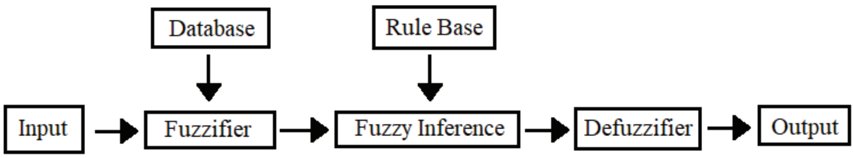

Figure 4. *Working Diagram of Fuzzy Logic (adapted from Şen, 2003)*

- **Input/Database**: Contains the input variables and all information about them to which the event to be examined is exposed. This is called the database or also simply the input.
- **Fuzzifier**: In this section, the control input information received from the system is converted into symbolic values (i.e., linguistic qualifiers).
- **Fuzzy Rule Base:** Contains all the rules, which can be written in the logical and IF-THEN type, which connect the inputs in the database to the output variables.
- Instead of telling the student driver to step on the gas 'this much' when the speed reaches 'this many' km/h, during training, rules such as 'IF the speed is low, step on the gas a lot' or 'IF the speed is high, step on the gas a little' are conveyed.
- **Defuzzification:** This is the unit where the fuzzy set outputs of the fuzzy inference engine are converted into real numbers by changing the scale.
- **Output:** It expresses the group of output values obtained from the interaction of information and fuzzy rule bases through fuzzy inference (Şen, 2003).
- **Fuzzy Inference Engine:** This mechanism includes a group of operations that bring together all the partial relationships established between the input and output fuzzy sets under the fuzzy rule base and ensure that the system behaves with a single output. This engine brings together the inferences of each rule and helps determine what kind of output the entire system will yield based on its inputs. Multiple inputs are processed by the rule base and inference engine and converted into a single output (Figure 5).

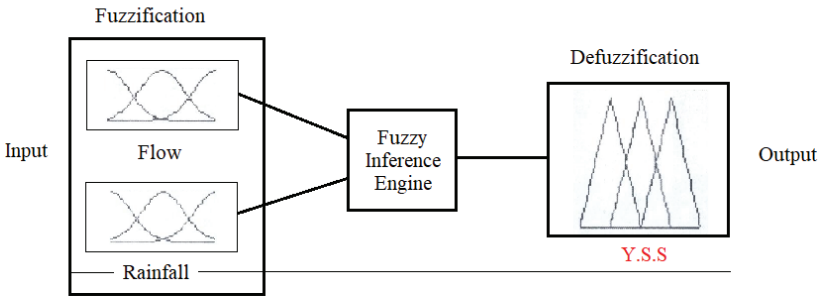

Figure 5. *Mamdani-type Fuzzy Model (Iheukwumere-Esotu & Yunusa-Kaltungo, 2021).*

Fuzzy Logic in Water Quality Evaluation

Although the use of fuzzy logic, which is among the artificial intelligence methods, is not very common in the field of water quality determination, it is becoming increasingly widespread (Chang & Chen, 2001; Xiong et al., 2001).

Observation of water quality does not have a significant value on its own. A pollution parameter with a certain value only gains meaning when there is information about the plan levels and regulations (Icaga, 2007). Conventional water quality regulations consist of quality classes defined by keen clusters and the boundaries between different classes have an internal vagueness (Silvert, 2000). Methods with upper and lower limits display two uncertainties. First, traditional water quality assessment methods use a discontinuous form. This classification technique can lead to an approximate and imprecise approach to the data since, when using this method, whether a parameter is close to or far from the limits will have equal significance in the concentration assessment. Second, each quality parameter can belong to one of four classes. Put differently, not all parameters can be found in a single class. The existence of several quality classes formed from a single sampling area can result in uncertainty in a given sampling area's quality definition (Icaga, 2007).

Fuzzy logic can be perceived as a language which allows the translation of complex statements of natural language into mathematical models (McNeil & Thro, 1994). Fuzzy logic can cope with unstable, uncertain, linguistic and highly variable data or information and thus possesses the capability to allow a transparent, reliable and logical flow of information from data gathering towards data use in environmental sciences (Adriaenssens et al., 2004).

Fuzzy logic can be implemented in the progress of environmental indexes by solving many common problems, such as inconsistency between observations and the necessity for precise value judgments. Fuzzy synthetic evaluation, that provides an alternative method that typically uses a numerical scale to define water quality and aggregates parameter values to a variety of quality attributes, has been used and studied in environmental quality assessments since the 1990s (Liou et al., 2003; Liou & Lo, 2005; Ludwig & Tulbure, 1996).

In this context, in a study aiming to establish a water quality index based on fuzzy logic with a river system, water quality parameters (DO, BOD, COD, pH, SS, NH_3-N, FWQ) taken from several rivers in Malaysia, India and Thailand were evaluated. As a result of the study comparing with the classical Water Quality Index (WQI), it was revealed that this water quality assessing index based on fuzzy logic yielded more reliable results or could determine the status of the river with 90% excellence. It was concluded that the new index would help decision makers in reporting the status of water quality and in investigating spatial and temporal changes in the river. Finally, it was suggested that fuzzy logic-based models could effectively determine many environmental policies (Raman et al., 2009).

In another research conducted in Sao Paulo to create a fuzzy-based water quality evaluation model, a fuzzy assessment model was attempted to be created based on nine water quality parameters used by CETESB (Companhia de Tecnologia de Saneamento Ambiental, São Paulo, Brazil) to assess water quality and this model was compared with the Water Quality Index (WQI). As a result, it was reported that the findings obtained using the fuzzy inference-based index were more practical compared to the classical assessment method currently employed by CETESB because it minimised the losses and/or deficiencies related to individual parameters (Roveda et al., 2010).

In another investigation, a more effective and efficient water quality index was attempted to be created based on water quality parameters (DO, TDS, turbidity, nitrate, faecal coliform and pH) obtained from the Karoon River in Iran (Semiromi et al., 2011). Therefore, a fuzzy-based model was attempted to be formed within the scope of the study. Six variables were used, and numerical scales related to the quality degree were created for each variable to evaluate the changes in different qualities and comprehensively convey the findings. The unit was operated in a fuzzy logic mode, which takes multiple input variables as its input and includes a fuzzification engine tailored to calculate membership function parameters. Finally, the development of the fuzzy model with a single river system was explained. While in most countries, the water quality index refers only to physicochemical parameters since great efforts are required to measure biological parameters, in the mentioned study, it was emphasised that fuzzy logic provides a better method to include special parameters in the water quality index due to its exceptional abilities in dealing with uncertain, nonlinear, and complex systems.

Sönmez et al. (2013) used a fuzzy logic evaluation method to classify the heavy metal pollution levels in the Karasu Stream in Erzurum, Türkiye. Monthly copper, zinc, manganese, lead, nickel, cadmium and iron measurements were made from 5 different localities on the river for 12 months. In the research, the fuzzy logic model was developed based on the classical classification method. According to their results, Sönmez et al. reported that using fuzzy logic has eliminated uncertainties and led to more sensitive assessments. Therefore, they concluded that the fuzzy logic method is a proper tool for evaluating water pollution status.

Atea et al. (2018) assessed the water quality of Germeçtepe Dam Lake (Kastamonu, Türkiye) by measuring 11 physicochemical parameters (i.e., BOD, COD, ammonia, phosphate, nitrite, nitrate, dissolved oxygen, conductivity, turbidity, pH and temperature) and classifying them with the help of a fuzzy logic system. They also compared the fuzzy logic-based system to a classical classification method. It was found that the fuzzy logic approach reached 90% success in the decision support system. Based on these findings, they have concluded that the fuzzy logic approach can be used in water quality assessment since it provides more accurate results.

In another research, an adaptive neuro-fuzzy inference system (ANFIS) was formed to predict cadmium levels in the Filyos River located in Türkiye (Sönmez et al., 2018). Monthly water samplings were performed from 7 stations on the river, and the cadmium concentrations were analysed. It was reported that a high correlation was detected between the observed and estimated Cd levels, indicating that the ANFIS model created was capable of yielding reliable estimates. It was stated to be accurate and robust. Thus, researchers have concluded that the ANFIS approach can be used in water quality assessment with high precision.

A study by Chanapathi and Thatikonda (2019) aimed to develop a Mamdani-type fuzzy-based regional water quality index (FRWQI) composed of 10 water quality criteria, including electrical conductivity, chemical oxygen demand, turbidity, alkalinity, suspended solids, nitrogen, pH, biological oxygen demand, faecal coliforms and dissolved oxygen. The surface quality of water was assessed by using various classifications from six different countries located in varying geographical origins. It was stated that, despite its various geographical origins, the model used was similar to water quality models employed in the United States, Malaysia, and India and could help globally in the self-assessment of regional water quality.

Jha et al. (2020) reported that the classical groundwater quality index (GQI) could not cope with the uncertainties in the evaluation of environmental problems in the groundwater quality assessment conducted in South India. To address this limitation, they proposed a new hybrid framework integrating Fuzzy Logic with GIS-based GQI to evaluate groundwater quality and spatial variance. As a result of the evaluation and comparison using ten distinct groundwater quality parameters assessed in pre-monsoon and post-monsoon seasons, they conveyed that the fuzzy logic-based decision-making approach is more credible and pragmatic for determining groundwater quality at a large scale. Based on this, it was reported that this fuzzy-based model could be helpful for water resource planners and decision-makers in effectively detecting and managing groundwater quality at the basin or catchment scale.

Another research conducted in Nigeria to compare the classical water quality index with a fuzzy-based water quality index reported that in the evaluation made on the BOD_5 parameter measured in twenty samples, WQI classified the waters of the entire study area as "poor", while Fuzzy Logic inference categorised 8.3% of the waters as "moderate". Based on this, since the fuzzy logic approach takes into account the measured values and surface water quality standards equally, whereas the classical water quality index only evaluates the latter, they concluded that Fuzzy Logic inference is superior and employable compared to classical methods (Oladipo et al., 2021).

In another study conducted in Morocco on groundwater quality assessment, a traditional Water Quality Index and a Fuzzy-based index were compared. Physio-chemical and bacteriological parameters (faecal coliforms, electrical conductivity, dissolved oxygen, ammonium, nitrate, nitrite, phosphate, suspended matter, five-day biochemical oxygen demand, chemical oxygen demand, turbidity, temperature and pH) obtained from nine different wells for two years were included in the model and compared. According to the results obtained, it was stated that the two classical and fuzzy-based quality assessment indices supported each other and that the fuzzy-based model they proposed could be used safely in water quality evaluation (Azzirgue et al., 2022).

In an investigation aimed at modelling WQI assessment using fuzzy logic, creating an artificial neural network model for WQI estimation and changing the Ukrainian method for assessing WQI by taking into account the level of adverse effects of hazardous chemical elements, a model was attempted to be created using four water quality parameters. The study results suggested changing the WQI assessment methodology used in Ukraine and also reported that the gradual and joint use of mathematical tools such as the fuzzy logic method and ANN could be instruments that would effectively evaluate and estimate WQI values, respectively (Trach et al., 2022).

Conclusion

When the overall evaluation of the studies is made, it is emphasised that water quality assessment is a very complex task, classical logic-based approaches alone are not sufficient to explain this complexity, the limits drawn alone are not a rational approach in water quality assessment, and the effects of water quality parameters on each other must definitely be considered in the assessment. Therefore, it has been reported that fuzzy-based approaches are tools that can be used in water quality assessment instead of classical logic approaches. It was concluded that the fuzzy-based water quality assessment approaches can be used to compare various water quality assessment indices and models created in different water resources. It is a more reliable and rational approach that can replace classical methods by being developed.

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Chapter 3

EFFECT OF THYME ESSENTIAL OIL AND EXTRACTS ON THE QUALITY CHANGES OF SEAFOOD

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Due to nutritional composition, high water content and weakness in connective tissues, seafood products create a convenient environment for microbial growth and this makes seafood products considered as perishable foods. Besides, the activities of autolytic enzymes in seafood products are relatively more active during storage and they are among the perishable foods since they contain unsaturated lipids, which cause the rate of deterioration to be higher than other foods. Spoilage in seafood can occur as off-odor formation, texture loss and changes in color, which reduces the preferability for consumers. In addition, high moisture content and pH close to neutral support the growth rate of microorganisms (spoilage organisms and pathogens in terms of the quality and safety) and cause quality losses. Furthermore, in seafood with high lipid content, lipid oxidation causes rancidity and enzymatic reactions cause protein denaturation and lipid degradation. Considering these factors related to the deterioration of seafood products, it is necessary to emphasize the safety of the consumer in maintaining the quality of seafood products and extending their shelf life with effective preservation methods. (Gram and Huss, 1996; Odeyemi et al., 2018; Zhuang et al., 2021; Olafsdottir et al., 2006).

Specific spoilage organisms are one of the main causes of spoilage in seafood which comprises a high moisture and protein-rich environment. These bacteria include *Pseudomonas*, *Shewanella* and *Photobacterium* species. Species of these bacterial genera metabolize compounds such as ammonia, sulfur compounds and biogenic amines in seafood and contribute to spoilage and cause quality losses in seafood. It has been reported that *Shewanella putrefaciens* forms terimethyl amine (TMA) from trimethyl amine oxide (TMAO), which contributes to the formation of the characteristic "fishy" odor as an indicator of spoilage in seafood. Similarly, it has been reported that Pseudomonas species can form biogenic amines, aldehydes and sulfur compounds and can be used as an indicator of spoilage (Zhu et al., 2022; Kuley et al., 2016; Wang et al., 2021; Emborg et al., 2002; Zhang et al., 2021; Dalgaard et al., 2006; Arulkumar et al., 2023). Many methods are used to reduce spoilage and extend the shelf life of seafood products. In this context, natural preservatives are preferred over synthetic conservatives. Thyme (*Thymus vulgaris*) essential oil is rich in bioactive components such as thymol and carvacrol. Since it contains these components, its antimicrobial and antioxidant properties contribute significantly to the extension of shelf life in seafood. In the studies conducted, the use of thyme essential oil in seafood products slows down the development of spoilage organisms and allows the shelf life to be extended. The antioxidant activity of Thyme EO contributes to the preservation of sensory components such as taste, color and texture in seafood. However, depending on the concentration of use, it has been reported that thyme EO has minimal effect on organoleptic properties in seafood products and contributes to the preservation of the quality of seafood products with minimal effect on flavor. Thyme EO has many usage methods in seafood. However, dipping in combination with edible films is generally the most common method. This combination creates a synergistic effect in extending the shelf life of seafood products and preventing quality losses and shows a higher rate of effect than single use (Pierozan et al., 2024; Kykkidou et al., 2009; Duman et al., 2015; Hernandez et al., 2015; Romulo et al., 2024; Boukhira et al., 2024).

The use of thyme EO in seafood is used as an alternative to synthetic preservatives due to its natural characteristics. From a consumer perspective, this use provides increased consumer preference and access to products treated with natural preservatives. However, successful applications of thyme EO require significant optimization of the concentration of use. In cases where optimization is not appropriate, sensory properties such as flavor and texture are negatively affected. In such cases, thyme EO is effective in slowing down microbial growth in the product to which it is applied, while causing losses in sensory properties. In this study, the effects of different concentrations of thyme EO on microbial quality, chemical changes and sensory parameters in seafood products were reviewed.

The usage of thyme EO and extracts in seafood

Thyme EO and extracts have a wide range of applications in seafood and studies show that thyme EO and extracts have a crucial importance in maintaining the quality of seafood. Balikçi et al. (2022a) conducted a study on the quality changes of thyme, rosemary and basil extracts in vacuum packed mackerel balls during storage under refrigerator conditions. The researchers treated mackerel balls with extracts obtained from different plants at a concentration of 0.05% and stored the samples for 28 days. Total mesophilic bacteria counts in vacuum packed mackerel balls were reported between 2-3 log cfu/g at the beginning of storage. The mesophilic bacteria counts, which increased with storage time, were reported to be approximately 5 log cfu/g on the 14th day of storage in the samples treated with thyme extract and it was reported by the researchers that the acceptable limit of 7 log cfu/g was not exceeded during storage. In addition, the researchers evaluated the sensory changes of raw mackerel balls samples using 5 point-scale. In the sensory method used in the study, appearance, color, odor and general acceptance parameters were evaluated. During the storage period, the appearance parameter in the thyme group samples scored 5.0 points, the highest value of the scale, until the 7th day of storage and decreased as the storage time increased. Compared to the control group samples, the researchers determined that the value for the control group samples was 2.8 on Day 28, the last day of storage, while this value was reported as 3.2 for the thyme group. For the color value, which is another sensory indicator, while the decrease in the color score in the control group samples started on the 7th day, they reported that there was no significant change in color until the 11th day of storage in the samples containing thyme extract. Odor changes, which is an important quality indicator in seafood products, were reported to start to decrease from the 4th day of storage for the control group in vacuum packed mackerel balls, whereas it was reported that it started to decrease on the 14th day of storage in samples containing thyme extract. Finally, the general acceptance value was reported by the researchers as 2.6 for the control group and 3.1 for the samples containing thyme extract on the last day of storage. The total volatile basic nitrogen (TVBN) value, which is one of the major chemical quality indicators of seafood products, was reported to be 16.52 mg/100 g at the beginning, 23.28 mg/100 g for the control group and 18.92 mg/100 g for the samples containing thyme extract at the end of storage.

In another study, researchers applied different concentrations (1 and 1.5%) of thyme and rosemary oil to Nile tilapia fillets and evaluated the microbiological, chemical and sensory changes during storage at 4C. The researchers reported the overall acceptability value of the group containing 1% thyme oil as 2 out of 5 on the 3rd day of storage and the group containing 1.5% thyme oil as 3 on the same day. In comparison with the control group, the sensory values were reported to be 1 on the 3rd day of storage. In terms of chemical quality, it was reported that the TVBN value of the control group samples was 19.15 mg/kg on the 2nd day of storage, while the samples containing 1% thyme oil were 10.07 and the 1.5% sample group was 8.12 mg/kg. Microbiologically, aerobic plate count, pscychotropic bacteria and coliform count battery groups were analyzed. Aerobic plate counts were reported to be $2x10^8$ cfu/g on the 2nd day of storage for control and 1% thyme oil containing group and $1x10^8$ cfu/g for 1.5% thyme oil containing group. For pscychotropic count, these values were reported as $4x10^7$ and $3x10^7$ cfu/g, respectively. Finally, similar results for coliform group bacteria were found by the researchers. The researchers reported that for Nile tilapia samples stored at 4C, a high concentration of thyme and rosemary (1.5%) provided the highest chemical and sensory quality of the samples (Elhafez et al.,2020).

Another study suggest that essential oil-emulsion based approach could prevent and maintain the quality of seafood. In which, the quality changes in carp fillets stored under chilled conditions after treatment with alginate films containing different concentrations (0.5, 1 and 1.5%) of thyme, oregano and pimento EOs were investigated. The researchers reported the total viable count values of carp fillets treated with alginate films containing different concentrations of thyme EO and 0.5, 1 and 1.5%

as 0.11, 2.26 and 2.10 cfu/g at the beginning of storage and 6.76, 4.27 and 3.59 on the 6th day of storage, respectively. For oregano, 3.10, 2.36 and 2.20 were reported respectively and 6.81, 4.46 and 3.49 log cfu/g at the end of storage, respectively. The researchers evaluated the samples from a sensory point of view and reported that the alginate coating did not make any difference for consumers in raw and cooked samples. The researchers reported negative effects on color and acceptability parameters for raw samples in emulsions containing high concentrations (1.5%) of EO, and reported that the negative effect was significantly reduced in the group with 1% concentration. The researchers concluded that the quality of the samples containing 1% emulsion was preserved and the shelf life of carp fillets stored under cold conditions increased by 2-4 days (Hao et al.,2022).

In another study, the effect of thyme, cinnamon and garlic EOs at 0.5 and 1% concentrations on sensory quality and *Aeromonas hyrophila* in Nile tilapia fillets stored under refrigerator conditions was investigated. In the sensory evaluation of the samples, the overall acceptability parameter was based on 20 points and the value of the control group was reported to be 18.51 at the beginning of the experiment. The overall acceptability value for 0.5% samples treated with Thyme EO was reported as 18.18 and 17.6 for samples containing 1%. On the last day of storage, the overall acceptability value was only reported for the group containing 1% thyme and was reported as 3.12. The number of *A.hyrophila* in Nile tilapia fillets was determined only in the group containing 1% thyme oil until the 12th day before the samples deteriorated and was reported to be 1.87x108 cfu. The researchers reported that by immersing the fish fillets in solutions containing EO at 0.5 and 1% concentrations, the shelf life could be extended by 6-9 days compared to the control group. Furthermore, they reported that the number of *A.hyrophila* can be reduced without negatively affecting the sensory properties of the samples (Kirrella et al., 2021).

In another study with snakehead (*Channa striata*) fillets, Liu et al. (2024) applied vacuum impragnation by coating snakehead fillets with chitosan enriched by thyme EO and maintained under cold storage conditions. Microbiologically, psychrophilic and mesophilic bacteria counts were examined in the samples and initial values were determined to be 4.90 and 3.72 log cfu/g, respectively. Psychrophilic bacterial counts, which increased with storage time, increased significantly on the 12th day of storage in samples stored at 4C and were reported as 5.18 log cfu/g in chitosan-coated samples enriched with thyme EO. Mesophilic bacteria counts showed a similar increase and were reported to be 4.92 log cfu/g on the 12th day of storage. Biogenic amine changes were also examined in the study. The researchers reported that the initial histamine level in snakehead fillets was 1.22 mg/kg and the histamine concentration increased to 3.55

mg/kh in the control group and this increase occurred on days 6 and 9. They reported that putrescine level increased from 2.96 mg/kg to 39.71 mg/kg in the control group and this level was 3.23 mg/kg in chitosan-coated samples enriched with thyme EO. In this context, the researchers reported that putrescine formation was significantly reduced in the chitosan-coated group enriched with thyme EO. According to the results of the research, they concluded that vacuum impregranation application in chitosan enriched with thyme EO could maintain the quality of snakehead fillets under cold storage conditions, prevent biogenic amine formation and slow down microbial growth.

In another study, quality changes of shrimp treated with Shirazi thyme (*Zataria multiflora*) oil nanoemulsion (SNE) were monitored during storage under refrigerator conditions. Carboxymethyl cellulose coated samples were enriched with different concentrations of SNE and quality changes were determined for 10 days. SNE-treated samples were microbiologically analyzed for arobic plate count, psychrophilic bacteria, lactic acid bacteria and Enterobacteriaceae. The researchers reported the initial APC values as approximately 2.5 log cfu/g. However, they reported that APC counts decreased significantly with the increase in SNE concentrations on the 10th day of storage. The researchers also reported that the number of psychrophilic bacteria was the highest in the control group and lower in the other treated groups with the increase in the concentration of SNE, similar to APC values. In terms of lactic acid bacteria, they reported that LAB values were the lowest in the group containing 30 mg/ml SNE. Concerning Enterobacteriaceae numbers, it was reported that higher numbers were obtained in the carbozymethyl celulose group compared to all other groups and that Enterobacteriaceae numbers were higher in samples containing sodium metabisulphide compared to samples containing SNE at different concentrations. In the study in which TVBN and TMA values were examined as chemical quality indicators, it was reported that TVBN and TMA values of the SNE group were lower than the other groups. The researchers reported that SNE-enriched carboxymethyl cellulose had a positive effect on the shelf life and quality of shrimp stored under refrigerator conditions, slowing microbial growth, melanosis and chemical changes. In addition, they reported that the use of SNE instead of sodium metabisulphide was effective in slowing melanosis. According to the results of the study, they concluded that the use of SNE at concentrations of 10 or 20 mg/ml is a more effective method in terms of extending the shelf life of shrimps (Rezaei et al., 2023).

Conclusion

Consequently, compared to chemical and synthetic preservatives, the use of thyme EO in seafood products is considered to have a more promising nature in terms of naturality, environmental friendly approaches and human health. In this study, the effects of thyme EO on the shelf life and quality of different seafood products at different concentrations and in combination with different processing techniques were evaluated. It was observed that thyme EO offers significant antimicrobial and antioxidant properties and thus contributes to the quality of the product in terms of providing chemical stability and inhibiting microbial growth in perishable foods such as seafood. However, it was revealed that thyme EO has an intense effect on the sensory properties of seafood due to its compositional characteristics. In this context, the importance of the optimum dose in the use of thyme EO in terms of the preservation and maintenance of sensory properties in seafood products has been highly emphasized. In future studies, it is expected that application methods will be reviewed and optimization techniques will be investigated, protective effects would be maximized and thyme EO would have a positive effect on sensory properties by determining the optimum dose during its use.

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Chapter 4

AN EVALUATION OF TURKEY'S SEAFOOD EXPORTS TO THE RUSSIAN FEDERATION

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"Trade, foreign relations and international disputes are closely interconnected and significantly influence each other." (Heejoon Kang & Rafael Reuveny, 2001)

THE RUSSIAN FEDERATION AND ITS GENERAL ECONOMIC OUTLOOK

The Russian Federation, with a land area exceeding 17 million km², is the largest country in the world and spans 11 time zones. It is located in northern Asia, between Europe and the Pacific Ocean, extending to the Arctic Ocean (Figure 1). With a population of 146.4 million, Russia shares land borders with 14 countries. Governed by a bicameral presidential system, the country's executive authority is vested in the President, while the government, led by the Prime Minister, shares executive powers. Legislative authority is vested in the Federal Assembly, which consists of the State Duma (lower house) and the Federation Council (upper house).

Some basic economic indicators of the Russian Federation are given in Table 1 (https://ticaret.gov.tr/data/5bcc5d4813b876034cfece26/RF%20%C3%9Clke%20Raporu%202024.pdf). In 2023, Russia became the world's 11th largest economy with a GDP of $2 trillion. Its economic strengths include high foreign exchange reserves and low external debt levels. In 2022, the economy contracted by 2.1% due to geopolitical sanctions. However, import substitution policies and a focus on domestic production led to 3.6% growth in 2023. In 2022, the Central Bank's foreign exchange reserves fell by $49 billion to $582.3 billion, and external debt decreased by $101 billion to $381.2 billion. In 2023, foreign exchange reserves increased by $4.5 billion to $586.7 billion, while external debt dropped by $55 billion to $326.6 billion.

Figure 1. Russian Federation (https://isib.org.tr/wp-content/uploads/2023/10/Rusya-Ulke-Raporu-2023.pdf)

Table 1: Russia/Main Economic Indicators

Indicator	2017	2018	2019	2020	2021	2022	2023
GDP (billion)	1.581	1.651	1.700	1.466	1.774	2.215	2.007
GDP (billion rubles)	91.84	103.86	109.61	107.66	135.29	153.44	171.04
Real GDP Growth	%1.8	%2.8	%2.2	%2.7	%5.6	%2.1	%3.6
GDP per capita ($)	10.77	11.24	11.58	10.18	12.62	15.65	13.75
GDP per capita (PPP $)	25.926	28.821	30.068	29.937	31.271	33.253	29.262
Exports (billion $)	357	449	423	337	492	592	425
Imports (billion $)	227	238	244	232	294	255	285
Trade Balance (billion $)	130	211	179	105	198	337	140
Unemployment rate (as of December)	%5.1	%4.8	%4.6	%5.8	%4.8	%3.9	%3.2
Consumer Inflation	%2.5	%4.3	3%	%4.9	%8.9	%12.2	%7.4
Central Bank policy rate (as of December 31, 2023)	%7.75	%7.75	%6.25	%4.25	%8.5	%7.5	16%
Total external debt (billion $)	518	455	491	467	482	381	327
International reserves (billion $)	433	469	454	596	631	582	587

GDP: Gross Domestic Product

B) GOODS TRADE AND TURKEY-RUSSIA ECONOMIC RELATIONS

Russia is one of the world's leading suppliers of raw materials, with rich reserves of natural gas, oil, minerals, as well as vast agricultural and forest lands. Its main exports include oil and oil products, natural gas, coal, grain, oilseeds, vegetable oils, and iron-steel products.

According to data from the Federal Customs Service, Russian exports reached a record high in 2022, increasing by 19.9% to $592.5 billion. In contrast, imports decreased by 11.7%, falling to $255.3 billion. In 2023, exports dropped by 28.3% to $425.1 billion, while imports rose by 11.7%, reaching $285.1 billion. During this period, Russia's trade surplus was recorded at $140 billion. Non-energy and non-commodity exports accounted for approximately 28% of total foreign exchange earnings. The main imports were machinery parts, electrical and electronic products, pharmaceuticals, mobile phones, vehicles and components, machinery, aircraft, and food products.

The trade volume between Russia and Turkey, which was $4.5 billion in 2000, increased to a record $37.8 billion in 2008, largely due to rising oil prices, and reached $68.1 billion in 2022. Turkey's exports to Russia grew from $5.8 billion in 2021 to $9.3 billion in 2022, a 61.8% increase, placing Russia in the 8th spot among Turkey's export markets. In 2023, exports further rose by 16.9% to $10.9 billion, with Russia accounting for 4.3% of Turkey's total exports. Turkey's main exports to Russia traditionally include fresh fruits and vegetables, motor vehicles and their parts, textiles and ready-made clothing, finished metal products, and electrical machinery and devices. In 2023, the top five export sectors were chemicals and related products, machinery and equipment, the automotive industry, electrical and electronics, and fresh fruits and vegetables (Hamilton and Mikulska, 2021; Balaban, 2023).

Turkey's imports from Russia reached $58.8 billion in 2022, making Russia Turkey's top import source with a 16.2% share. In 2023, imports from Russia decreased by 22.5%, falling to $45.6 billion. The main imported goods were natural gas, coal tar, crude oil, iron and steel, and non-ferrous metals. The decline in imports from Russia was attributed to fluctuations in commodity prices (Figure 2) (Ndondo, 2023).

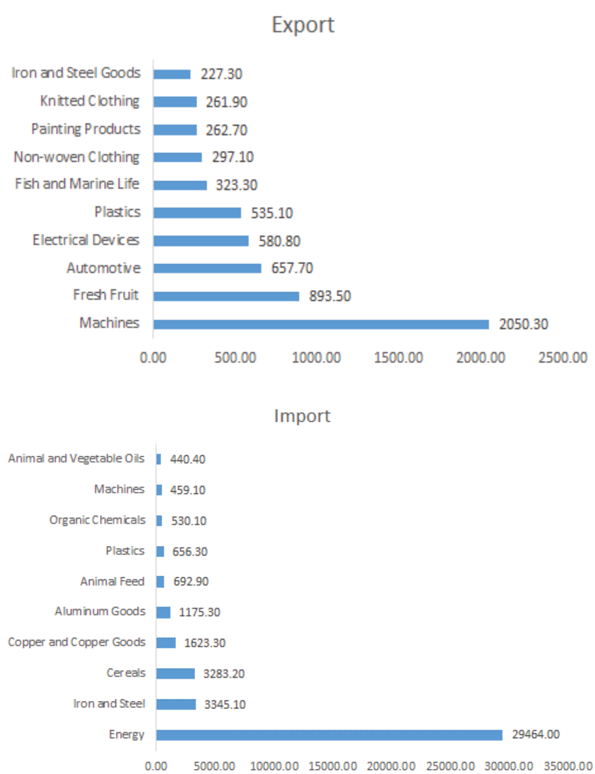

Figure 2. Export and import amounts between the Russian Federation and Türkiye (USD) (https://www.deik.org.tr/uploads/rusya-bilgi-notu-ocak-2024.pdf)

C) CONSUMPTION OF FISH AND FISH PRODUCTS IN RUSSIA

The Russian Ministry of Health's standard for fish consumption is set at 24 kilograms per person per year, or 1-2 servings per seven days. But only 36% of Russians buy fish several times a week. 45% of the country's residents buy it once or several times a month, and 81% buy it every month. However, in comparison with data for European countries, the consumption rate of fish products in Russia is quite high – 35% of Europeans eat fish less than once a month (Komlatsky, 2024).

The most popular and purchased fish in Russia is mackerel (33%). It is followed by herring (32%), pink salmon (27%), trout (25%), salmon (21%) and pollock (20%) (Fig. 3). For everyday consumption, Russians most often buy canned fish, preserves (20%), frozen, salted or lightly salted fish (19% each). The largest number of fish consumers are among the economically active population of Russia aged 35 to 44 years (41%), women (37% versus 34% men), Russians with higher education (40%), family people (37%) and those with a high income (62%). When buying food for themselves and their families, 31% of Russians often refuse to buy fish, mostly because of its high cost.

Considering that taste preferences are one of the most important reasons for including fish dishes in the diet, in order to increase demand for fish, it is recommended to expand the range of inexpensive and easy-to-prepare fish products, and at the point of sale, offer services for cleaning and cutting them, semi-finished products from popular types of fish - trout, pink salmon, pollock. The main places to buy fish products are grocery stores and supermarkets "near home". Due to the relatively low cost of fish products, they are most often chosen by Russian families over 45 years old. Large hypermarkets are the second most popular places to buy fish products. They are most often chosen by young people under 24, as well as Russian families with children. Hypermarkets are more actively visited by those who value a variety of products and prefer to buy live or fresh fish. Specialized seafood stores are third in popularity. Their main audience is women, Russians aged 25–34, people with 1–2 children. Such consumers are motivated by concern for the health of their children and can often afford to buy expensive products. Every sixth Russian buys fish at the market, but only 2% of "fish" consumers trust online sellers of such products. With most Russians choosing their local supermarkets, fish companies should partner with local stores to attract attention to their brands, creating a lasting association with excellent quality in the minds of consumers. Owners of online stores today are losing a large number of potential fish buyers, so when planning sales of such products, one should focus on the most important customer requests - product freshness, trusted producers and suppliers. In particular, you can inform potential customers about new product arrivals, periodically open "live" showcases where customers can get acquainted with the products, so that they can then order them online without fear. When choosing fish, Russians are primarily guided by its price (50%), appearance (46%) and expiration date (41%). A quarter (26%) point out the fundamental importance of the product's taste characteristics. At the same time, people pay little attention to the presence of a discount - only 7% of respondents are ready to buy fish because of the promotion. More than a fifth of the population considers fish to be "food for the elite", which indicates a lack of budget lines of fish products. This belief is mainly held by Russians with a low income (36%), people living in a family of five or more people (34%). Buying natural caviar, live and chilled fish is difficult for many consumers. A large share of Russian buyers (30%) considers canned and preserved fish to be inexpensive and accessible. Residents of the country are ready to include natural caviar and seafood in their diet more often when their cost decreases. As for live fish, respondents do not seek to increase the frequency of its consumption. The opposite situation is observed with salted and lightly salted fish: it is among the leaders in frequency of consumption, its cost is estimated as moderate, while more than a third of Russians (34%) would like to consume it more often. Only 4% of Russians would not include fish products in their diet more often than they do today.

A third of Russians (30%) believe that the quality of Russian fish products is not high enough due to underdeveloped conditions for fish production and delivery. Mistrust of fish products is more often noted by people aged 55 and older (36%). In addition, 35% of Russians do not want to overpay for chilled fish. Many respondents are sure (30%) that frozen or smoked fish loses vitamins that are beneficial for the body. This opinion is mainly shared by young people aged 18 to 24 (34%). To improve the situation and win the trust of potential customers, manufacturers need to increase the openness of their production through social networks, talk about cooking and storage technologies, and promote information about the health benefits of fish with the help of opinion leaders. The situation with fish consumption in the country can be radically improved, but for this, the government and business should act together, under the auspices of the state regulator. The tactics of success are to increase people's trust in fish producers, optimize logistics chains and retailers' pricing policies. "Fish" enterprises need to expand their range of products by introducing high-quality, inexpensive and easy-to-cook semi-finished fish and seafood products, and the market needs a competent strategy for promoting such products so that cooking and eating fish becomes fashionable. It is important to focus on popularizing the principles of healthy and varied nutrition, including fish and seafood in the diet, which are not very popular in the country today.

One of the options is the creation of a national program to increase the availability of fish products, including high-quality information to the population about the benefits of fish, conducting all-Russian communication campaigns, as well as implementing measures to strengthen and unite intra-industry interaction. (https://foodmarket.spb.ru/archive/2023/222831/222840/#:)

D) THE RUSSIAN TROUT AND ATLANTIC SALMON MARKET

The Russian trout and Atlantic salmon market in 2023 grew by 10% compared to 2022 and exceeded 250 thousand tons. In Russia in 2023, the volume of salmon farming amounted to 80 thousand tons, and aquaculture production of trout reached 77 thousand tons. Another significant segment of the Russian red fish market is Pacific salmon (pink salmon, chum salmon, coho salmon, etc.). In 2023, their catch increased by 2.3 times compared to 2022 and exceeded 600 thousand tons. Against this background, sales of pink salmon, the main commercial salmon, have actively increased (Komlatsky, 2024). According to monitoring data from the Analytical Center of the Fish Union, in 2023, Russians bought 70% more pink salmon by weight than in 2022. Meanwhile, salmon imports in 2023 amounted to 42 thousand tons, increasing by 23% compared to 2022. More than 92% was frozen salmon, 8% was frozen salmon fillet. Almost 100% of supplies were from Chile. Trout imports in 2023 amounted to 52 thousand tons, also exceeding the 2022 figure by 23%. One of its main suppliers is Türkiye.

"In 2023, even against the backdrop of one of the best salmon fishing seasons in the Far East, imports of salmon and trout partially recovered, and aquaculture production of these fish species also increased," the Fish Union notes on its Telegram channel. The Fish Union analysts attribute the market growth to the continuing increase in demand for red fish, which has been popular with Russian consumers in the retail and catering sectors year after year (https://b-port.com/news/290079)

E) TURKEY'S SEAFOOD PRODUCTION

Turkey has established a prominent position in aquaculture, particularly in the cultivation of Rainbow Trout (*Oncorhynchus mykiss*), Sea Bass (*Dicentrarchus labrax*), and Sea Bream (*Sparus aurata*). This success gives Turkey a significant export advantage in meeting the growing global demand for seafood (Çelik and Akmermer, 2021).

The most widely farmed trout species in Turkey are the rainbow trout. The main reason for its prevalence in Turkey is its suitability for farming conditions (Guzel and Arvas, 2011; Parrino et al., 2020). The production of rainbow trout in Turkey began in the 1970s, initially in small enterprises, and transitioned to integrated facilities in the 1990s. Belonging to the Salmonidae family, trout thrive in cold, clear, oxygen-rich rivers, springs, and lakes, and are considered among the most delicious and popular freshwater fish (Arısoy et al., 2021; Yıldırım and Çantaş, 2022). The most commonly farmed species belong to the genera Salmo, Salvelinus, and Oncorhynchus. Globally, the most preferred trout species include Atlantic salmon, sea trout, brook trout, rainbow trout, brown trout, and alpine trout (Kocabaş, et al., 2013; Kalaycı et al., 2018). The optimal conditions for trout growth vary, but for an average trout farm, a minimum water flow of 100 liters per second is required, with an ideal water temperature of 11-16 °C (Çelikkale, 1988).

There are no statistical records on aquaculture in Turkey before 1985. However, aquaculture efforts began in the late 1960s with the farming of carp and rainbow trout, and by the early 1980s, gilthead sea bream and European seabass were also introduced. In recent years, significant advancements have been made in Turkey's aquaculture systems. The relocation of fish farms to open and deep waters has necessitated the development of new techniques suitable for these environments. Accordingly, improvements have been made in areas such as cage size, net systems, and feeding methods, with technologies that surpass global standards (Bilgüven and Can, 2018).

Currently, 69% of aquaculture production takes place in the sea across 432 facilities. Muğla leads marine aquaculture with 42.8%, followed by İzmir, Elazığ, Aydın, Mersin, and Trabzon (BSGM, 2022). In inland waters, there are 1,707 facilities, with Elazığ accounting for 31% of production. In inland aquaculture, 97% of the fish produced are trout. According to 2023 data, total production from aquaculture in Turkey amounts to 319,529 tons, with gilthead sea bream, European seabass, and trout accounting for 28.03% (154,111 tons), 30.41% (160,802 tons), and 29.61% (154,600 tons) of the total, respectively. Other species make up 11.95% of the total production (TUIK, 2023).

F) TURKEY'S SEAFOOD EXPORTS TO THE RUSSIAN FEDERATION

The Netherlands held a leading position in fish supplies to Russia in 2020. But since then, their share has significantly decreased. Currently, the Netherlands is in third place with a purchase volume of $98 million. Italy is in second place with a purchase volume of $132 million. This change highlights Russia's growing dependence on Turkish supplies and the volatility of the market situation (https://fish-info.ru/news/rekordnyy-rost-importa-ryby-iz-turtsii-v-rossiyu/)

Turkey, known for its rich marine resources and variety of fish, continues to strengthen its position in the Russian market (Can et al., 2020). According to the Turkish statistical service, in the first seven months of this year (2024), the volume of fish supplies to Russia reached a record 190.5 million dollars. This is 15 million dollars more than in the same period last year, when the volume of purchases amounted to 175 million dollars. Thus, Russia remains the main buyer of Turkish fish for the fourth year in a row. According to the analytical center of the Russian Fish Union, in the first half of 2024, Russia imported 30,500 tons of fish and seafood from Turkey, which is 35% more than in the same period last year. In value terms, Turkish exports to Russia rose 15% to $153 million. This is a small amount compared to Russia's huge industrial imports, but it represents a significant market shift in a highly competitive industry. In particular, frozen trout imports increased by more than 40% to almost 18,000 tons, while chilled trout imports grew by almost 80% to 9,000 tons. Frozen sea bass imports (pictured above) increased by 25% to 500,000 tons. Now more than 50% of Turkish frozen fish exports and 14% of chilled fish exports are sent to Russia, the Fish Union reported. Frozen fish accounts for 58% of Russian fish and seafood imports from Turkey in monetary terms.

(https://russiaspivottoasia.com/russian/rossiya-zakupila-na-35-bolshe-ryby-u-turczii-v-pervom-polugodii-2024-goda/).

G) FUTURE EXPECTATIONS

Türkiye, by maximizing its fish supply to Russia to a historic high, not only strengthens its position in the Russian market but also creates new opportunities for further development of bilateral relations in the field of trade (https://fish-info.ru/news/rekordnyy-rost-importa-ryby-iz-turtsii-v-rossiyu/). Therefore, considering current trends, it is expected that Türkiye will continue to increase its fish supply to Russia.

Due to its geographical proximity, logistical advantages, and high product quality, Türkiye is seen as a reliable supplier for Russia. In the future, Türkiye can further strengthen this position and expand its reach not only to Russia but also to neighboring countries and European markets.

The increasing global demand for healthy food and the recognized health benefits of seafood present an additional opportunity to Türkiye. Therefore, Türkiye can capitalize on this trend by developing marketing strategies that highlight the health benefits of seafood in Russia. This approach can increase seafood consumption and help Turkey grow its market share. Especially for young, health-conscious consumers, Türkiye can position itself as a reliable supplier of healthy seafood. Additionally, developing semi-processed, easy-to-use, and practical products can increase demand in both domestic and international markets.

The underdeveloped state of online seafood sales in Russia presents another opportunity for Türkiye. By utilizing digital marketing and e-commerce platforms, Türkiye can offer fresh and reliable seafood directly to Russian consumers. This allows Türkiye to reach a wider audience through digital platforms and optimize its supply chain. Collaborating with local stores can further enhance the perception of the quality and freshness of Turkish seafood among Russian consumers.

Sustainability is an increasingly important concept for today's consumers. By focusing on sustainable production and maintaining high-quality standards, Türkiye can gain a competitive advantage in international markets. Innovation in the seafood sector will be a key factor in Turkey's future success. Specifically, by developing environmentally friendly production processes in the fishing and aquaculture sectors, Türkiye can become a model for sustainable fishing. As environmental awareness increases in Russia, such practices will enhance Turkey's competitiveness not only in Russia but also on the global stage.

The increasing cooperation in seafood trade between Türkiye and Russia opens the door for joint projects and investments in the fishing industry. Türkiye can take the lead in establishing fish farms, sharing technological expertise, and initiating ventures that strengthen seafood trade between the two countries.

As a result, increased trade between the two countries may lead to greater willingness to cooperate in other areas and resolve disputes between them.

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Chapter 5

FUZZY LOGIC APPROACHES TO WATER QUALITY ASSESSMENT

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Introduction

Fuzzy logic, conceptualized by Lotfi Zadeh in the mid-20th century, has revolutionized many fields by introducing a way to handle imprecision and uncertainty. Its application in water quality assessment is particularly significant due to the inherent complexity and variability of natural water systems. Traditional deterministic models often struggle to encapsulate this variability, which is where fuzzy logic's flexibility becomes advantageous (Zadeh, 1965).

The adoption of fuzzy logic in environmental sciences, especially in water quality modeling, reflects its capacity to integrate human-like reasoning into computational processes. This method provides a framework suitable for evaluating complex and fluctuating datasets, essential for effective environmental management. Numerous studies highlight the effectiveness of fuzzy logic models in capturing the nuances of water quality parameters like pH, dissolved oxygen, and turbidity. These models enable stakeholders to formulate more adaptive and responsive management strategies (Gharibi et al., 2012). One major area of focus within fuzzy logic applications is the development of Water Quality Indices (WQIs). These indices convert complex data into a single score, which can be easily interpreted by policymakers and the public. This simplification is essential for effective communication and action (Abdullah et al., 2008). The application of fuzzy logic in developing Water Quality Indices (WQI) offers nuanced insights that surpass traditional indices' capabilities (Gharibi et al., 2012).

As environmental challenges become more complex, the demand for models that can accurately represent the intricacies of natural systems grows. Fuzzy logic, with its foundation in linguistic variables and human reasoning, is uniquely positioned to fulfill this demand. Its adaptability makes it suitable for various environmental conditions, providing a universal applicability that transcends geographical boundaries (Scannapieco et al., 2012).

In recent years, fuzzy logic has been increasingly utilized to simplify complex datasets into comprehensible indices, thereby enhancing decision-making processes related to environmental management. The method's ability to handle uncertainty and imprecision is particularly beneficial in contexts where data may be incomplete or imprecise, such as in developing countries where resources for extensive monitoring are limited (Oladipo et al., 2021).

Fuzzy logic's role in environmental monitoring systems is critical as it provides insights that are not only precise but also inclusive of variations and uncertainties. This inclusivity is vital for effective communication and action, especially when dealing with diverse stakeholders and policymakers (Bokingkito & Caparida, 2018).

Moreover, the integration of fuzzy logic with other computational techniques such as artificial neural networks (ANNs) and genetic algorithms opens up new possibilities for enhancing predictive capabilities and model accuracy. These hybrid approaches leverage the strengths of multiple methodologies, resulting in robust solutions for complex environmental systems (Ramadan et al., 2012).

As we continue to face global environmental challenges, the need for innovative modeling techniques becomes ever more pressing. Fuzzy logic offers a pathway toward more effective management of water resources, a critical component of sustainable development. Its potential applications are vast, and ongoing research promises to unlock even more possibilities (McKone & Deshpande, 2005).

Fuzzy logic provides a unique approach to handling the uncertainties inherent in water quality assessment. The application of fuzzy logic in water quality assessment has gained traction over the past decades, offering a flexible framework for evaluating diverse water bodies' health. This includes rivers, lakes, and groundwater systems. The core advantage lies in its capacity to synthesize complex datasets into understandable indices, enhancing decision-making processes related to environmental management (Raman et al., 2009). Unlike traditional models, fuzzy logic allows for a degree of imprecision, making it particularly suited for environmental data, which often exhibits variability and ambiguity. This method has been increasingly applied in developing Water Quality Indices (WQI) that offer more nuanced insights than conventional indices. The growing interest in fuzzy logic is evident in various studies, which aim to enhance the precision and applicability of water quality assessments (Raman et al., 2009; Trach et al., 2022). Numerous studies highlight the effectiveness of fuzzy logic models in capturing the nuances of water quality parameters like pH, dissolved oxygen, and turbidity. These models enable stakeholders to formulate more adaptive and responsive management strategies (Gharibi et al., 2012). The adaptability of fuzzy logic makes it suitable for various environmental conditions, providing a universal applicability that transcends geographical boundaries (Trach et al., 2022).

In summary, the introduction of fuzzy logic to water quality modeling represents a significant advancement in environmental science. It provides a flexible framework that enhances our ability to assess, monitor, and manage water quality in a rapidly changing world (Sheehan & Gough, 2016).

Theoretical Framework of Fuzzy Logic in Water Quality Assessment

The theoretical underpinnings of fuzzy logic lie in the concept of fuzzy sets, where elements have degrees of membership rather than binary states. This is particularly advantageous in water quality assessment, where parameters like chemical oxygen demand (COD), biological oxygen demand (BOD), and nutrient levels exhibit a range of conditions (Zhu, 2005). Fuzzy logic is based on the concept of partial truth, where variables may have a range of values between completely true and completely false. This is particularly useful in water quality assessment, where parameters such as pH, turbidity, and biological oxygen demand do not always conform to binary states. The fuzzy logic model uses membership functions to classify water quality into different categories based on these parameters. By employing rules and linguistic variables, fuzzy logic systems can mimic human reasoning, providing a more flexible evaluation framework (Gharibi et al., 2012).

In fuzzy logic systems, water quality parameters are treated as fuzzy variables and evaluated using linguistic terms such as "low," "medium," and "high." These terms are mapped to numerical values using membership functions, enabling a more nuanced interpretation of water quality data (Yaseen et al., 2018).

The rule-based approach of fuzzy logic models complex systems, allowing them to simulate human decision-making processes. For example, in water quality assessment, rules might take the form of "IF pH is high AND turbidity is low THEN water quality is good." These rules are derived from expert knowledge and empirical data, ensuring the system accurately reflects real-world conditions (Kambalimath & Deka, 2020).

The aggregation of fuzzy rules results in a fuzzy output, which is then defuzzified to provide a crisp value for decision-making. This defuzzification process is crucial as it transforms complex input data into a clear and actionable output (Wang et al., 2007).

One of the significant advantages of fuzzy logic in water quality assessment is its ability to handle incomplete and imprecise data. This is particularly relevant in regions where data collection is challenging due to logistical or financial constraints. Fuzzy logic systems can make reasonable inferences even with limited data, providing valuable insights into water quality conditions (Raman et al., 2009).

The use of fuzzy logic aligns with the broader trend toward soft computing techniques, which prioritize flexibility and adaptability over rigid accuracy. These approaches are increasingly favored in ecological modeling due to their ability to accommodate the inherent uncertainty and variability of natural systems (Semiromi et al., 2011).

In developing fuzzy logic models for water quality, the selection of suitable membership functions and the formulation of appropriate rules are critical. This process often involves collaboration between domain experts and modelers to ensure that the system accurately reflects expert knowledge (Trach et al., 2022).

As the field evolves, the integration of fuzzy logic with other computational techniques is becoming more prevalent. Hybrid models that combine fuzzy logic with neural networks or genetic algorithms are showing promise in improving model robustness and predictive accuracy. These models take advantage of the strengths of each approach, resulting in more comprehensive solutions for water quality assessment (Rajaee et al., 2020).

The theoretical advancements in fuzzy logic are paving the way for more sophisticated environmental models that can better inform policy and management decisions. As such, ongoing research and development in this area are crucial for addressing the complex challenges of water resource management in the face of global environmental change (Icaga, 2007).

Applications of Fuzzy Logic in Water Quality Assessment

Fuzzy logic has been applied in various studies globally to assess and monitor water quality. For instance, a study on the Karoon River in Iran utilized fuzzy logic to develop a comprehensive Water Quality Index (WQI) that integrated multiple parameters, aiding local management strategies (Semiromi et al., 2011). This approach has been adopted in various regions to address specific local water quality challenges. Each case study reinforces the adaptability of fuzzy logic in diverse environmental contexts, proving its utility in routine assessments.

A fuzzy logic model was developed for river water quality in Malaysia, incorporating six input parameters to generate a single output. This model demonstrated the potential of fuzzy logic to simplify complex datasets, facilitating easier interpretation for decision-makers (Abdullah et al., 2008). The Tanjung Karang watershed in Indonesia benefited from a fuzzy logic approach to evaluate agricultural activities' impact on water quality. The model's ability to integrate diverse data sources was instrumental in guiding sustainable agricultural practices (Gharibi et al., 2012). A study in Poland employed fuzzy logic to evaluate ecological status based on biological and chemical parameters, demonstrating the method's effectiveness in capturing complex ecosystem interactions (Trach et al., 2022). In another study, researchers monitored the water quality of the Ganges River by fuzzy logic, integrating parameters such as biochemical oxygen demand and phosphates. The findings were crucial for informing policy decisions aimed at improving water quality (Raman et al., 2009). A study in Australia used fuzzy logic to evaluate urban runoff impacts on marine ecosystems. The model's ability to incorporate wide-ranging data sources was key to providing a comprehensive coastal water quality assessment (Abdullah et al., 2008). In addition, fuzzy logic models have been used to assess drinking water quality in rural communities, addressing challenges associated with limited data availability and resource constraints, providing insights into public health-impacting water quality issues (Semiromi et al., 2011).

A study on the Sele River in Italy compared traditional binary methods with fuzzy logic approaches for water quality assessment. The fuzzy logic model provided a more nuanced understanding of water quality, highlighting its effectiveness in optimizing sampling frequency and improving monitoring accuracy (Scannapieco et al., 2012).

Some researchers applied fuzzy logic to assess water quality in the Ikare community, comparing it with traditional Water Quality Index methods. The fuzzy logic approach proved superior in capturing the complexity of water quality parameters, demonstrating its applicability in diverse environmental contexts (Oladipo et al., 2021).

Raman et al. (2009) introduced a fuzzy logic-based application designed for river water quality assessment. By integrating parameters such as dissolved oxygen (DO), biochemical oxygen demand (BOD), and chemical oxygen demand (COD), the model achieved a 90% accuracy rate in evaluating river status across Malaysia, India, and Thailand. This approach demonstrated the utility of fuzzy logic in handling complex, multi-parameter systems, particularly in integrating pathogens into water quality indices.

Jinturkar et al. (2010) applied a fuzzy logic model to groundwater quality assessment in Chikhli, India. Their study used physico-chemical parameters to develop a water quality index (WQI), ranging from 1 (poor quality) to 10 (excellent quality). While most samples were suitable for drinking, exceptions included elevated levels of hardness, calcium, and magnesium, demonstrating fuzzy logic's potential to highlight critical deviations from standards.

Bórquez-López et al. (2018) compared fuzzy logic feeding strategies with traditional methods in shrimp farming, achieving a 35% reduction in feed usage without adverse effects on growth and survival. Similarly, Li et al. (2023) developed a dual-input fuzzy logic control system for ammonia nitrogen management, achieving over 95% savings in water and power consumption. These findings underscore fuzzy logic's value in optimizing resource use and ensuring sustainable aquaculture practices.

Yalcuk and Postalcioglu (2015) used fuzzy logic to monitor trout farm pool water quality. Their system integrated a graphical user interface (GUI) to simplify parameter analysis for stakeholders, enhancing accessibility and decision-making capabilities.

Bokingkito and Caparida (2018) leveraged IoT architecture alongside fuzzy logic to develop a real-time water quality monitoring system. By defining fuzzy sets and implementing rules for defuzzification, their system facilitated timely interventions, showcasing the potential for integrating fuzzy logic with modern technologies.

Gutiérrez et al. (2006) applied neuro-adaptive fuzzy logic to assess water quality in the Bogota Plain, Colombia. By combining fuzzy logic with neural networks, this method achieved significant regression with traditional water quality indices, emphasizing its reliability.

de Oliveira et al. (2014) developed a Fuzzy Raw Water Quality Index (IQABF) to evaluate the treatability of raw water. Compared to deterministic models, IQABF was more restrictive and consistent, demonstrating its ability to handle uncertainty and support water treatment processes.

Azzirgue et al. (2022) conducted an exploratory study using fuzzy logic and water quality indices (WQIs) to assess groundwater in the Jouamaa Hakama region, Morocco. They evaluated physical, chemical, and bacteriological parameters, finding that fuzzy logic effectively identified wells with poor water quality. The study highlights fuzzy logic's suitability for decision-making in resource-constrained settings.

The application of fuzzy logic has shown significant promise in environmental monitoring, particularly for predicting complex variables such as sea surface temperature and heavy metal concentrations in aquatic ecosystems. Kale (2020) developed a fuzzy logic model to predict sea surface temperature (SST) in the Çanakkale Strait, Türkiye. The author highlighted the fuzzy logic's capability to effectively model complex environmental phenomena with high accuracy. Sonmez et al. (2013) proposed a fuzzy logic-based classification model to evaluate heavy metal pollution in Turkey's Karasu Stream. Using a dataset of monthly measurements of metals like copper, zinc, and lead, the study demonstrated fuzzy logic's ability to provide nuanced evaluations, aiding environmental decision-making. A separate investigation by Sonmez et al. (2018) addressed challenges posed by heavy metal pollution in aquatic environments, which are typically difficult to model due to their nonlinear dynamics. Their findings underlined fuzzy logic's robustness and accuracy, suggesting its broader applicability in water quality monitoring.

A study by Fahmi et al. (2017) developed an environmental monitoring system using fuzzy logic to handle decision-making under uncertainty. This system was applied to monitor environmental conditions, including water quality, showcasing fuzzy logic's utility in real-time environmental assessments (Fahmi et al., 2017).

Burmakova (2024) discusses the integration of fuzzy logic with machine learning for predicting water quality in environments affected by oil spills. The study emphasizes the role of fuzzy logic in managing uncertainties inherent in environmental datasets. Mendoza Gómez et al. (2022) applied fuzzy logic to evaluate the Water Supply Management Index in Leon, Guanajuato, Mexico. This approach facilitated monitoring progress towards national development goals.

These global case studies underscore the adaptability of fuzzy logic models in diverse environmental contexts, demonstrating the method's potential to enhance water quality assessment and management, contributing to sustainable resource use and improved environmental outcomes (Gharibi et al., 2012).

Integration with Other Techniques

Fuzzy logic models are often integrated with other computational techniques like artificial neural networks (ANN) and genetic algorithms (GAs) to enhance prediction capabilities and model accuracy. Such hybrid models leverage the strengths of multiple approaches, providing robust solutions for complex environmental systems. This integration has been shown to improve the predictive performance of water quality models, making them more reliable for policy and decision-making (Abdullah et al., 2008).

The integration of fuzzy logic with other modeling techniques enhances its applicability and accuracy in water quality assessment. Hybrid models combining fuzzy logic with artificial neural networks (ANNs) improve predictive accuracy, as ANNs excel at pattern recognition within complex datasets (Yaseen et al., 2018).

Fuzzy logic's combination with genetic algorithms optimizes fuzzy model parameters, offering better performance. This hybrid approach effectively calibrates membership functions and rule sets, resulting in more accurate assessments (Ramadan et al., 2012).

Integrating geographic information systems (GIS) with fuzzy logic adds a spatial dimension to water quality modeling. GIS manages and analyzes spatial data, and when combined with fuzzy logic, develops maps depicting regional water quality variations, crucial for planning and management (Gharibi et al., 2012).

Some fuzzy logic models integrate statistical analysis techniques to enhance data interpretation and validation. This allows statistical significance testing within the fuzzy framework, providing robust decision-making foundations (Kambalimath & Deka, 2020).

Machine learning algorithms offer promising integration with fuzzy logic. Techniques like decision trees refine fuzzy logic models, improving their classification and prediction capabilities, effective in large, complex datasets typical of environmental monitoring (Rajaee et al., 2020).

The development of hybrid models combining fuzzy logic with these techniques is driven by the need for more comprehensive and flexible modeling tools. As environmental challenges become more complex, the demand for integrative approaches accommodating diverse data types and uncertainties grows (Sheehan & Gough, 2016).

Molato (2022) introduced AquaStat, an Arduino-based system for real-time water quality monitoring in tilapia aquaculture. The system utilized fuzzy logic for assessing parameters like pH and temperature, proving its efficacy in preventing fish kill events and enhancing aquaculture sustainability.

In practice, integrating fuzzy logic with other techniques significantly enhances model performance. In river water quality assessments, hybrid models demonstrate superior accuracy in predicting pollution levels compared to traditional models, crucial for effective environmental management and policy-making (Raman et al., 2009).

Advances in computational technology enable the processing of increasingly complex models, supporting ongoing development of integrative approaches. As these technologies evolve, opportunities for further enhancements in water quality modeling using fuzzy logic will likely expand, offering new innovation avenues (Wang et al., 2007).

Challenges and Future Directions

Despite its advantages, fuzzy logic modeling in water quality assessment faces several challenges. The subjective nature of defining membership functions and rule bases can lead to model output inconsistencies, highlighting the need for standardized model development approaches (Trach et al., 2022).

Computational complexity associated with large fuzzy systems is resource-intensive and time-consuming. This necessitates developing more efficient algorithms and computational techniques to streamline the modeling process (Abdullah et al., 2008).

Data quality and availability pose significant challenges to fuzzy logic modeling. In many regions, data collection is limited by logistical, financial, or technical constraints, affecting the accuracy and reliability of model predictions. Addressing these data gaps is critical for enhancing fuzzy logic models' applicability (Gharibi et al., 2012).

Future research directions include developing hybrid models integrating fuzzy logic with machine learning and artificial intelligence techniques. These models have the potential to improve model accuracy and adaptability, offering more precise water quality assessments (Raman et al., 2009).

Incorporating real-time monitoring data into fuzzy logic models is a promising future research avenue. This integration would enable dynamic and responsive water quality assessments, providing timely insights for decision-makers and stakeholders. As the field progresses, developing standardized frameworks and best practices for fuzzy logic modeling is essential. As noted by Semiromi et al. (2011), these frameworks will ensure consistency and reliability across different applications, enhancing the credibility of fuzzy logic models in environmental management.

Conclusion

Fuzzy logic modeling presents a promising avenue for water quality assessment, offering enhanced flexibility and precision. It also offers a robust approach to water quality assessment, capable of handling the inherent uncertainties and complexities of environmental data. Its adaptability to various contexts and integration with other techniques make it a valuable tool for sustainable resource management. As environmental monitoring becomes increasingly critical, the continued advancement of fuzzy logic methodologies will play a vital role in sustainable resource management. Ongoing research and development will continue to enhance its capabilities, paving the way for more effective environmental monitoring and management strategies.

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Chapter 6

ASSESSMENT OF THE MEAT YIELD OF FRESHWATER MULLET (*Squalius semae* TURAN, KOTTELAT & BAYÇELEBI, 2017) IN THE RESERVOIR OF THE TUNCELI UZUNÇAYIR DAM

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1. INTRODUCTION

The importance of nutrition for the healthy development, functioning and protection of the human body from diseases has become an increasingly emphasized issue in recent years (Mol, 2008). Seafood is a significant source of protein, vital nutrients, vitamins and minerals. It also contains high levels of two types of omega-3 polyunsaturated fatty acids: eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) (Sioen et al., 2007; Tilamia and Sampels, 2018). Seafood has a crucial role in combating hunger and malnutrition due to its nutritional properties. Recent studies have shown that Omega-3 fatty acids (EPA, DHA) found in seafood are helpful for brain health, bone formation, dementia, metabolism, and can reduce the risk of coronary heart disease, cardiovascular illnesses and cancer (Dyerberg, 1985; Lauritzen et al., 2000; Arts et al., 2001; Su et al., 2003; Watkins et al., 2003; Calder, 2004; Rudkowska et al.; 2010; Lund, 2013).

Squalius semae, which is among the economic species of Uzunçayır Dam Lake, is known as freshwater mullet. The freshwater mullet, *S. semae*, a common cyprinid species of economic importance, is extensively found in several regions including Europe, the Black Sea, Caspian Sea, Azov Sea basins, the Caucasus and Anatolia (Geldiay & Balık, 2009; Çoban et al., 2013; Aydın, 2015; Demirol et al., 2016; Özcan et al., 2017). This species, previously mentioned as "*Squalius cephalus*" in research conducted in the Euphrates River basin, was reported as "*Squalius semae*" in the genetic study conducted by Turan et al. (2017).

The higher the meat yield of the fish species consumed, the more likely it will be possible to meet the daily nutrient requirements of humans. In order for the nutrients in fish meat to be sufficiently effective in human nutrition, the meat yield of fish species that can be consumed should be as high as possible. Although meat yield in fish varies depending on various factors such as fish species, age, diet, sex and reproductive period, it has been reported that the average meat yield varies between 30-60 % (Çelikkale at al., 1977; Göğüş & Kolsarıcı, 1992). Understanding the flesh yield characteristics of fish is crucial for consumers and processing technologies due to its direct impact on product processing (Cibert et al., 1999). While there have been studies on fish meat productivity generally, none have focused on the freshwater mullet species that inhabit the area in question and are economically significant there. Therefore, this study set out to fill that gap by calculating the meat productivity of the species as well as the proportions of different body parts to total body weight.

Fig 1. *Squalius semae*

2. MATERIALS AND METHODS

2.1 Study area and sampling

Uzunçayır Dam Lake, where the study was conducted, was constructed on the Munzur River between 1996-2003 to produce energy (Gündüz et al., 2018). The samples used in the study were carried out on mullet fish sampled with monofilament gillnets with 44, 56, 64, 72, 80, 100 mm mesh size from Uzunçayır Dam Lake between March 2011 and April 2012.

2.2. **Morphological data and meat yield**

The captured fish were taken to the laboratory of Elazığ Fisheries Research Institute Directorate where essential measurements were conducted. Otoliths were utilized to determine the age of the fish (Aydın et al., 2004). The total, fork, and standard lengths of the fish samples were measured using a fish measuring ruler with a precision of 1 mm. After the abdomens of the examined specimens were opened, the internal organs were removed and the internal organ weights were determined, and the head and fins were cut and the head and fin weights were determined. The total body weight, viscera weight, head weight, skin weight, spine weight, and fin weight of the fishes were measured with a digital balance accurate to ±0.1 g.

In order to determine the weight of the bony structures, the samples were boiled in water for 5-10 minutes and then separated from the edible parts. Then the remaining meat particles were removed and weighed after drying with blotting paper. After the fins, head, bones, skin and internal organs were removed, the meat weights of the fish were weighed and the ratio of this to the total body weight was evaluated as edible % meat yield (Erkoyuncu et al., 1994).

Meat Yield (%) = (Wy/Wt) x 100

Wy: Weight of edible part (g)

Wt: Total fish weight (g)

2.3 Statistical analysis

The data obtained from the study are presented with mean values and standard deviation values. One-way analysis of variance (ANOVA) was used to compare parametric data with more than two variables and DUNCAN was preferred as a multiple comparison test. The results were evaluated at 95% confidence interval and $p<0.05$ significance level. All statistical analyses were performed in SPSS 22.0 package program.

3. RESULTS

The values obtained for total length and body weight, head, viscera, spine, skin and fin weight of freshwater mullet (*S. semae*) samples according to age groups are given in Table 1. The age distribution of 96 *S. semae* specimens was determined to be between I and VII years old. According to the age distribution (I, II, III, IV, V, VI, VII, VII), the average lengths varied between 14.70±0.31 – 31.13±1.15 cm, while the average body weights were determined as 30.98±2.94 – 389.43±46.48 g. Head weight of the examined specimens varied between 7.3 - 58.56 g, internal organ weight between 2.62 - 55.63 g, skin weight between 2.55 - 31.23 g, spine weight between 1.58 - 12.01 g, fin weight between 0.65 - 6.36 g and consumable meat portion between 18.28 - 225.64 g (Table 1).

Table 1. *Mean body weights of freshwater mullet (S. semae) in Uzunçayır Dam Lake according to age groups*

Age groups	N	Total length (cm)	Body weight (g)	Average weight of non-consumed body parts (g)					Consumable portion (fillet) (g)
				Head weight	Viscera weight	Skin weight	Spine weight	Fin weight	
I	6	14.70±0.31	30.98±2.94	5.3±0.62	2.62±0.40	2.55±0.19	1.58±0.27	0.65±0.06	18.28±1.68
II	13	20.1±0.70	90.65±9.13	14.37±1.44	9.41±0.99	7.51±0.77	3.14±0.24	1.61±1.17	54.34±5.77
III	22	23.35±0.38	156.98±7.92	22.94±1.30	18.86±1.24	12.96±0.70	5.26±0.27	2.49±0.13	94.46±5.21
IV	21	24.99±0.64	191.67±15.15	30.9±2.60	23.79±2.06	15.28±1.45	6.76±0.60	3.11±0.27	111.83±9.03
V	17	26.96±0.82	253.65±26.79	40.18±4.37	31.81±3.73	19.78±2.09	8.46±0.88	4.09±0.41	149.32±16.31
VI	10	28.56±0.95	326.78±34.63	49.2±5.57	42.84±5.79	28.58±3.50	9.5±0.84	5.17±0.55	191.49±21.47
VII	7	31.13±1.15	389.43±46.48	58.56±8.76	55.63±7.06	31.23±4.13	12.01±1.46	6.36±0.54	225.64±26.79

The ratios of head, viscera, skin, spine, fins and meat productivity to body weight of *S. semae* specimens according to age groups are given in Table 2. It was determined that meat productivity of *S. semae* was distributed between 57.94 - 60.18 g %. Other values determined were: head weight/body weight 14.61 - 17.10 %; visceral weight/body weight 8.45 - 14.28 %; skin weight/body weight 7.80 - 8.75 %; spine weight/body weight 2.91 - 5.11 %; fin weight/body weight 1.58 - 2.10 %.

The average meat yield for all samples was 59.11 %, with the highest meat yield (60.18 %) in the III age group and the lowest meat yield (57.94 %) in the VII age group. The average head weight was 15.56 %, internal organ weight was 12.03 %, skin weight was 8.15 %, spine weight was 3.45 % and fin weight was 1.66 %.

Table 2. *Relationship between body weights and other parts of freshwater mullet (S. semae) in Uzunçayır Dam Lake according to age groups (%)*

Age groups	N	Average weight of body parts not consumed (%)					Consumable portion (fillet) (%)
		Head weight	Viscera weight	Skin weight	Spine weight	Fin weight	
I	6	17.10	8.45	8.23	5.11	2.10	59.01
II	13	15.85	10.39	8.28	3.46	1.77	59.95
III	22	14.61	12.01	8.26	3.35	1.58	60.18
IV	21	16.12	12.41	7.97	3.53	1.62	58.34
V	17	15.84	12.54	7.80	3.33	1.61	58.87
VI	10	15.06	13.11	8.75	2.91	1.58	58.60
VII	7	15.04	14.28	8.02	3.09	1.63	57.94
Total	96	15.56	12.03	8.15	3.45	1.66	59.11

The relationships between fish weights and various body parts were examined; $y=0.5868x+0.3909$ ($R^2= 0.991$) between fish weight and fillet weight. $y=0.6156x+1.2093$ ($R^2= 0.9919$) between fish weight and carcass weight. $y=0.0288x+0.8184$ ($R^2= 0.8946$) between fish weight and bone weight. $y=0.1338x-1.5378$ ($R^2= 0.\ 8532$). $y=0.0806x+0.1658$ ($R^2= 0.9022$) between fish weight and skin weight. $y=0.1551x-0.1136$ ($R^2= 0.9618$) between fish weight and head weight. $y=0.0152x+0.1994$ ($R^2= 0.9377$) between fish weight and fin weight (Fig 2), (X=fish weight (g), y=body parts weight (g)).

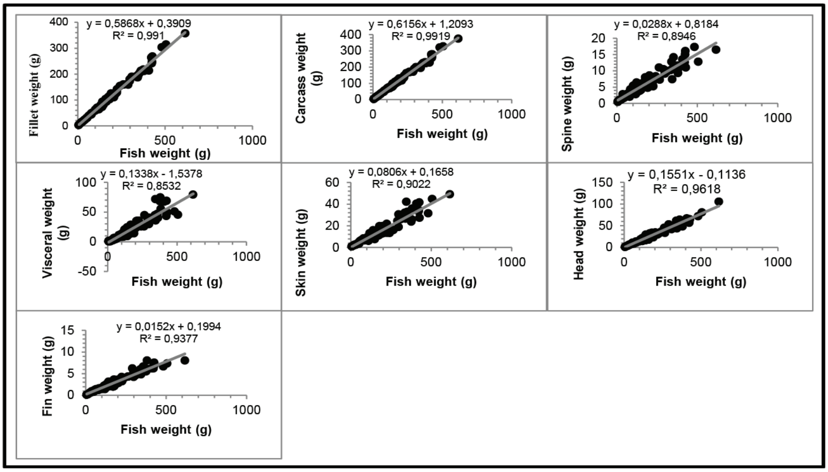

Fig 2. *Relationships between fish weight and various body parts in mullet fish*

4. DISCUSSION

In freshwater mullet (*Squalius semae*), the mean lengths were 14.70±0.31-31.13±1.15 cm and mean weights were 30.98±2.94-389.43±46.48 g according to age groups (I -VII). The average % meat yield of the consumable parts was 59.11, the lowest meat yield was found in the VII age group (57.94 %) and the highest meat yield was found in the III age group (60.18 %). The average head weight of freshwater mullet analyzed according to age groups was 15.56%, internal organ weight 12.03 %, skin weight 8.15 %, spine weight 3.45% and fin weight 1.66 %.

Meat yield of fish varies according to species, age, sex, breeding season and nutritional status of the environment. In our study, the average meat yield was determined as 59.11 %, whereas Çelikkale (1977) determined meat yield as 56.5 % in cultured carp and Aras et al. (1992) determined average meat yield as 61.44 % in *Capoeta umbla* species in Karasu River. Similarly, Özdemir and Temizer (1992) determined the average meat yield of carp as 61.53 % in their study conducted in Çıldır Lake. Şevik (1997), on the other hand, determined the meat yield of *C. regium* as 70.39 % in his study carried out in the Euphrates River. Duman et al. (2003) calculated the meat yield of the *B. c. pectoralis* in the Keban Dam Lake. Alagöz Ergüden (2013) reported the average meat productivity of *C. regium* as 79.40 % in their study conducted in Seyhan Dam Lake. In previous research conducted on various species within the Cyprinidae family, Kurt Kaya et al. (2013) found that the average meat output of *Capoeta trutta* was 57.57% and the average meat yield of *Capoeta umbla* was 61.92 %. In their study conducted in Karacaören Dam Lake, Özcan and Balık (2006) found that the average meat yield of *Chondrostoma meandrense* was 66.95 %. Similarly, Diler and Becer (2001) concluded that the meat yield of *Vimba vimba tenella* ranged from 63.76 % to 71.02% for males and from 67.97% to 70.06% for females. The study examined *Chondrostoma regium*, a species from the Cyprinidae family, and found that the average meat output was 66.72 % (Kurt Kaya et al., 2022). Şaşı (2009) determined that the average meat yield of *C. bergamae* was 66.31 %. Aydın et al. (2009) calculated the skin, fin, head, skeleton and internal organ ratios of rainbow trout according to age groups as 9.94-13.13%; 1.04-1.32%; 9.26-12.93%; 3.32-4.60% and 11.45-16.72%, respectively. Duman et al. (2011) discovered that the IV age group had the highest meat yield (61.07 %) and the I age group had the lowest meat yield (58.04 %) in *S. t. macrostigma*. Şaşı and Saudiu (2018), mentioned that the average performance of carcass weight, head weight, visceral weight and fin weight were found to be 67.10 %, 16.00 %, 9.90 % and 6.30 %, respectively, from the study conducted on *Squalius cephalus*.

When comparing the average meat yield values obtained in this study with those of other studies, it is evident that they exhibit similar results. However, it is also apparent that certain studies display variations. These variations are believed to be influenced by factors such as fish size, fishing season, species, age, reproductive stage, food, and stomach content at the moment of catch.

5. CONCLUSION

In conclusion, it is seen that *S. semae*, which has a wide geographical distribution and economic importance in our country, has an important potential among other fish species as well as carp species in terms of meat yield. In the light of the findings, this species can be considered as an important source to meet the daily animal protein needs of the people in the region.

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Chapter 7

RELATIONSHIPS BETWEEN OTOLITH DIMENSIONS-FISH DIMENSIONS OF *Paracapoeta trutta* (HECKEL, 1843) IN THE MURAT RIVER (PALU-ELAZIĞ)

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INTRODUCTION

Paracapoeta trutta (Heckel, 1843) is a species of cyprinid fish that is indigenous to the Middle East (Syria, Iraq, Iran and Turkey), covering most of the Iranian region of the Tigris-Euphrates basin (Abdoli, 2000). The body is laterally flattened and characterized by a robust build and medium-sized scales covering its body. The head length is always smaller than the maximal body height and is 4.5-5 times the standard length. The mouth is small and located on the underside of the head, bearing a pair of short barbels at the corners. The barbel length is shorter than the eye diameter, and the eye diameter is 4-6 times the head size. The lower lip is horny and sharp-edged. A scaleless carina is seen on the dorsal region in front of the dorsal. The last bony ray of the dorsal fin is very well developed, which easily distinguishes this species from others. This ray is very well ossified, carries very strong teeth along its posterior margin, and its length is approximately twice that of the soft rays. The anal fin is much smaller than the dorsal fin and when laid back its free tip does not reach the base of the caudal fin. The caudal fin is deeply forked and the tips of its lobes are pointed. The color is dark on the back, but turns gray-brown on the sides and under the belly. On the dorsal half of the body (in the upper zone of the lateral line), there are irregularly distributed small and black spots. The same spots can often be seen on the dorsal fin. The other fins are spotless (Geldiay and Balık, 2009). It is also a dominant and widely distributed species with high economic value in inland waters (Aydın et al., 2003; Aydın et al., 2012; Kurt Kaya et al., 2013; Çat and Yüksel, 2014; Gündüz et al., 2018).

In bony fish, the inner ear region is located in the otic capsule. There are three semicircular canals in each ear region and structures called 'otoliths' made of calcium carbonate in the cavities within the sac. Each of these sacs and the otoliths within them are named as the sacculus (sagitta), the asteriscus (asteriscus), and the utriculus (lapillus) (Secor et al., 1992). Bony fish maintain their balance thanks to otoliths and at the same time, these otoliths perform the function of hearing (Campana, 1999).

In fish, otolith morphology is used in many areas such as the identification of new fish species, determination of phylogenetic relationships, taxonomic revision, ecomorphology studies and determination of relationships between otolith growth and fish growth (Tuset et al., 2008). Otolith formation and growth depend on environmental factors. Otoliths, which are generally used in fish growth and age determination, explain the biological formation of fish and are important studies for fish stocks (Samsun and Samsun, 2006).

There are two important reasons for knowing the correspondence between otolith features and fish size. The first reason is that the size of fish can be estimated from otoliths found in archaeological studies and in the stomachs of predatory fish, and the other is that after determining the age of otoliths, when unexpected results are obtained, comparison with fish size can be made to ensure accuracy (Echeverria, 1987).

For freshwater species in our inland waters, the fish length-otolith biometry relationship has been studied by many researchers (Şen et al., 2001; Şen et al., 2002; Aydın et al., 2004; Samsun and Samsun, 2006; Eroğlu and Şen, 2009; Başusta et al., 2013a; Başusta et al., 2013b; Karachle et al., 2015; Dörtbudak and Özcan 2015; Düşükcan et al., 2015; Doğan and Şen 2017; Gündüz et al., 2017; Düşükcan 2018; Düşükcan and Çalta 2018; Başusta and Tan 2019; Yüksel and Aydın, 2023).

This study was carried out to determine the relationship between otolith dimensions and fish dimensions of *Paracapoeta trutta* in the Murat River (Palu-Elazığ).

MATERIAL and METHODS

The Murat River is the longest of the two main branches of the Euphrates River in Eastern Anatolia, stretching 722 km. It forms from the confluence of streams originating from Aladağ and Muratbaşı Mountain, located to the north of Lake Van (Bulut and Saler, 2014). The river flows through the Diyadin Plain, where it gathers tributaries from the Eleşkirt area near Ağrı, and then continues southwestward towards the Malazgirt Plain. After absorbing the Hınıs Stream from the Bingöl Mountains, it curves sharply and enters the Muş Plain from the north, receiving the Karasu Stream, which descends from Mount Nemrut. The river continues its westward journey, passing through narrow passages near Palu. At this point, it takes in the Harinket Stream from the left, flowing from the Ulu Plain of Elazığ, as well as the Munzur-Peri Stream from the right, the most significant tributary from Tunceli. The Murat River ultimately converges with the Karasu River at Keban, which is another tributary of the Euphrates (URL-1, 2024). Fish sampling locations the Murat River (Palu Elazığ), are indicated in Figure 1 (Station 1: 38°67’94.61”N 39°89’56.46”E; Station 2: 38°63’43.97”N 39°73’10.54”E).

Figure 1. *Sampling stations (URL-2, 2020).*

In this study, 53 *P. trutta* fish were caught with a gillnet with 25-45 mesh size in March 2020. The caught samples were preserved in 5% formaldehyde solution. The total length (TL) of the fish brought to the laboratory was measured with a ± 1 mm precision measuring board and their weights were weighed with 0.01 g. Sex determinations were made macroscopically. The right and left otoliths of the fish were removed with the help of forceps and cleaned in 10% NaOH solution, then dried and preserved. Otolith length (OB) and otolith width (OG) were measured with a Motic brand binocular microscope and an Olympus brand ocular micrometer (Figure 2). Right and left otolith weights (OA) were weighed with a BEL ENGINEERING brand precision scale (± 0.0001 g). The relationships between otolith dimensions and fish length and fish weight were calculated using the linear (y = ax + b) regression model. Repeated measurements were made on the right and left otolith dimensions. It was calculated with Student t-test that there was no difference between the right and left otoliths and right otolith measurements were used in the calculations.

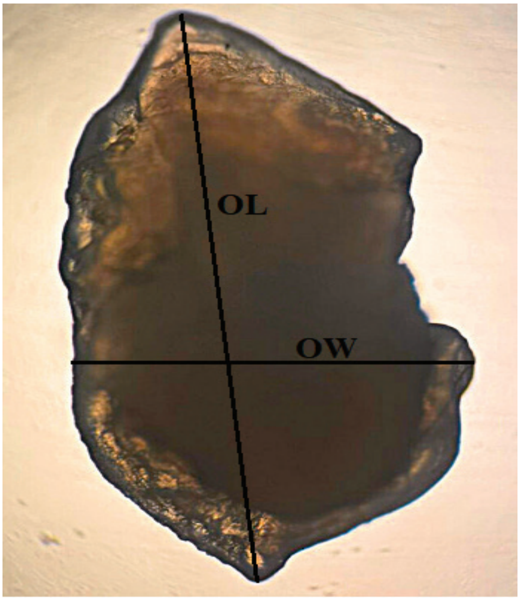

Figure 2. *Otolith length (OL) and otolith width (OW) in P. trutta from Murat River*

RESULTS and DISCUSSION

To investigate the otolith biometry of *P. trutta* in the Murat River, 53 fish (21 females and 32 males) were examined. It was determined that the examined fish varied between total length: 196-367 mm; otolith length: 1.76-3.56 mm; otolith width: 1.24-2.46 mm and otolith weight: 0.0016-0.0046 g (Table 1). The smallest otolith length value in *P. trutta* obtained throughout the study was 1.76 mm and was detected in the female fish with a total length of 196 mm and a weight of 86 g. The largest otolith length was 3.56 mm and was detected in the male fish with a total length of 367 mm and a weight of 415 g. The differences between right and left otoliths and otolith length, otolith width and otolith weight according to gender were found to statistically insignificant ($p>0.05$). Therefore, since there was no difference between the right and left otoliths, the right otolith was used in the study. Otolith length, otolith width, otolith weight, total length and fish weight values of *P. trutta* in the Murat River according to sex are given in Table 1.

Table 1. *Otolith length, otolith width, otolith weight, total length and total weight values of P. trutta in the Murat River according to sex.*

Sex		n	Min	Max	Mean	SD	SE
Female	Otolith length (mm)	21	1.76	3.10	2.55	0.37	0.08
	Otolith width (mm)	21	1.24	2.21	1.83	0.26	0.05
	Otolith weight (g)	21	0.0034	0.0079	0.0030	0.0007	0.0002
	Total length (mm)	21	196	338	283.02	40.30	8.79
	Total weight (g)	21	86	387	255.28	73.67	16.08
Male	Otolith length (mm)	32	1.80	3.56	2.60	0.39	0.07
	Otolith width (mm)	32	1.31	2.46	1.88	0.27	0.05
	Otolith weight (g)	32	0.0036	0.0101	0.0032	0.0007	0.0001
	Total length (mm)	32	199	367	288.75	40.93	7.24
	Total weight (g)	32	103	415	267.25	76.49	13.52
All	Otolith length (mm)	53	1.76	3.56	2.59	0.40	0.06
	Otolith width (mm)	53	1.24	2.46	1.86	0.28	0.04
	Otolith weight (g)	53	0.0034	0.0101	0.0032	0.0007	0.0001
	Total length (mm)	53	196	367	287.0	42.48	5.84
	Total weight (g)	53	86	415	263.83	79.73	10.95

The total length-otolith length relationship of *P. trutta* in the Murat River was found as OL = 0.0081TL + 0.1982 (R^2 = 0.8826) in females, OL = 0.0091TL + 0.0295 (R^2 = 0.8663) in males and OL = 0.0088TL + 0.0688 (R^2 = 0.8579) in all individuals (Figure 3).

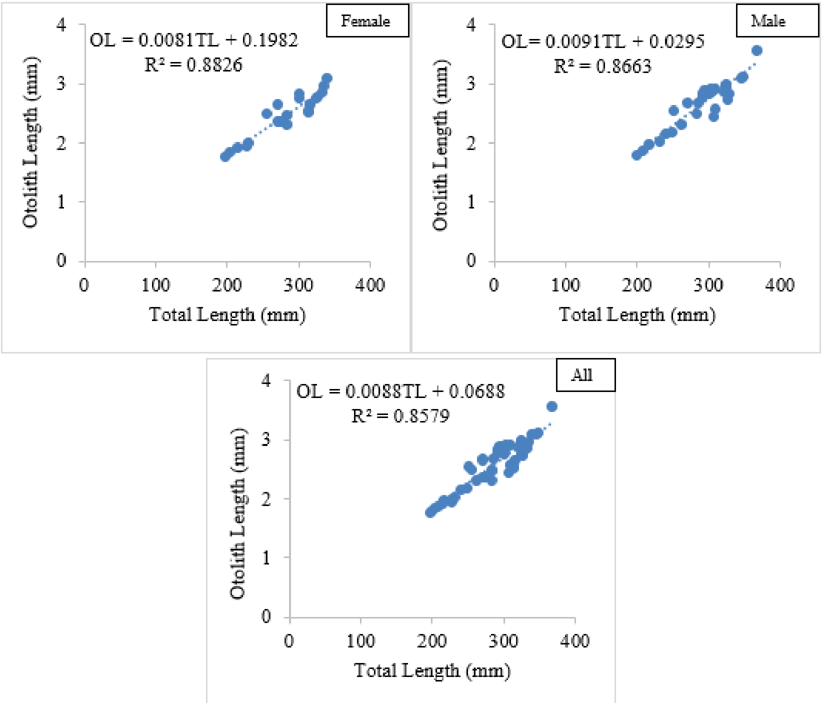

Figure 3. *Total length-otolith length relationships of P. trutta in the Murat River*

The total length-otolith width relationship of *P. trutta* in the Murat River was found as OW = 0.0055TL + 0.2788 (R^2 = 0.797) in females, OW = 0.0062TL + 0.0894 (R^2 = 0.8158) in males and OW = 0.0059TL + 0.1656 (R^2 = 0.8072) in all individuals (Figure 4).

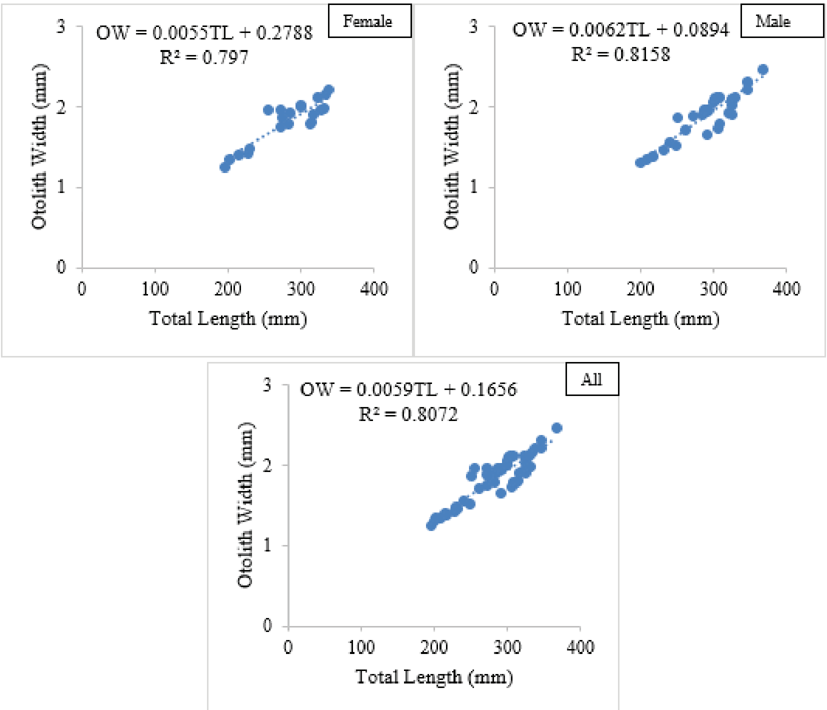

Figure 4. *Total length-otolith width relationships of P. trutta in the Murat River*

The total length-otolith weight relationship of *P. trutta* in the Murat River was found as OWe = 2E-05TL - 0.0014 (R^2 = 0.7177) in females, OWe = 3E-05TL - 0.0036 (R^2 = 0.6063) in males and OWe = 3E-05TL - 0.0027 (R^2 = 0.6273) in all individuals (Figure 5).

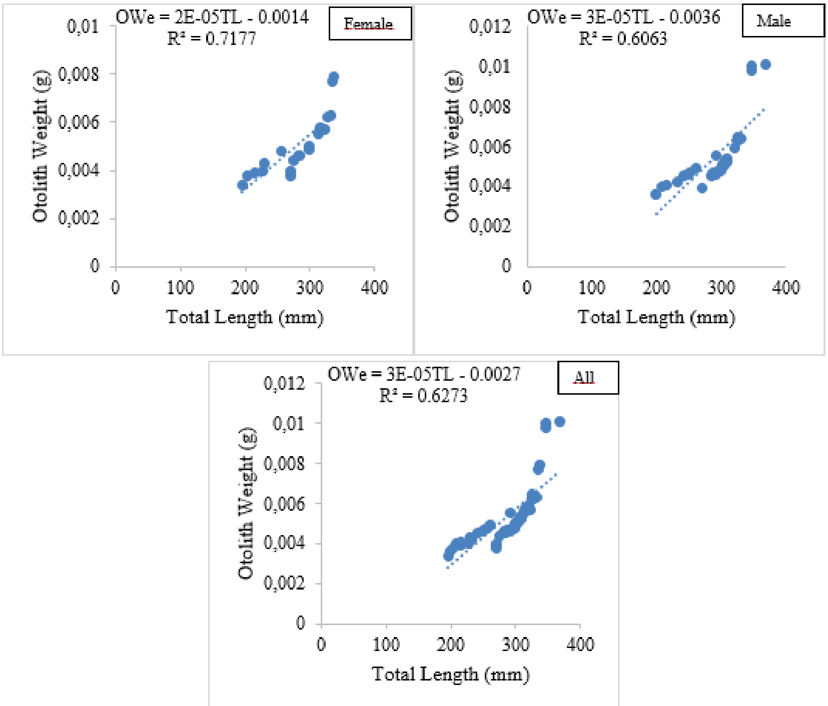

Figure 5. *Total length-otolith weight relationships of P. trutta in the Murat River*

The total weight-otolith weight relationship of *P. trutta* in the Murat River was found as OWe = 1E-05TW + 0.0019 (R^2 = 0.7713) in females, OWe = 2E-05TW + 0.0005 (R^2 = 0.7156) in males and OWe= 2E-05TW + 0.0012 (R^2 = 0.7077) in all individuals (Figure 6).

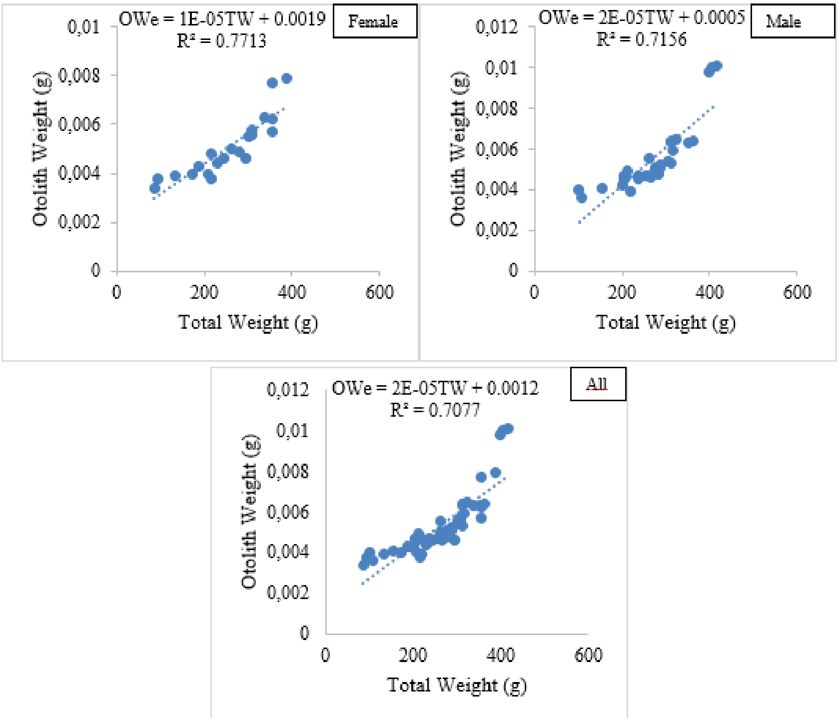

Figure 6. *Total weight-otolith weight relationships of P. trutta in the Murat River*

The otolith length-otolith width relationship of *P. trutta* in the Murat River was found as OW = 0.687OL + 0.1159 (R^2 = 0.9347) in females, OW = 0.6839OL + 0.0821 (R^2 = 0.9593) in males and OW = 0.6728OL + 0.1273 (R^2 = 0.946) in all individuals (Figure 7).

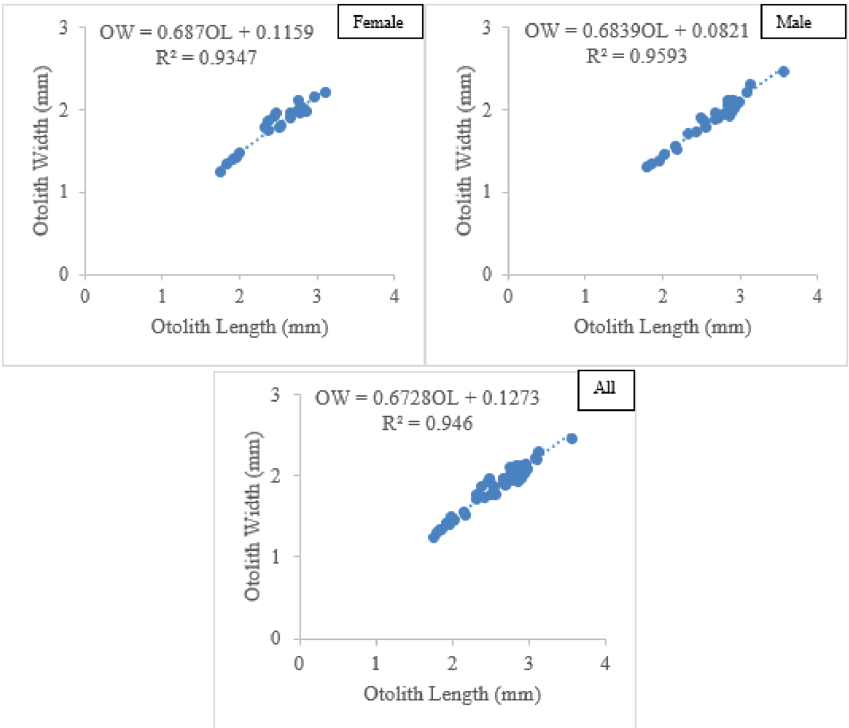

Figure 7. *Otolith length-otolith width relationships of P. trutta in the Murat River*

The otolith length-otolith weight relationship of *P. trutta* in the Murat River was found as OWe = 0.0026OL - 0.0014 (R^2 = 0.6749) in females, OWe = 0.0029OL - 0.0022 (R^2 = 0.4884) in males and OWe = 0.0027OL - 0.0018 (R^2 = 0.5456) in all individuals (Figure 8).

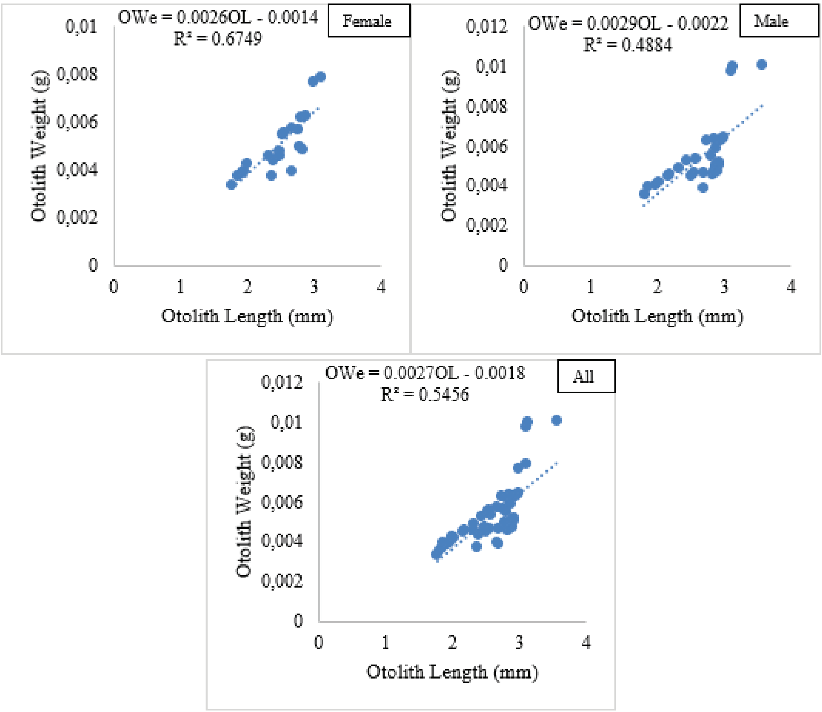

Figure 8. *Otolith length-otolith weight relationships of P. trutta in the Murat River*

The otolith width-otolith weight relationship of *P. trutta* in the Murat River was found as OWe = 0.0033OW - 0.001 (R^2 = 0.5538) in females, OWe = 0.0041OW - 0.0023 (R^2 = 0.479) in males and OWe = 0.0038OW - 0.0018 (R^2 = 0.5041) in all individuals (Figure 8).

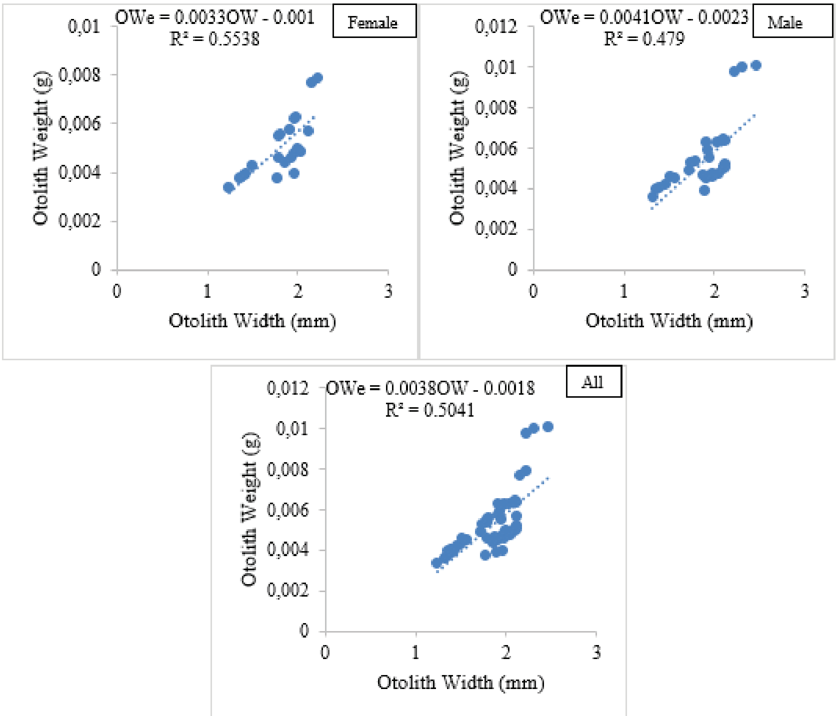

Figure 9. *Otolith width-otolith weight relationships of P. trutta in the Murat River*

According to the coefficients of determination, the lowest relationship was found between otolith width-otolith weight in male individuals ($R^2 = 0.479$) and the highest relationship was found between otolith length-otolith width in male individuals ($R^2 = 0.9593$). In their study investigating the relationship between otolith dimensions and fish length of red spotted trout (*Salmo trutta macrostigma*) in the Munzur River, Başusta et al. (2013a) reported that there was a parallelism between fish length and otolith length and found a high correlation value. In their study on otolith biometry and fish length of *Lepidotrigla dieuzeidei* living in the Mediterranean, Başusta et al. (2013b) stated that there was no statistically significant difference ($p>0.05$) between right and left otolith dimensions and that they could be used without distinguishing one from the other. Karachle et al. (2015) reported that the relationships between otolith dimensions and fish length of *Synchiropus phaeton* and *Trachinus draco* fish in İskenderun Bay had a strong and positive correlation. In their study on the relationship between otolith biometry and fish length of siraz fish (*Capoeta umbla*) in İkizce Stream (Şırnak), Dörtbudak and Özcan (2015) reported that there was no statistically significant difference in otolith length and otolith width according to the right and left regions. In their study on otolith biometry and fish length relationship in *Capoeta trutta* living in Keban Dam Lake, Doğan and Şen (2017) found a positive relationship between otolith length, width, weight and total length. They also reported that the difference in terms of the sizes of the right and left otoliths was insignificant (P>0.05). In their study on fish length and otolith biometry in *Capoeta trutta* in Özlüce Dam Lake, Düşükcan (2018) reported that; According to otolith biometry-fish length relationship equations, it was reported that there were strong positive relationships between total length and otolith length, width and weight, and that the coefficients of determination were high, and there was no statistically significant difference (P>0.05) between the right and left otoliths. In their study on total length-otolith biometry in *Barbus gyrpus* fish species caught in Karakaya Dam Lake, Düşükcan and Çalta (2018) found a strong positive relationship between total fish length and otolith biometry. In their study on otolith size-fish size relationships in *Uranoscopus scaber* caught in the Northeastern Mediterranean, Başusta and Tan (2019) reported moderate and strong positive relationships between fish length and weight and otolith sizes according to the regression analysis results.

In conclusion, this study has investigated the relationships between otolith sizes and fish sizes of *P. trutta* in the Murat River for the first time. It can be said that otolith growth occurs along with the growth of the fish and that otolith length and fish length increase in parallel. Since the difference between the sizes of the right and left otoliths was found to be insignificant (P>0.05), either the right or left otolith pair can be preferred in new studies to be conducted on this species. The findings obtained in the study are parallel to the findings in previous studies. Thus, this study will guide otolith biometry studies to be conducted on *P. trutta* living in different water sources.

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Chapter 8

CHEMICAL COMPOSITION AND FIBER PROPERTIES OF WOOD OF FIR SPECIES NATURALLY GROWING IN TÜRKİYE: A LITERATURE REVIEW

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INTRODUCTION

Fir trees are evergreen coniferous trees belonging to the genus *Abies*, which is part of the Pinaceae family. They are closely related to pines and spruces. The *Abies* genus consists of around 50 species, including numerous subspecies, varieties, and nearly 150 cultivars. Firs are evergreen trees commonly found in forests, characterized by a pyramidal shape when young and a conical crown as they mature. Young trees have light grey, thin bark, which becomes thick and cracked with age (Yener, 2012). Mediterranean firs have fragmented and restricted distributions, consisting mainly of relict populations of predominantly endemic species. The majority of fir species are concentrated in the Black Sea region and the eastern Mediterranean (Alizoti et al. 2011).

Fir wood is typically regarded as having lower technical value than pine wood, but it is still commonly used in carpentry for its softness and ease of working. It is also utilized in general construction, paper production, composite wood and glued products, plywood, veneer, panels, and poles, as well as for fuel wood. Additionally, the cones, buds, bark and of fir trees may have considerable amounts of fine, resin-rich turpentine (Alizoti et al. 2011). The *Abies* genus plays a crucial role both economically and ecologically. Economically, firs offer valuable resources such as timber, resins, Christmas trees, and ornamental plants. Ecologically, they enhance biodiversity, support wildlife, prevent soil erosion, and assist in water regulation and carbon sequestration. These trees are essential for maintaining forest health, providing ecosystem services, and supporting climate regulation, making them a key component of both natural environments and human-managed landscapes.

A thorough understanding of the chemical composition and fiber properties of wood is essential to fully exploit its potential in various applications. This paper offers a detailed review of the chemical composition and morphological properties of naturally occurring fir species in Türkiye.

TURKISH FIR (*Abies bornmuelleriana* Mattf.)

Turkish fir (*Abies bornmuelleriana*), also known as Bornmüller's fir, is a rare coniferous tree native to northern Türkiye, primarily along the Black Sea coast (Hrivnák et al. 2017). It grows at high altitudes, from sea level to 2 000 meters, often in mixed stands with other species. This tree is a hybrid, likely between the Grecian fir (*Abies cephalonica*) and Caucasian fir (*Abies nordmanniana*). Turkish fir prefers acidic, well-drained soils and tolerates a wide range of temperatures and harsher climatic conditions compared to other conifers (EUFORGEN, 2024a).

The tree is known for its silvery foliage, which is visible due to its upward-growing needles, and its pleasant fragrance, making it a popular ornamental species. It has economic, ecological, and recreational value and is a first-class forest tree, reaching heights of 30-40 meters in suitable conditions. Endemic to Türkiye, it is primarily found in the Western Black Sea and Marmara regions (Figure 1), where it forms beautiful stands with species like *Fagus orientalis* and *Pinus sylvestris* (Yaltırık and Efe, 2000).

Figure 1. The distribution area of Turkish fir (EUFORGEN, 2024a).

The chemical composition of Turkish fir wood is detailed in Table 1.

Table 1. Chemical composition of Turkish fir wood from various regions.

Geographical Region	H (%)	α-C (%)	L (%)	HWS (%)	CWS (%)	1% NaOH (%)	E (%)	A (%)	Reference
-	70.67	-	28.64	2.24	1.47	-	2.88[1]	0.46	Tank (1964)
-	83.30	57.06	28.51	1.65	-	10.57	1.89[1]	0.25	Uçar and Yılgör (1995)
Düzce	78.80	-	27.92	2.20	-	11.64	0.15[2]	0.30	Özdemir (2004)
Bursa	78.28	-	27.68	2.35	-	11.71	0.36[2]	0.39	Özdemir (2004)
Bartın	76.03	51.46*	28.27	2.72	4.21	11.02	-		Alkan (2004)
Bartın	72.8	56.0	26.7	2.3	0.6	7.3	-	-	Istek et al. (2005)
-	70.18	41.96	27.68	2.89	1.37	9.94	4.86[1]	0.36	Temiz (2006)
Bartın	75.35	49.21	27.89	-	-	-	1.84[2]	-	Tumen et al. (2010)

Bolu	71.84	-	28.38	3.64	-	-	-	-	Akgül and Korkut (2012)
Bartın (HW)	70.02	46.37	26.64	2.32	1.50	7.57	1.78[2]		Ataç and Eroğlu (2013)
Bartın (SW)	70.78	45.42	27.79	2.43	1.35	8.60	1.82[2]		Ataç and Eroğlu (2013)
Karabük	73.70	43.53	30.33	-	-	-	2.69	0.36	Özbay (2015)
West Black Sea	79.86	55.61	29.50	3.60	2.33	-	2.68[2]	-	Sivrikaya et al. (2016)

H: Holocellulose, **α-C:** α-cellulose, **L:** Lignin, **HWS:** Hot water solubility, **CWS:** Cold water solubility, **1% NaOH:** 1% NaOH solubility, **E:** Extractives, **A:** Ash, SW: Sapwood, HW: Heartwood, *Kürschner-Hoffer, [1]Alcohol/benzene, [2]Ethanol.

The fiber properties of Turkish fir wood are detailed in Table 2.

Table 2. Fiber properties of Turkish fir wood from various regions.

Geographical Region	**FL (mm)**	**FW (µm)**	**LW (µm)**	**CWT (µm)**	**SR**	**FR**	**RR**	**Reference**
Bolu	3.35	38.90	-	7.64	-	-	-	Aytuğ (1959)
- (Normal stem diameter)	3.74	37.87	-	5.74	-	-	-	Tank (1964)
- (Large stem diameter)	3.82	41.56	-	6.26	-	-	-	Tank (1964)
Bartın	4.09	49.02	33.65	7.68	83.54	68.63	0.45	Alkan (2004)
Bartın	2.90	39.70	19.60	10.10	-	-	-	Istek et al. (2005)
Bartın (HW)	2.75	41.33	31.72	5.26				Ataç and Eroğlu (2013)
Bartın (SW)	3.58	49.58	39.50	5.04				Ataç and Eroğlu (2013)

FL: Fiber length, **FW:** Fiber width, **LW:** Lumen Width, **CWT:** Cell wall thickness, **SR:** Slenderness ratio (FL/FW), **FR:** Flexibility ratio [(LW/FW)*100], **RR:** Runkel ratio [(2xCWT)/LW], EW: Earlywood, LW: Latewood, SW: Sapwood, HW: Heartwood.

CAUCASIAN FIR (*Abies nordmanniana* (Steven) Spach)

Caucasian fir (*Abies nordmanniana*) is a coniferous evergreen tree native to the coastal mountains of the Black Sea in Türkiye and southern Georgia (Figure 2) (Nielsen et al. 2020). Its pure stands are rare in Türkiye. It often grows alongside other species like *Fagus orientalis*, but is not found in large (Yaltırık and Efe, 2000).

It thrives in moist, mountainous regions at elevations between 900 and 2 200 meters, though it can also be found at sea level. This species is well-adapted to cold climates and heavy snowfalls, growing up to 60 meters tall with thick, grey bark for protection against the elements (EUFORGEN, 2024b).

Figure 2. The distribution area of Caucasian fir (EUFORGEN, 2024b).

Caucasian fir is economically important in Türkiye, with its white, softwood used in general construction, veneer, plywood, and the paper industry. The tree's long needle retention makes it a popular choice for Christmas trees in Europe. It has a pyramidal shape with horizontal branches and dense foliage (Nielsen et al. 2020). The needles are dark green with distinct stomata bands, and the cones are reddish-brown, averaging 15-16 cm in length (Yaltırık and Efe, 2000). The chemical composition of Caucasian fir wood is detailed in Table 3.

Table 3. Chemical composition of Caucasian fir wood from various regions.

Geographical Region	H (%)	α-C (%)	L (%)	HWS (%)	CWS (%)	1% NaOH (%)	E (%)	A (%)	Reference
-	69.85	-	30.02	1.71	1.04	8.85	3.91[1]	0.56	Tank (1964)
Artvin	76.52	-	28.95	1.87	-	12.12	0.66[2]	0.37	Özdemir (2004)
Trabzon	77.97		27.54	2.16	-	12.36	0.18[2]	0.33	Özdemir (2004)
Trabzon	84.63	51.11	27.25	1.71	4.39	11.35	-	-	Alkan (2004)
- (SW)	-	45.10	28.10	3.80	2.20	12.20	2.30[1]	0.50	Hafızoğlu and Usta (2005)
- (HW)	-	44.30	29.50	6.30	4.40	15.70	5.40[1]	0.80	Hafızoğlu and Usta (2005)
Artvin	73.88	44.82	27.34	2.50	2.78	9.12	0.24[1]	0.31	Odabaş Serin and Güleç (2014)

Giresun (1.30 m stem height)	75.38	-	28.15	-	-	-	-	-	Topaloglu and Erisir (2018)
Giresun (6.30 m stem height)	76.73	-	28.49	-	-	-	-	-	Topaloglu and Erisir (2018)
Giresun (12.30 m stem height)	77.04	-	29.53	-	-	-	-	-	Topaloglu and Erisir (2018)
Artvin (RW)	60.81	35.77	30.28	4.02	2.37	14.96	7.65[3]	0.72	Peşman et al. (2021)
Kastamonu (OW)	83.00	42.07	26.76	1.56	1.40	9.37	2.30[2]	0.37	Kaz (2022)
Kastamonu (CW)	79.07	30.69	30.14	3.00	2.27	13.15	3.06[2]	0.50	Kaz (2022)
Kastamonu	-	-	28.65	-	-	-	-	-	Beram and Yasar (2022)

H: Holocellulose, **α-C:** α-cellulose, **L:** Lignin, **HWS:** Hot water solubility, **CWS:** Cold water solubility, **1% NaOH:** 1% NaOH solubility, **E:** Extractives, **A:** Ash, SW: Sapwood, HW: Heartwood, OW: Opposite wood, CW: Compression wood, RW: Root wood.[1]Alcohol/benzene, [2]Ethanol, [3]Acetone.

The fiber properties of Caucasian fir wood are detailed in Table 4.

Table 4. Fiber properties of Caucasian fir wood from various regions.

Geographical Region	**FL (mm)**	**FW (µm)**	**LW (µm)**	**CWT (µm)**	**SR**	**FR**	**RR**	**Reference**
Trabzon	2.88	43.0	-	5.57	-	-	-	Aytuğ (1959)
- (Normal stem diameter)	3.85	39.82	-	5.54	-	-	-	Tank (1964)
- (Large stem diameter)	3.93	40.43	-	6.18	-	-	-	Tank (1964)
Trabzon	3.09	42.52	34.72	3.90	72.63	81.65	0.22	Alkan (2004)
- (MADw 10536)	3.06	36.70	16.40	-	-	-	-	Esteban et al. (2009)
- (BFH 14031)	3.03	36.80	18.00	-	-	-	-	Esteban et al. (2009)
Giresun (1.30 m stem height)	2.67	33.88	20.47	6.71	-	-	-	Topaloglu and Erisir (2018)
Giresun (6.30 m stem height)	2.31	36.95	24.90	6.03	-	-	-	Topaloglu and Erisir (2018)
Giresun (12.30 m stem height)	2.47	35.92	27.17	4.37	-	-	-	Topaloglu and Erisir (2018)
Artvin (RW)	4.67	60.30	48.22	6.04	-	-	-	Peşman et al. (2021)
Kastamonu (OW)	2.54	39.42	18.77	10.13	-	-	-	Kaz (2022)
Kastamonu (CW)	2.16	34.55	14.28	10.32	-	-	-	Kaz (2022)

FL: Fiber length, **FW:** Fiber width, **LW:** Lumen Width, **CWT:** Cell wall thickness, **SR:** Slenderness ratio (FL/FW), **FR:** Flexibility ratio [(LW/FW)*100], **RR:** Runkel ratio [(2xCWT)/LW], OW: Opposite wood, CW: Compression wood, RW: Root wood.

CILICIAN FIR (*Abies cilicica* Carr.)

Cilician fir (*Abies cilicica*) is a conifer endemic to the eastern Mediterranean, found in Lebanon, Syria, and southern Türkiye (Figure 3) (Awad et al. 2014). It thrives in mountainous areas, typically at elevations between 900 and 2 100 meters, preferring well-drained, rocky, and moist calcareous soils. The species is often found in mixed forests with other conifers and broadleaf trees. Its wood is used locally for construction and furniture, and the tree is occasionally used in landscaping and as a Christmas tree due to its attractive appearance (EUFORGEN, 2024c).

Cilician fir grows up to 25-30 meters in height. The species is found in steep, high, and karstic terrains in the Taurus Mountains and the Amanos Mountains, with a distribution that covers a wide area of southern Türkiye's high forest levels. Its bark is ash grey and smooth, becoming cracked and scaly with age. The tree has distinctive light green needle leaves, and its cones are the largest among Turkish fir species, measuring 15-25 cm in length. The species is divided into two subspecies: subsp. *cilicica* and subsp. *isaurica*. In Türkiye, Cilician fir is primarily found in the Mediterranean region, where it mixes with other species like cedar, black pine, junipers, and oaks. It is the only functional shade tree in this region, creating harmonious mixtures with light trees (Yaltırık and Efe, 2000).

Figure 3. The distribution area of Cilician fir (EUFORGEN, 2024c).

The chemical composition and fiber properties of Cilician fir wood are detailed in Table 5 and Table 6, respectively.

Table 5. Chemical composition of Cilician fir wood from various regions.

Geographical Region	**H (%)**	**α-C (%)**	**L (%)**	**HWS (%)**	**CWS (%)**	**1% NaOH (%)**	**E (%)**	**A (%)**	**Reference**
-	71.60	-	29.12	1.09	0.41	9.81	3.32[1]	0.43	Tank (1964)
Andırın	78.52	-	27.87	1.78		9.76	0.47[2]	0.30	Özdemir (2004)
Göksun	78.20	-	27.52	1.77	-	9.67	0.39[2]	0.30	Özdemir (2004)
Akseki	79.74	-	27.78	2.78	-	11.07	0.29[2]	0.37	Özdemir (2004)
- (SW)	-	41.70	28.60	4.00	2.00	7.50	4.00[1]	0.40	Hafızoğlu and Usta (2005)
- (HW)	-	44.90	27.00	4.40	2.60	11.10	5.50[1]	0.30	Hafızoğlu and Usta (2005)
Andırın	70.29	50.98	29.42	1.80	0.31	9.37	1.36[1]	0.53	Güleç (2011)

H: Holocellulose, **α-C:** α-cellulose, **L:** Lignin, **HWS:** Hot water solubility, **CWS:** Cold water solubility, **1% NaOH:** 1% NaOH solubility, **E:** Extractives, **A:** Ash, SW: Sapwood, HW: Heartwood, [1]Alcohol/benzene, [2]Ethanol.

Table 6. Fiber properties of Cilician fir wood from various regions.

Geographical Region	**FL (mm)**	**FW (µm)**	**LW (µm)**	**CWT (µm)**	**SR**	**FR**	**RR**	**Reference**
Adana	2.65	34.1	-	5.88	-	-	-	Aytuğ (1959)
- (Normal stem diameter)	3.83	37.53	-	5.39	-	-	-	Tank (1964)
- (Large stem diameter)	4.02	38.25	-	5.77	-	-	-	Tank (1964)
- (INIA 0008)	3.38	38.10	15.50	-	-	-	-	Esteban et al. (2009)
- (BFH 14036)	2.91	39.30	15.70	-	-	-	-	Esteban et al. (2009)

FL: Fiber length, **FW:** Fiber width, **LW:** Lumen Width, **CWT:** Cell wall thickness, **SR:** Slenderness ratio (FL/FW), **FR:** Flexibility ratio [(LW/FW)*100], **RR:** Runkel ratio [(2xCWT)/LW].

TROJAN FIR (*Abies equi-trojani* Aschers. et Sint.)

Trojan fir (*Abies equi-trojani*) is a coniferous, monoecious, wind-pollinated tree species native to a few small areas in the Mount Ida region of northwestern Türkiye, near the ruins of Troy. It grows in montane forests, typically at elevations between 700 and 2 000 meters, often in mixed stands with deciduous and coniferous trees. Trojan fir is more tolerant of lower and warmer regions than other fir species, making it more dominant than species like Turkish fir (*Abies bornmuelleriana*) at lower latitudes (EUFORGEN, 2024d).

Trojan fir shares morphological characteristics with both Turkish fir and Greek fir (*Abies cephalonica*), particularly in the shape of its needle leaves. The species produces cylindrical cones, 15-20 cm long, with curved tips. It typically forms pure or mixed forests with Black Pine and Beech at altitudes between 1,300 and 1,800 meters in the Kazdağı region. Compared to other local fir species, Trojan fir grows more quickly, making it an important species in forest systems. Its natural distribution is limited to the forests of Bayramiç Forest Management and surrounding areas in Western Anatolia (Yaltırık and Efe, 2000).

This species is valuable not only ecologically, providing habitat and food for wildlife, but also economically. Its light, non-resinous wood is prized in the woodworking industry for construction, furniture, and other uses. Trojan fir is typically found on north-facing slopes in humid bioclimates (EUFORGEN, 2024d).

Figure 4. The distribution area of Trojan fir (EUFORGEN, 2024d).

The chemical composition of Trojan fir wood is detailed in Table 7.

Table 7. Chemical composition of Trojan fir wood from various regions.

Geographical Region	**H (%)**	**α-C (%)**	**L (%)**	**HWS (%)**	**CWS (%)**	**1% NaOH (%)**	**E (%)**	**A (%)**	**Reference**
-	71.30	-	28.62	1.99	1.53	10.18	3.77[1]	0.41	Tank (1964)
Kalkım	78.24	-	27.54	1.67	-	10.24	0.35[2]	0.38	Özdemir (2004)
Bayramiç	78.15		29.64	2.51		12.06	0.18[2]	0.29	Özdemir (2004)

H: Holocellulose, **α-C:** α-cellulose, **L:** Lignin, **HWS:** Hot water solubility, **CWS:** Cold water solubility, **1% NaOH:** 1% NaOH solubility, **E:** Extractives, **A:** Ash, [1]Alcohol/benzene, [2]Ethanol.

The fiber properties of Trojan fir wood are detailed in Table 8.

Table 8. Fiber properties of Trojan fir wood from various regions.

Geographical Region	FL (mm)	FW (µm)	LW (µm)	CWT (µm)	SR	FR	RR	Reference
Balıkesir	3.34	40.5	-	5.31	-	-	-	Aytuğ (1959)
- (Normal stem diameter)	3.79	36.22	-	5.36	-	-	-	Tank (1964)
- (Large stem diameter)	3.82	36.57	-	5.51	-	-	-	Tank (1964)
-	3.47	38.00	17.50	-	-	-	-	Esteban et al. (2009)
Kastamonu (795 m altitude, 3 years old)	1.26	31.10	-	-	-	-	-	Özden Keleş (2020)
Kastamonu (1350 m altitude, 3 years old)	1.25	26.30	-	-	-	-	-	Özden Keleş (2020)

FL: Fiber length, **FW:** Fiber width, **LW:** Lumen Width, **CWT:** Cell wall thickness, **SR:** Slenderness ratio (FL/FW), **FR:** Flexibility ratio [(LW/FW)*100], **RR:** Runkel ratio [(2xCWT)/LW].

CONCLUSIONS

The chemical composition of *Abies* wood is complex, involving several key constituents that determine its properties, utility, and ecological role. These constituents include polysaccharides like cellulose and hemicellulose, phenolic compounds like lignin, and various extractives, with each contributing distinct features to the wood's physical characteristics. The wood fibers of *Abies* species have distinct properties that make them suitable for various applications, particularly in the paper and pulp industry. The tree's anatomical features, chemical content, and the morphological characteristics of the fibers themselves affect these attributes. In conclusion, the chemical composition and fiber morphology of wood of tree species growing naturally in Turkey vary depending on the tree species, the region where it grows and its location on the tree.

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Chapter 9

INVESTIGATION OF MICROPLASTIC POLLUTION IN TURKISH COASTS IN THE CONTEXT OF DIFFERENT ELEMENTS OF BIOTA

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Introduction

Plastics are synthetic organic compounds composed of elements like carbon, nitrogen, sulfur, hydrogen, chlorine and oxygen (American Chemistry, 2005). Due to their lightness, durability, reusability, cheapness and ease of use, plastics are widely used nowadays (Laist, 1987; Andrady & Neal, 2009).

The historical use of plastic materials dates back to the 1800s when rubber technology progressed. Charles Goodyear discovered the vulcanisation of natural rubber, and the development of the plastic sector carried on since then, with a substantial increase on a regular basis (Stevenson et al., 2008). Later on, various convenient plastic types that have better features (i.e., more durable, cheaper, more flexible, lighter, etc.) were produced. Today, a variety of plastic types, including polystyrene (PS), polypropylene (PP), low-density polyethylene (LDPE), polyvinyl chloride (PVC), high-density polyethylene (HDPE), terephthalate (PETE or PET), etc., are being utilised in many fields.

Microplastic term typically refers to the particles no longer than 5 mm (Lambert & Wagner, 2018). However, there have been many other definition attempts. For example, it was proposed that microplastics term ought to refer to the particles that are smaller than 1 mm (Andrady, 2011; Browne et al., 2011). Another definition suggested that particles that fall between 1 mm and 2.5 cm should be called mesoplastic (GESAMP, 2015). Likewise, another classification was proposed that defines the particles bigger than 5 mm as macroplastic, particles between 1-5 mm as mesoplastic, particles between 0.1-1 mm as microplastic, and particles smaller than 0.1 mm as nanoplastic (Lambert et al., 2014). Nonetheless, 5 mm is typically recognised as the upper limit for microplastic definition since this size could contain particles that organisms can ingest (GESAMP, 2015).

Sources of microplastics and their involvement in the marine ecosystem

There are two sources of microplastics: primary and secondary microplastics. Microplastic particles that are intentionally produced in response to sectoral demand (e.g., textile industry: microfibers; cosmetic industry: micropellets; etc.) and put into use are called primary microplastics, while microplastic particles formed by the degradation and fragmentation of waste are called secondary microplastics (Cole et al., 2011).

Considering the widespread use of microplastics, a lot of waste products are expected to be produced. Especially in cases where these wastes are not disposed of sufficiently, plastics or microplastics spread into the environment can be transported to the water environments from a variety of sources. The lightness of these materials further increases the risk of transportation.

Due to anthropogenic activities, microplastics can directly, as a result of unfiltered domestic or industrial wastewater discharge, or indirectly mix into aquatic ecosystems (e.g., sea, freshwater, river, lake) (Ryan et al., 2009). Microplastics can be dispersed in aquatic ecosystems through natural means such as wind, water currents, turbulence and oceanographic effects (physical properties of water and wave movements) (Ballent et al., 2012; Turra et al., 2014).

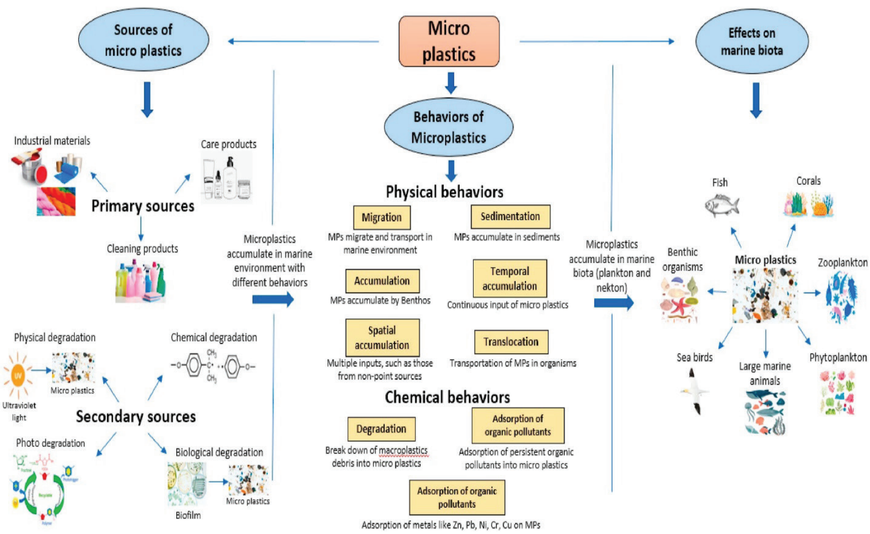

Figure 1. *Microplastics' sources, behaviours and effects on marine biota ecosystem (Nawab et al., 2023).*

Apart from all these, the main factors affecting the distribution of microplastics include their density, shape and size (Eerkes-Medrano et al., 2015). The density of microplastics impacts the sinking speed of microplastics in the aquatic ecosystem, causing them to spread on the water surface, water column and sediment (Ma et al., 2020). The density values of microplastics vary according to the polymer types (Ngo et al., 2019). Microplastics with low density values generally remain on the water surface. It has been determined that these types of microplastics prevent the respiration of zooplankton and the photosynthesis of algae (Song et al., 2014). On the other hand, Microplastics with high density values are often observed in sediment. These microplastics can reach benthic invertebrates' digestive systems and cause their death (Näkki et al., 2017; Naidu et al., 2018).

Distribution of microplastics along Turkish coasts and their effects on biota

It has been noted that microplastics enter the sea and various water environments from areas such as surface waters, beaches, etc. (Lusher et al., 2017). Rivers are among the most essential sources that carry microplastics to the marine environments (Lechner et al., 2014). Atmospheric movements, insufficient discharge systems, currents and many other factors can cause microplastics to be transported to the seas.

Türkiye's total coastline is 8592 km (Ministry of Environment, Urbanization and Climate Change, 2023), excluding the islands, and has coasts to the Mediterranean, Aegean Sea, Black Sea and Sea of Marmara. In this context, Türkiye is one of the countries with the largest area and diversity among coastal countries. This situation undoubtedly causes difficulties in protecting and ensuring the sustainability of the marine ecosystem. Considering the fact that marine litter and plastics can be transported by various means, it poses a risk element in terms of plastic pollution in the coastal regions. This risk element is valid for all living beings in the aquatic ecosystem and may have different effects on all of them.

To date, many evaluations have been made to reveal the status of microplastic pollution in different groups of biota in aquatic ecosystems. Although the most frequently investigated group in this context is bony fishes, the statuses of plankton, invertebrates, water birds, cartilaginous fish and mammals have also been examined (Lusher, 2015).

Likewise, many studies have been conducted on the effects of microplastics on different elements of the biota on the Turkish coasts.

Fishes

As is known, fish are one of the most fundamental elements of the aquatic ecosystem and are in the group directly affected by pollutants due to their physiology. On the other hand, because of their high economic significance, they also occupy an important place in the food chain and constitute a carrier step in the consumption web. For this reason, it is essential to investigate the levels of microplastic pollution and accumulation in fish in the marine ecosystem. In this regard, microplastic accumulations in fish species in recent studies on the coasts of Türkiye are given in Table 1.

Table 1. *Microplastic accumulations in some economic fish species caught off the coasts of Türkiye.*

Species	Site	*n*	Organ/Tissue	MP count (p/ind)	Reference
Mullus barbatus	Southeast Black Sea	120	GIT	2.79	Onay et al. (2023)
Trachurus mediterraneus	South Black Sea	121	GIT	0.22	Mutlu et al. (2022)
M. barbatus	Northeast Mediterranean	43	GIT	3.22	Kılıç and Yücel (2022)
			Gill	3.54	
Mullus surmuletus		41	GIT	7.56	
			Gill	4.65	
Saurida undosquamis		39	GIT	3.57	
			Gill	2.70	
Mugil cephalus		20	GIT	26.15	
			Gill	3.85	
M. barbatus	Northeast Mediterranean	207	GIT	1.39	Güven et al. (2017)
Nemipterus randalli		135		1.31	
Pelates quadrilineatus		135		1.48	
S. undosquamis		99		1.22	
Sparus aurata		110		0.87	
T. mediterraneus		98		1.77	
Upeneus pori		78		0.69	
Engraulis encrasicolus	Southeast Black Sea	360	GIT	0.11	Gedik et al. (2023)
Sardina pilchardus	Northeast Mediterranean	21	GIT	0.80	Kılıç (2024)
			Gill	0.20	
Boops boops		11	GIT	1.20	
			Gill	0.30	
Diplous annularis		21	GIT	0.50	
			Gill	0.40	
Dicentrarchus labrax	East Aegean Sea	23	GIT	0.30	Eryaşar et al. (2024)
S. aurata		17		0.41	
Pagellus erythrinus		18		0.50	
Scomber scombrus		12		1.08	

E. encrasicolus	South Black Sea	163	GIT	0.15	Eryaşar et al. (2022)
M. barbatus		104		0.40	
Merlangius merlangus		104		0.28	
Chelon ramada	Northeast Mediterranean	30	GIT	3.40	Kılıç (2022)
			Gill	1.90	
T. mediterraneus	East Sea of Marmara	228	GIT	2.31	Aytan et al. (2023)
Symphodus cinereus		61		1.35	
Gobius niger		31		1.42	
Chelidonichthys lastoviza		19		2.80	
Trachinus draco		15		2.33	
Lithognathus mormyrus	Northeast Sea of Marmara	20	GIT	0.40	Gündoğdu et al. (2020a)
	East Aegean Sea	25		0.80	
	Northeast Mediterranean	10		0.50	
Chelon saliens	Northeast Sea of Marmara	22		2.20	
	East Aegean Sea	22		4.30	
	Northeast Mediterranean	18		0.90	
M. barbatus	South Black Sea	82	Brain	0.16*	Atamanalp et al. (2021)
			Gill	0.62*	
			Muscle	0.51*	
			GIT	0.76*	
Alosa immaculata		82	Brain	0.24*	
			Gill	1.00*	
			Muscle	0.72*	
			GIT	1.26*	

**Calculated from the data presented in the respective publication.*

GIT: Gastrointestinal Tract.

In research conducted around the world, various microplastic levels have been reported. In a study evaluating 11 different benthic fish species in the Bering-Chukchi Seas, the MP exposures were 0.04-1.67 MP/individual (Fang et al., 2018); in a study investigating four bony fish species in Australia and Fiji, the MP exposures were 1.58±0.23 and 0.86±0.14 MP/individual, respectively (Wootton et al., 2021); for two bony fish species captured off the west coast of Iceland, it was 0.26 MP/individual (de Vries et al., 2020); in the Yellow Sea, China, it was 0.26 MP/individual in 19 bony fish species (Sun et al., 2019); in a study evaluating 24 bony fish species in Beibu Gulf, China, it was found that 12 species were affected and the exposure rates were 0.23±0.08 MP/individual (Koongolla et al., 2020). Although the study data conducted on the coasts of Türkiye, as displayed in Table 1, are generally similar to studies carried out worldwide, it is evident that the results of some studies conducted in the Black Sea and the Aegean are respectively high. On the other hand, it was also observed that these differences are also reflected in fish species. Unequivocally, many factors, such as the pollution status of the region where the catch is performed, seasonal exposure levels, water movements, and the habitat or feeding habits of the species being caught, constitute the source of these differences. Furthermore, it has been reported that micro and macro plastics are less common in fish inhabiting the open seas, while they are found in higher amounts in coastal species (Murphy et al., 2017).

Numerous creatures can uptake microplastics from sediment and the aquatic environment. This may happen in two different ways: either directly with ingestion or through the gills (also called dermal intake). Moreover, studies have demonstrated that planktonic organisms may absorb microplastics of specific sizes. In the aquatic food chain, these planktonic creatures serve as microplastic transporters and are a food source for fish. Some microplastics originate directly from feed or the aquatic environment, in addition to those that enter the fish body in this manner.

Toxicity levels of plastic polymers may vary. The type of plastic, its chemical structure, and the absorption of chemical pollutants with plastic affinity influence the negative effects of microplastics (Zhu et al., 2019). Typically, they can cause hormonal imbalances, stress, liver toxicity, bioaccumulation, olfactory impairment, gill obstruction, cardiotoxicity, impaired intestinal absorption, and growth retardation in fish (Kayhan, 2019).

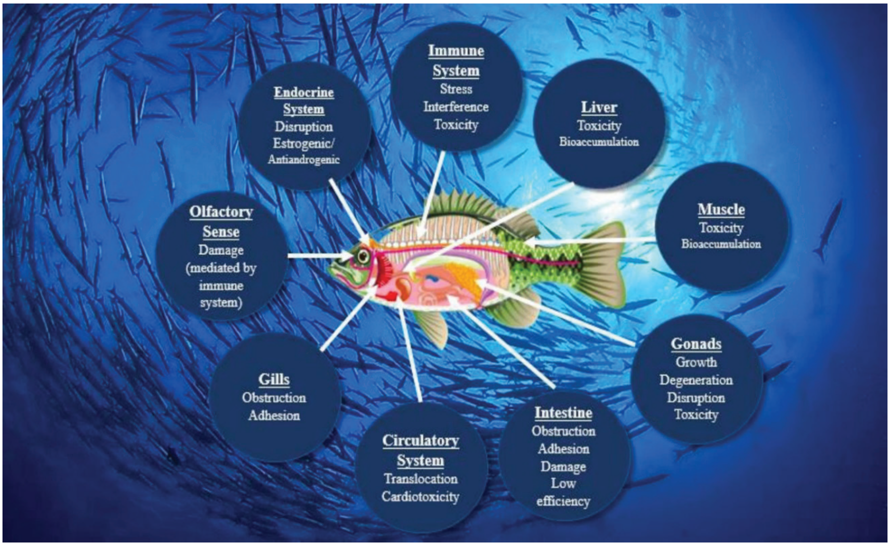

Figure 2. *Toxic effects of microplastics on fishes (Gola et al., 2021).*

Microplastics found in the aquatic environment are seen as a source of contamination for aquatic products and humans, as well as carrying toxic and harmful substances (Rochman et al., 2013). Undoubtedly, this contamination can also threaten the well-being of humans, the end consumers, in extreme cases.

Invertebrates

Many aquatic organisms examined in the invertebrate group are significant species due to their economic value. In addition, because of their physiology, invertebrates tend to accumulate some pollution elements more than other higher organisms like fish. Therefore, determining the pollution levels of creatures in this group is essential in estimating the pollution element of the aquatic environment. The levels of some pollution elements ingested by organisms in this group provide the opportunity to create pollution indices directly. Of course, there has yet to be a study succeeding to create an index for microplastics. However, since they are consumed organisms and act as carriers for microplastics in the consumption chain, it is essential to monitor them. Turkish waters also host many creatures belonging to the invertebrate group and constitute production areas for important farmed species such as mussels and some other crustaceans. In this context, data on microplastic levels in some invertebrates sampled from Turkish waters are presented in Table 2.

Table 2. *Microplastic levels in some invertebrate species sampled off the coasts of Türkiye.*

Species	Site	*n*	Organ/Tissue	MP count (p/ind)	Reference
Mytilus galloprovincialis	Whole Sea of Marmara	412	Whole soft tissue	2.06	Gedik et al. (2022)
M. galloprovincialis	South Black Sea, East and South Sea of Marmara and East Aegean Sea	342	Whole soft tissue	0.69	Gedik and Eryaşar (2020)
Miscellaneous mussel species	Southeast Sea of Marmara	410	Whole soft tissue	1.21*	Yıbar et al. (2024)
Patella caerulea	Northeast Mediterranean	160	Whole soft tissue	0.29	Yücel and Kılıç (2023a)
M. galloprovincialis	East Aegean Sea	60	Whole soft tissue	8.72	Yozukmaz (2021)
Ruditapes decussatus		60		8.74	
Spondylus spinosus	Northeast Mediterranean	30	Whole soft tissue	1.80-2.60	Çevik and Gündoğdu (2018)
Chamelea gallina	South and Southwest Black Sea	335	Whole soft tissue	0.65	Gedik and Gozler (2022)
Donax trunculus	South Black Sea	51	Whole soft tissue	1.69	Şentürk et al. (2020)
C. gallina		31		2.07	
Abra alba		4		0.00	
Anadara inaequivalvis		2		4.00	
Pitar rudis		1		4.00	
Brachidontes pharaonic	Northeast Mediterranean	245	Whole soft tissue	0.40	Yücel and Kılıç (2023b)
Pinctada imbricata radiata	East Aegean Sea	30	Stomach	2.17*	Aksakal et al. (2021)
Parapenaeus longirostris	Northeast Mediterranean	46	GIT and Hepatopancreas	18.8	Yücel (2023)
Callinectes sapidus	Dardanelles	45	Stomach	1.02*	Acar et al. (2022)

**Calculated from the data presented in the respective publication.*

GIT: Gastrointestinal Tract.

There have been many studies on microplastic accumulation in the bodies of aquatic invertebrates in recent years. It is seen that these studies aimed at understanding the mechanism of toxicity as well as determining the direct accumulation amounts (Devriese et al., 2015; Akhbarizadeh et al., 2019; Gomiero et al., 2019; Scanes et al., 2019; Hara et al., 2020; Gündoğdu et al., 2020b; Ojeda-Barrios et al., 2020). When compared with the findings obtained from the coasts of Türkiye, it is generally consistent, and it has been stated in most studies that the differences may be due to regional pollution elements, seasonal changes or the living habits of the species.

Invertebrates ingest microplastics present in water bodies. These synthetic polymers do not undergo any enzymatic degradation via a metabolic pathway after ingestion because there is no enzyme available to degrade them into simpler, non-toxic chemical compounds. Moreover, the absorption of different organic/inorganic chemicals, dyes or heavy metals makes microplastics more toxic. This is because these contaminants are also toxic. The absorption of these contaminants onto microplastic depends on different properties of the microplastic such as its chemical composition, shape, size, etc. (Gola et al., 2021).

Ultimately, it is essential to monitor the levels and relationships of microplastics in invertebrates and study controlling them, mainly because of the necessity of protecting species that have high demand for human consumption and the overall ecosystem.

Zooplankton

Zooplankton are an important link between primary producers and higher trophic levels. Therefore, they play a significant role in the marine food chain (Steinberg & Landry, 2017). For example, copepods are a favourite prey for ecologically and economically crucial planktivorous fish, and copepod faecal pellets are essential food sources for benthic organisms (Turner, 2002).

This situation makes it essential to investigate the presence and number of MPs in the marine environment. Because these microplastics can negatively affect the function and health of zooplankton and may also be carried to a higher trophic level by being ingested by zooplankton. In this regard, although the study data on zooplanktonic organisms sampled from the Turkish coasts are limited, they are displayed in Table 3.

Table 3. *Microplastic levels in some zooplankton species sampled from off the coasts of Türkiye.*

Species	Site	*n*	Organ/Tissue	MP count (p/ind)	Reference
Calanus euxinus	Southeast Black Sea	1126	Whole organism	0.024	Aytan et al. (2022)
Acartia (Acartiura) clausii		1065		0.008	
Miscellaneous bivalve larvae	Southeast Black Sea	2478	Whole organism	0.007	Şentürk and Aytan (2024)
Miscellaneous gastropod larvae		230	Whole organism	0.125	

The number of studies on microplastic levels in zooplankton sampled from the Turkish coasts is rather limited and has remained only specific to the Black Sea. However, studies on microplastic amounts in zooplankton species worldwide have increased considerably in recent years. These studies cover a wide range, from investigating the toxic effects of microplastics in laboratory conditions to the microplastic contents of individuals sampled from the natural environment (Andrady, 2011; Cole et al., 2013; Desforges et al., 2015; Sun et al., 2017, 2018; Kosore et al., 2018; Amin et al., 2020; Bottorell et al., 2019; Taha et al., 2021).

The findings obtained from the Turkish coasts yielded similar results when compared with similar organisms in other seas in terms of characteristics such as quantity, size, and type (Desforges et al., 2015; Sun et al., 2017, 2018; Kosore et al., 2018; Amin et al., 2020; Taha et al., 2021). In fact, the amounts detected in Turkish waters, as shown in Table 3, are lower than those in the compared studies. Of course, this situation is directly affiliated with the microplastic exposure of the sampling area. Again, water movement in the selected region, the species and feeding habits of the organism, and mobility directly affect microplastic accumulation.

Conclusion and Recommendations

In this paper, where studies on the effects of microplastics on living creatures on the coasts of Türkiye are examined, the most fundamental conclusion is that there are still very few and limited studies. Another finding that stands out in the studies that have intensified in recent years is that the studies have not spread to the entire coastline of Türkiye and are clustered in some areas. This situation will cause a deficiency in healthy and holistic monitoring. Likewise, the fact that the studies have focused primarily on fishes, which are higher organisms and dominant food sources in final consumption, is a significant deficiency in terms of determining risk factors. It is essential to reveal the microplastic exposure of zooplankton, which is also of great importance in terms of biological transfer along the food chain, for other marine areas in order to make general assessments.

Although the data obtained from the studies seem to be within normal limits when compared to the data worldwide, the lack of a standard on this subject, the lack of knowledge of which amount is too much and which amount is too little, or the absence of a clear statement of the possible effects of which amounts or types on various living groups, will always leave such studies suspended. Therefore, it is necessary to increase these studies and establish standards in the near future against this type of pollution, which is a major problem worldwide. It is important to take the required precautions by increasing the *in vivo* studies on the toxic effects of microplastics on aquatic organisms and the possible effect mechanisms in their transmission to humans through these organisms.

Ultimately, the prevalence of microplastics in marine environments is rapidly increasing, and urgent actions are required to alleviate this global problem. Measures such as minimising the use and production of plastics, proper disposal of plastic waste, replacing MP additives with environmentally friendly chemicals and encouraging recycling and energy recovery can help reduce the risk of microplastics consumption by marine biota. Of course, these measures should not only be addressed in the context of Türkiye but also implemented by all stakeholder countries due to the nature of plastic pollution.

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Chapter 10

SOME ALGAE SPECIES AS BIOINDICATORS OF HEAVY METAL POLLUTION IN AQUATIC ECOSYSTEMS: A REVIEW

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Introduction

In recent years, a large number of natural and synthetic chemicals have been produced and used. However, the environmental effects of many of these substances are unknown. Although many of these chemicals do not immediately effect aquatic ecosystems, the total pollutant load has contributed to observed changes in the structure and function of aquatic ecosystems (Oertel and Salanki, 2003).

People have used metals not only in advanced civilizations but also in ancient world. An example of this is the recent studies that have found that Greenland's glaciers have reached a concentration that can be detected as a global metal accumulation (Markert et al., 1999). One of the most important global problems that pose an increasing threat to the environment is the toxic heavy metals (HMs) found in the air, soil and water. Non-essential metals (such as Hg, Cd, Cr, Pb and As) are toxic to all living things, both in chemical compound forms and in elemental forms, depending on their concentrations (Stankovic and Stankovic, 2013).

Aquatic ecosystems, which are an important resource for many human activities, have become one of the most threatened ecosystems in the world. In recent years, HM pollution in aquatic ecosystems has attracted the attention of scientists due to its harmful effects on aquatic organisms as well as public health related to water resources. HMs that cause pollution in aquatic ecosystems may be of natural or anthropogenic origin. Rapid and unplanned developments in industry, unplanned and rapid urbanization, and unconscious use of synthetic chemicals in agriculture are among the main causes of HM pollution in aquatic ecosystems. These anthropogenic pollutant sources lead to deterioration of water quality (WQ) and extinction of aquatic organisms (Yeole and Patil 2005; Malik et al., 2013).

Organisms that can be used to identify and/or measure the impact of pollutants on the environment and that indicate changing environmental conditions are defined as bioindicators (BIs). The assessments made based on the status of BIs will indirectly provide an estimate of the current natural state or pollution level/degree of that ecosystem (Manickavasagam et al., 2019). BIs in aquatic ecosystems include organisms such as algae, macrophytes, zooplankton, bivalve mollusks, seabirds and fish (Bonanno and Orlando-Bonaca, 2018).

The purpose of using BIs is to determine the cumulative effects of environmental changes, based on the hypothesis that they are integrated over or reflected by the current status or trends in the diversity, abundance or accumulation of pollutants (Bartell, 2006; Zukal et al., 2015; Bonanno and Vymazal, 2017; Bonanno and Orlando-Bonaca, 2018).

Algae are an important component of biological monitoring programs as they are an ecologically important group in many aquatic ecosystems. Algae have a significant role in WQ assessment because of their rapid reproduction rates and very short life cycles, making them important BIs of short-term effects. In recent years, BIs have been widely used to determine the quality of aquatic ecosystems. In this review, general information is given about BIs and some algae used as BIs for HM pollution in aquatic ecosystems.

Bioindicators and Their Significance

In writings over 2000 years old (Hippocrates, translated by Littre in 1861), a connection between biological dysfunction and the environment has been proven. Although this information is very old, it is a more recent phenomenon that environmental pollution has been taken seriously by both society and scientists.

Different definitions of BIs have been made by various researchers. Periodic monitoring of indicators in ecological assessment studies of WQ was first made legal by the US Environmental Protection Agency (USEPA) in 1972 (Young et al., 2014). In this study by Young et al. (2014), it was aimed to compile information on the importance, characteristics and usefulness of BIs and biomarkers that should be examined in aquatic ecosystems, especially those related to animal species. McGeoch (1998) defines a BI as "a species or group of species that readily reflects the abiotic or biotic status of an environment, represents the effect of environmental change on a habitat, community or ecosystem, or indicates the diversity of a subset of taxa or the overall diversity in an area". In 1999, Gerhardt defined a BI as a species or group of species that readily reflects the abiotic or biotic status of an environment, represents the effect of environmental change on a habitat, community or ecosystem, or indicates the diversity of a subset of taxa or the overall diversity in an area (Gerhardt, 1999). Various researchers have defined organisms that respond to sudden changes in important factor combinations, indicating the long-term interaction of environmental factors, as BIs. Other researchers consider only organisms that respond to changes in their metabolism, activity, or other aspects of their biology or that accumulate toxic substances in the environment as BIs (Hamza-Chaffai, 2014).

Organisms or biological processes that are used to detect and/or measure the impact of pollutants on the environment and that indicate changing environmental conditions are called BIs. In order to indirectly estimate the current natural state or pollution level/degree in an ecosystem, an evaluation is made according to the status of BIs (Manickavasagam et al., 2019).

Selecting the right BI depends on the purpose of the study (such as changes in habitat, restoration, climate change), (Manjula et al., 2024). The criteria used in BI selection are given in Fig. 1.

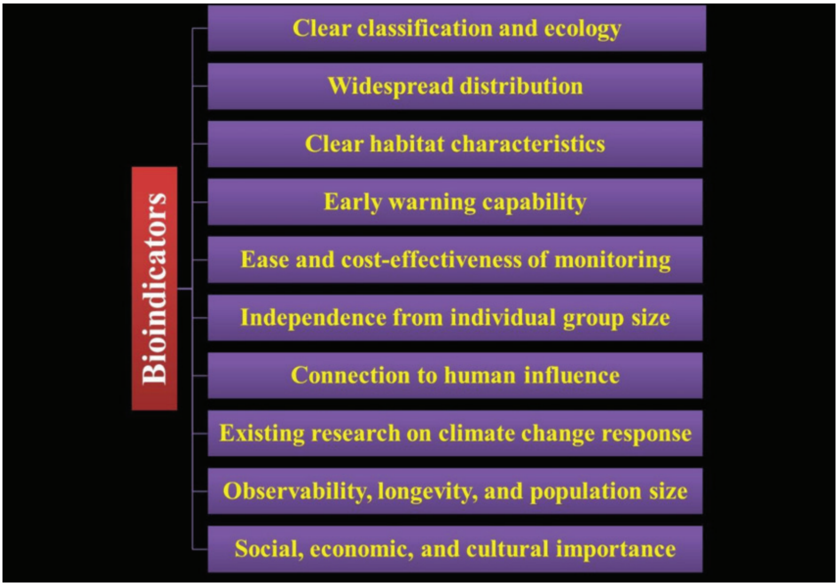

Figure 1. *Selection criteria of BIs (Manjula et al., 2024)*

BIs are used to detect changes occurring in ecosystems as well as to indicate the positive or negative effects of these changes. If there are pollutants that may affect the biodiversity in the ecosystem, changes in the environment and the species in it can be detected through BIs (Walsh 1978; Peterson, 1986; Gerhardt, 2002; Holt and Miller 2010; Parmar et al., 2016). For this reason, BI species are widely used in effectively monitoring the state of the environment due to their resistance to variability occurring within the ecosystem in which they are located (Parmar et al., 2016).

Gerhardt (1999) reported that it is useful;

(a) in situations where the specified environmental factor cannot be measured,

(b) in situations where the specified factor is difficult to measure (such as pesticides and their residues or complex toxic wastes),

(c) in situations where the environmental factor is easy to measure but difficult to interpret (such as whether the observed changes are ecologically significant).

Other researchers consider only organisms that respond to changes in their metabolism, activity, or other aspects of their biology or that accumulate toxic substances in the environment as BIs (Fureder and Reynolds, 2003).

The advantages of BIs over chemical analyses are given below (Manickavasagam et al., 2019; Parmar et al., 2016; Kumari and Paul, 2020);

- Flora and fauna used as BIs provide clues about the cumulative effect of chemical pollutants on the ecosystem and habitat change over time.
- The degree of environmental stress on organisms cannot be determined by physical and chemical parameters. On the other hand, the degree of environmental stress can be determined and monitored by BIs.
- High cost devices are required for chemical analysis of pollutants. However, it is a more effective method in terms of using BIs.
- Species used as BIs have the ability to show the dangerous effects of pollutants in the ecosystem.
- Chemical substances found in low amounts in the environment can be determined by chemical analysis. However, the potential toxic effects of these chemicals can only be determined by the response of the species living there.
- It is difficult to determine the indirect effect of biological accumulation with chemical analyses. HMs have the ability to accumulate in living things. Therefore, they accumulate in increasing amounts along the food chain. It is difficult to determine the presence of pollutants with the ability to accumulate chemically or physically. Therefore, BIs are used.

Many scientists have grouped bioindicators according to the criteria given below. They are: (Manickavasagam et al., 2019; Jain et al., 2010);

- Their distribution must be wide,
- They must show restricted mobility, site specificity, low genetic variability, possess narrow and specific ecological demands and tolerance,
- They should not be omnivores,
- Medium to long generation time,
- They must have ecological importance in their ecosystems,
- They must be sensitive to specific pollutant,
- BI species should be representative of the response of other taxa or the entire ecosystem.

- BI species should be easy to sample, separate, preserve and diagnose, should be easy to culture under laboratory conditions and should be low cost.

BIs provide useful information in estimating the natural state of a particular area as well as the level/degree of pollution (Khatri and Tyagi, 2015). The advantages of using BIs are (Fig. 2):

- Effects on organisms can be determined.

- To monitor the synergistic and antagonistic effects of various pollutants on organisms.

- Early detection and monitoring of harmful effects of toxins on plants and animals, including humans.

- They can be easily counted because they are widely available.

- They are economical compared to special measuring systems/ devices (Markert et al., 2003; Parmar et al., 2016).

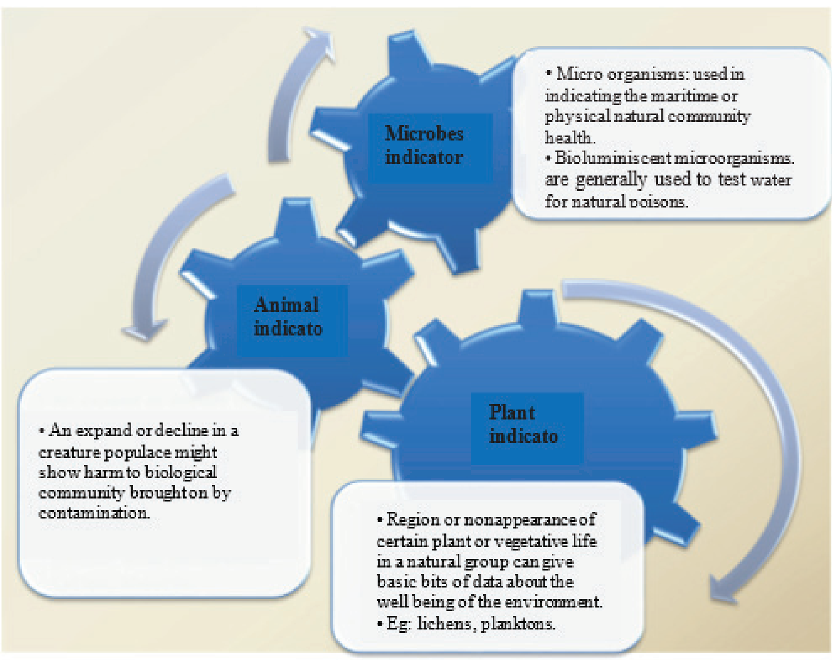

Figure 2. *Types of bioindicator (Parmar et al., 2016)*

Today, various organizations such as the World Conservation Union and the International Union for Conservation of Nature use and promote BIs as a tool for biological monitoring and assessing human impacts

(Parmar et al., 2016). MacFarlane et al. (2003) classified BIs according to their mode of action and origin in the organism (Fig. 3).

- **Accumulative BIs:** BIs that accumulate single or more elements and chemical compounds are called cumulative BIs.

- **Sensitive BIs:** Sensitive BIs are those that represent a specific change when exposed to chemicals or elements. These changes may be related to tissue, morphology, cytology, and organism or population behavior.

- **Active BIs:** BIs used to detect the concentrations of compounds and elements in the environment by exposure to a specific place and within a specific time period are called active BIs.

- **Passive BIs:** BI types collected from natural ecological communities that are used to analyze the concentrations of compounds and elements and their direct and indirect effects are called passive BIs (Liaqat et al., 2023).

BIs can be divided into three categories according to different application areas: (Gerhardt, 2002):

a) Environmental indicators: BIs are a species or group of species that respond predictably to environmental disturbance or change (accumulators, bioassay organisms).

b) Ecological indicators: A species that is sensitive to pollution, habitat fragmentation or other stress factors. The response of a BI species is representative of the community.

c) Biodiversity indicators: BIs in this group are used as indicators of species richness of an indicator taxon or a community. However, this definition has been expanded to include "measurable biodiversity parameters" (such as species richness, endemism, genetic parameters, population-specific parameters and landscape parameters).

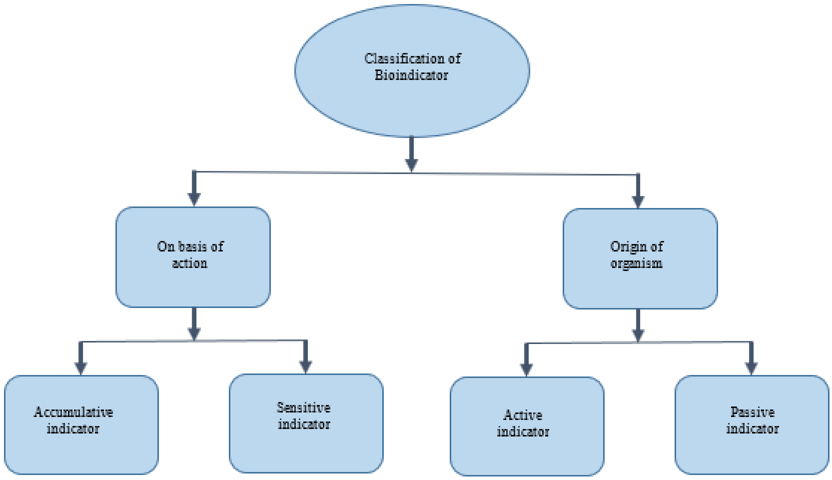

Figure 3. *Sub-types of BIs (Parmar et al., 2016)*

BIs are members or groups of flora and fauna that are used to indirectly determine the concentrations of HMs in the ecosystem and are systematically collected and analyzed to determine potential health risks to organisms and humans (Stankovic and Stankovic, 2013).

It has been determined that there has been a steady increase in the publication of articles on indicators since the 1970s and 35% of these articles have been published in the last 5 years. Most articles using the term indicator or BI are about some type of pollution, environmental quality or human health research. Most of these articles on pollution are about HM pollution and other chemical pollution, and a few are about oil pollution research (Burger, 2006).

Bioindicator Algae

Aquatic organisms are effected by anthropogenic stress and cause various changes in the biological integrity of aquatic ecosystems. Algae have also been used as BIs to assess the status of aquatic ecosystems and determine the degree of WQ (Omar, 2010). Kolkwitz and Marsson (1908) were the first researchers to classify algal species according to their tolerance to various types of pollution. They reported that the presence of certain algal species could define various degradation zones in a river. Patrick (1949) developed community indices, providing information indicating that a healthy community consists of numerous species in several groups of organism, including algae. Palmer (1969) provided a composite algal species rating to identify clean and polluted waters. Patrick (1971) proposed a numerical approach for WQ studies using diatom flora attached to glass slides as an artificial substrates.

Algal communities in which the loss or dominance of certain BI species precedes biochemical or physicochemical changes are defined as BIs. These can also be defined as short-term indicators of environmental stress (Adams, 2005).

Polysaccharides in the cell wall of algae provide amino, carboxyl, phosphate and sulfate groups for metal binding and all have ion exchange properties. The reason for using algae as BIs and for monitoring HM pollution in aquatic ecosystems is that these species reflect the concentration of HMs in the water in which they are found (Zbikowski et al., 2007). Algae can prevent HM toxicity because they have intracellular and extracellular mechanisms (Scheidegger et al., 2011). Algae limit the uptake of HMs into their cells by excretion of nonspecific ligands, reducing HM bioavailability, or changing the concentration and affinity of metal transporter proteins (Soldo et al., 2005).Due to the high negativity on their surfaces, algae have the ability to attract and accumulate many HM ions in water. This has made the use of algae important in determining and combating pollution in water (Rao, 1986). Therefore, Cladophora species are among the best BIs used in the investigation of HM pollution in the aquatic ecosystem (Förstner and Prosi, 1979).

Microalgae, which have an important role in marine and freshwater ecosystems, are one of the first groups affected by HM pollution. For this reason, microalgae are considered HM indicators and are used as BIs (Carfagna et al., 2013). When microalgae cells are exposed to high HM concentrations, changes occur in the physiological state of microalgae cells. In addition, there are changes in the rates and dynamics of cell division, photosynthesis, and cell size and morphology. High HM concentrations can even cause the deterioration of main organelles (Levy et al., 2008; Wang and Chen, 2009; Gong et al., 2009; Manimaran et al., 2012; Franklin et al., 2024).

Algae are a group of organisms frequently used in HM uptake studies due to their easy availability and high binding affinity (Roy and Shane, 1993). Algae have a great ability to take up and accumulate HMs from the environments in which they live (De Fillips and Pallaghy, 1992). Algae are highly sensitive to both organic and inorganic pollutants, most of which are terrestrially derived (Bringmann and Kuhn, 1980). This has made the use of algae important in determining and combating pollution in water (Rao, 1986).

- Blue-green algae *Synechococcus leopoliensis* and Dunaliella have high HM accumulation properties. *Anabaena cylindrica* exposed to Cd shows significant deformities, color loss and increases in the number of heterocysts (Jain et al., 2010).

- *Selenastrum capricornutum*,
- *Ceramium strictum*,
- *Ceramium teniucorine*,
- *Phaeodactylumn tricornutum*,
- *Champia parvula* are used as an indicator of HM pollution.
- *Chlorella ellipsoidea* is an indicator because its growth stops when exposed to Cu, Zn, Ni and Cd. Chlorophyll a content, protein content and ATP level decrease depending on the HM level.

Macrophytes are considered to be good indicators for monitoring metals in sediments (Reiner and Duthie, 1993). Macroalgae are widely used to determine HM pollution in marine and freshwater ecosystems (Whitton, 1984; Maeda, and Sakaguchi, 1990; Haritonidis, and Malea, 1999; Kamala-Kannan et al.,2008; Al-Homaidan et al., 2011). They are used as BIs due to their distribution, size, long life, being found in polluted areas, having the ability to accumulate HMs very well and being easy to identify. For this reason, it is preferable to measure HM concentrations in BI organisms rather than in water and/or sediment in aquatic ecosystems (Stengel et al., 2004; Al-Homaidan et al., 2011).

Cladophora species are among the best BIs used in the investigation of HM pollution in the aquatic environment (Förstner et al., 1981). The filamentous green alga *Cladophora glomerata* (Fig. 4) can grow rapidly in rivers under suitable conditions. Therefore, the metal content in the cells of young individuals is used to distinguish between new and long-term pollution in streams. Since Cladophora is rarely found in waters in late winter and early spring, *Lemanea fluviatiilis* is used instead of Cladophora to monitor pollution in water during this period. Although Cladophora accumulates less metal than some bryophytes, the curve of the metal-algae metal relationship in water is much steeper in Cladophora. Therefore, Cladophora is considered a more sensitive indicator for comparing different regions (Varol, 2002). In recent years, Enteromorpha and/or Cladophora species from green algae have been used by many researchers to detect HM concentrations in many parts of the World (Al-Homaidan et al., 2011). Species of green algae Cladophora sp. and Enteromorpha sp. have been reported as indicators of HM contamination all over the world (Sfriso et al., 1995; Leal et al., 1997; Brown et al., 1999; Fytianos et al.,1999; Wang and Dei, 1999; Brown et al., 1999; Muse et al., 1999; Marsden and DeWreede, 2000; Chmielewska and Medved, 2001; Sawidis et al., 2001;

Storelli Zet al., 2001; Villares et al., 2002; Topcuoglu et al., 2003; Stengel et al., 2004; Gosavi et al., 2004; Daka, 2005; Zbikowski et al., 2007; Żbikowski et al., 2007; Strezov and Nonova, 2009; Dahlia and Hassan, 2017; Dora et al., 2022; Salo and Salovius-Laur´en, 2022).

Macroalgae play an important role in determining metal concentrations and obtaining data on environmental quality and HM pollution levels. In addition, since most macroalgae have relatively long life cycles, they can reflect short-term fluctuations in HM concentrations in their environment. For this purpose, species belonging to the genera Fucus, Enteromorpha, Laminaria and Ulva (Fig. 5) from macroalgae are generally the most commonly used indicator species in determining HM levels in the sea. Especially Ulva species are considered to be very good indicator species since they easily accumulate many metals in their bodies. In addition, studies have determined that brown algae Padina and Sargassum species (Fig. 5) are good indicator species in pollution studies (Olgunoğlu, 2008).

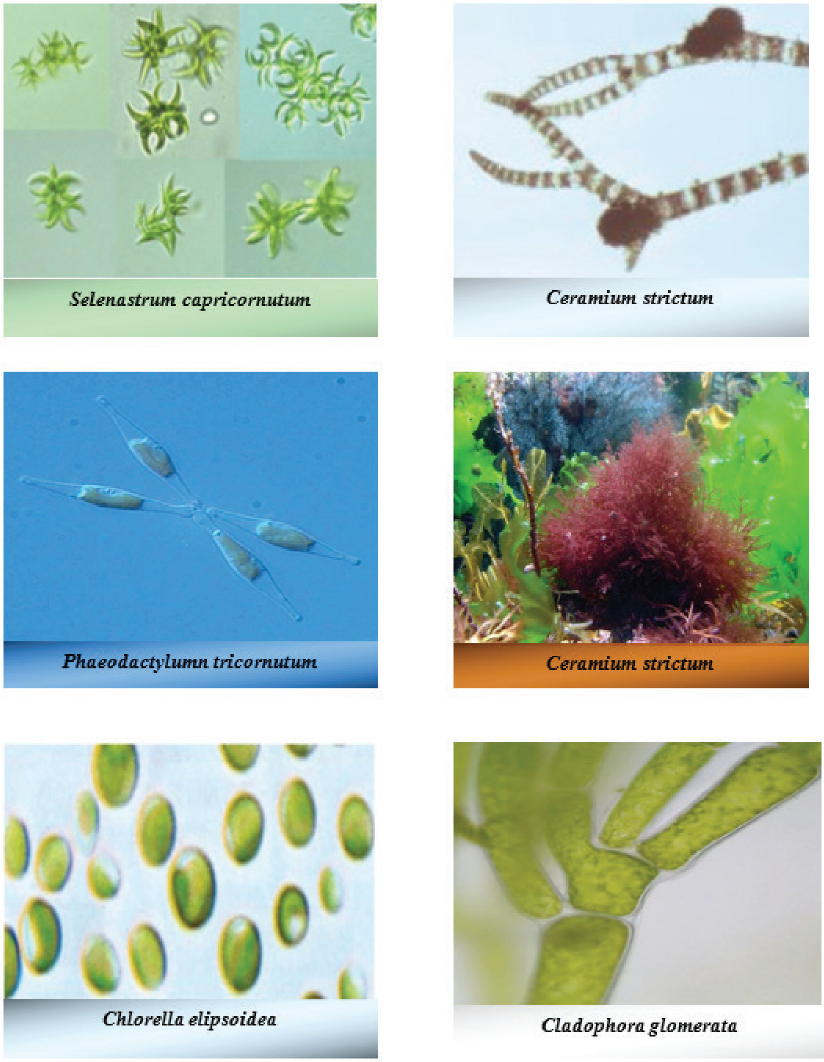

Figure 4. *Some microscopic algae species of HM bioindicators in aquatic ecosystems*

Figure 5. *Some macroalgae species of HM bioindicators in aquatic ecosystems*

Conclusion

Naturally occurring BIs are used to assess the health of the environment and identify positive or negative changes in the environment. They are also an important tool for detecting the effects these changes may have on humans. BI species are widely used in assessing and monitoring environmental health and biogeographic changes occurring in the environment. The concepts of BI and biomonitor should not be confused. A BI is defined as an organism, part of an organism, or a community of organisms that provides information about the quality of an ecosystem or part of an ecosystem. A biomonitor is an organism, part of an organism, or a community of organisms that provides information about quantitative aspects of the quality of the environment. Although a biomonitor organism is always a BI, a BI does not necessarily meet the requirements of a biomonitor organism (Markert, 1996; Markert et al., 1999). Algae are an important component of biological monitoring programs to assess water quality in aquatic ecosystems. Microscopic examination of water samples collected from aquatic ecosystems provides potentially useful early warning signals of deteriorating environmental conditions by determining the diversity and density of algae species. Therefore, the use of algae as BIs provides important information about the health of aquatic ecosystems.

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