



## REVIEW OPEN ACCESS

# An In-Depth Analysis of the Finfish Aquaculture in Türkiye: Current Status, Challenges, and Future Prospects

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## ABSTRACT

Aquaculture emerges as a crucial solution for addressing the global food shortage of an estimated 10 billion people by 2050. In Türkiye, aquaculture plays a significant role in supporting the economy and ensuring food security. Over the past two decades, finfish production in Türkiye surged from 61,163 to 547,505 t, generating \$1.7 billion in export revenue across over 100 countries. This growth has been driven by technological advancements, robust governmental support, and increasing global demand for aquaculture products. However, the sector also faces persistent challenges, including the need to enhance sustainability, mitigate ecological impacts, and manage finite resources. As Europe's leading fish producer, the Turkish aquaculture sector must continue to innovate and expand to meet the demands of a growing population. Despite the expanding research on Turkish finfish aquaculture, there is no comprehensive review that consolidates both scientific progress and sectoral developments. This study fills that void by combining a bibliometric analysis of 1958 scientific publications from 1983 to 2023 with an in-depth sectoral evaluation, providing a holistic understanding of the Turkish aquaculture sector. The bibliometric analysis highlights key research areas, trends, and knowledge gaps, while the sectoral overview examines production trends, dynamics of the feed industry, technological innovations, and economic factors. It also addresses challenges such as climate change impacts, reliance on imported feed ingredients, and disease issues, discussing potential avenues for sustainable growth through innovation, policy reforms, and technological integration. This review serves as a valuable resource for researchers, policymakers, and industry stakeholders, offering insights into the current state and future directions of finfish aquaculture in Türkiye.

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## 1 | Introduction

Ensuring food security will become more difficult for the global population expected to be 10 billion in 2050 [1, 2]. Although global human diets are largely dependent on staple crops such as rice, wheat, and maize, these plant-based sources often fall short of delivering certain essential nutrients. On the other hand, blue food (food derived from aquatic animals, algae being caught or cultivated in freshwater and marine environments) provides essential nutrients, including amino acids, omega-3 fatty acids, and micronutrients such as vitamin A and iodine, which are frequently deficient in plant-based diets [3, 4]. However, illegal, unreported and unregulated fishing, along with increasing aquatic pollution, are causing the depletion of wild fish stocks, posing serious threats to biodiversity and potential sustainability [5–11]. Aquaculture is becoming increasingly essential for global food security by providing a sustainable and scalable source of fish protein [12–14]. In 2022, aquaculture yielded 130.9 million tonnes, significantly enhancing food security by providing 15% of global animal protein intake, employing over 20 million people, and generating a farm-gate value of \$312.8 billion [15]. In line with the Blue Transformation initiative launched by the Food and Agricultural Organization of the United Nations (FAO), aquaculture plays a crucial role in advancing several UN Sustainable Development Goals (SDGs), including efforts to eliminate poverty, safeguard the environment, and promote global prosperity. The initiative draws attention to the importance of sustainable growth in the production of “blue food” in developing a sustainable and inclusive food system [15, 16]. Aquaculture surpassed capture fisheries in global aquatic animal production, with a total of 94.4 million tonnes (excluding algae) making up 51% of the world’s total production. It also set a record by surpassing 57% of aquatic animal products for human consumption. Inland aquaculture yields 59.1 million tonnes, whereas mariculture and coastal aquaculture add another 35.3 million tonnes [15, 17]. Aquaculture provides a vital solution to feeding a growing global population while mitigating the environmental impacts of overfishing and promoting sustainability in line with the SDGs.

Although a relatively new entrant among global aquaculture producers, Türkiye has shown in a short time that it has significant potential in aquaculture production [18, 19]. This potential is primarily attributed to its diverse geographical features, which provide a wide spectrum of salinity and temperature conditions across distinct marine ecosystems, including the Black Sea to the north, the Aegean Sea to the west, and the Mediterranean Sea to the south. Türkiye possesses significant geographical and physical advantages that are conducive to aquaculture development, with substantial opportunities for both inland waters and marine aquaculture [20]. Total aquaculture production in Türkiye reached 556,287t in 2023, reflecting steady growth over the past two decades, with finfish farming increasing from 61,163t in 2002 to 547,505t in 2023. This growth has been supported by approximately 2352 operating facilities, including 1829 in inland waters and 533 in the open sea, with a combined estimated capacity of 784,864t. This indicates not only the increase in production volume but also the improvement in product quality and the use of advanced technology. Rapid sector development has paved the way for fish farming to become increasingly critical in Turkish

agricultural policies and economic planning [21]. At the same time, it has become a strategic area for the country’s economy with its contribution to significant export revenues [22]. In addition, the export capacity of the sector has substantially expanded, with Turkish finfish now exported to over 100 countries, reflecting increasing global demand and the strategic strengthening of Turkish production and international market presence [23]. The development of the Turkish aquaculture sector and its experience with ups and downs through the way of progress has not been previously examined and thoroughly reported to the global stakeholders. An effort in this direction can be a good example to those trying to develop the sector for their food supply and to increase their competence in the international market.

This review provides a comprehensive evaluation of finfish aquaculture in Türkiye, combining a systematic literature review, bibliometric analysis, and sectoral evaluation. It outlines the historical development and current status of finfish aquaculture, pinpoints main influences on the industry, and assesses both the challenges and opportunities concerning technology, sustainability, and market dynamics. Although aquaculture in Türkiye is diversifying to include shellfish and crustaceans, finfish farming continues to lead in production volume, economic contribution, and research activity. Therefore, this review focuses exclusively on finfish aquaculture. The bibliometric analysis reviews scientific publications to identify research trends, knowledge gaps, and areas requiring further investigation, while the sectoral analysis compiles data on production, advancements in the feed industry, and economic factors. Finally, this review concludes by exploring the future direction of the Turkish aquaculture sector and proposing sustainability strategies, providing valuable insights for stakeholders, researchers, and policymakers.

## 2 | Methods

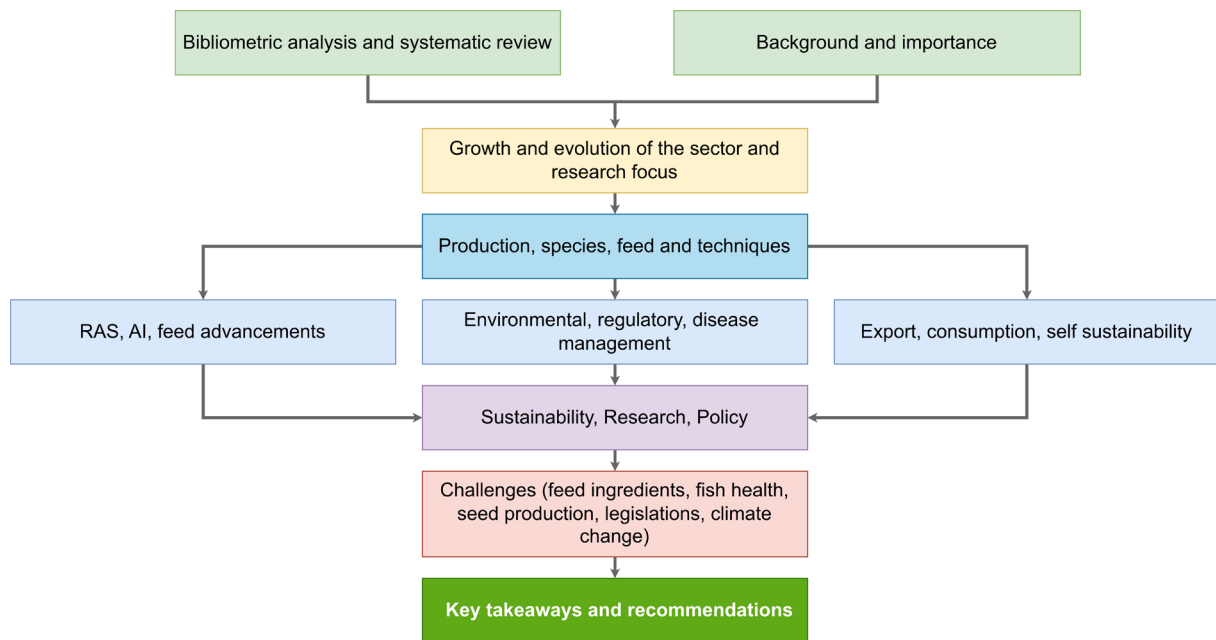
### 2.1 | Framework and Methodological Overview

The present review integrates two synergistic methodologies to assess the status of the Turkish finfish aquaculture sector: (1) a bibliometric and systematic literature review, providing a quantitative evaluation of research trends, and (2) a descriptive industry overview, which compiles significant advancements, challenges, and future directions. The conceptual framework (Figure 1) demonstrates how these two methods are combined to offer a comprehensive evaluation of both academic and industrial progress. The following sections detail the sources of data and criteria for methodologies used for analysis.

### 2.2 | Literature Search, Data Extraction and Data Collection

A systematic literature search was conducted using the Web of Science (WoS) database on December 19, 2023. A topic search (search in title, abstract, and keyword fields) was performed using the following search string in the WoS database:

“(TS=(*Platichthys flesus* OR *Scophthalmus maximus* OR *Psetta maxima* OR *Sciaena umbra* OR *Dentex dentex* OR *Argyrosomus*



**FIGURE 1** | Conceptual framework outlines the logical development of the review, which is structured into two main components: A bibliometric and systematic examination of research in Turkish aquaculture and alongside a comprehensive sectoral analysis.

*regius* OR *Umbrina cirrosa* OR *Pagrus* OR *Oreochromis* OR *Silurus glanis* OR *Clarias gariepinus* OR *Acipenser* OR *Huso huso* OR *Cyprinus carpio* OR *Salmo* OR *Salvelinus* OR *Dicentrarchus labrax* OR *Sparus aurata* OR *Oncorhynchus mykiss* OR *Diplodus* OR *Pagellus* OR *Ctenopharyngodon idella* OR *Lithognathus mormyrus* OR *Sarpa salpa* OR *Thunnus thynnus*) AND AD=(Turkey)”

The search terms were carefully selected to ensure comprehensive coverage of finfish species relevant to Turkish aquaculture. Selection was based on criteria such as commercial importance, potential for future aquaculture development, and ecological or economic relevance. For a methodical and evidence-based approach, we mainly used species data from the Turkish Statistical Institute (TUIK) and the Food and Agriculture Organization (FAO) aquaculture production statistics. We also incorporated species that, though not yet widely farmed, have been the focus of research for their potential in Turkish aquaculture.

Following the search step, the obtained research articles were manually filtered. The article review process was conducted in two sequential stages: (1) the evaluation of the inclusion stage and (2) the data extraction stage. A single reviewer executed both stages. Only peer-reviewed articles specifically focused on finfish aquaculture conducted in Türkiye were included. The inclusion and exclusion process is detailed in the PRISMA flow diagram [24], which visually maps out each step of the screening (Figure 2).

Bibliometric data of the included publications (title, journal, year of publication, author names, affiliations, and keywords) were retrieved from the WoS database. The data collected were subsequently analyzed to discern trends in publication, networks of collaboration among institutions, institutes contributing to finfish research, leading journals where these articles are published, and frequently used keywords.

Aquaculture-related data were manually extracted from each included publication, focusing on two main aspects: (1) the target taxa studied and (2) the main research focus of the article. Through a collaborative discussion among the authors, articles were sorted into 16 distinct research categories, ensuring uniform classification. Where there was uncertainty, decisions were made by consensus to uphold the reliability of the categorization. The defined research focus areas include growth performance, fish health/diseases, toxicology, feed formulation, alternative feed ingredients, feed additives/supplementation, fish processing techniques, fillet quality, developmental studies, morphological studies, physiology, reproduction, genetics, culturing techniques, food safety, and economy. The categorized data concerning target taxa and research focus were analyzed to identify research trends, gaps, and dominant themes in Turkish aquaculture literature. The distribution of studies across different research areas was examined to assess which topics received the most and least attention. Additionally, the findings from the systematic analysis were compared with sectoral data, including production trends and industry challenges, to evaluate whether scientific research corresponds with industry demands.

Additionally, annual aquaculture production statistics encompassing both national fisheries and aquaculture production, along with annual fish import and export data were retrieved from the TUIK. The global aquaculture and fisheries data were retrieved from the Fisheries and Aquaculture statistics of FAO. These production data were used to describe production and market trends. National feed production data were retrieved from the General Directorate of Food Control of the Ministry of Agriculture and Forestry of Türkiye and applied in ARIMA (autoregression integrated moving average) models for trend visualization and forecasting future estimates.

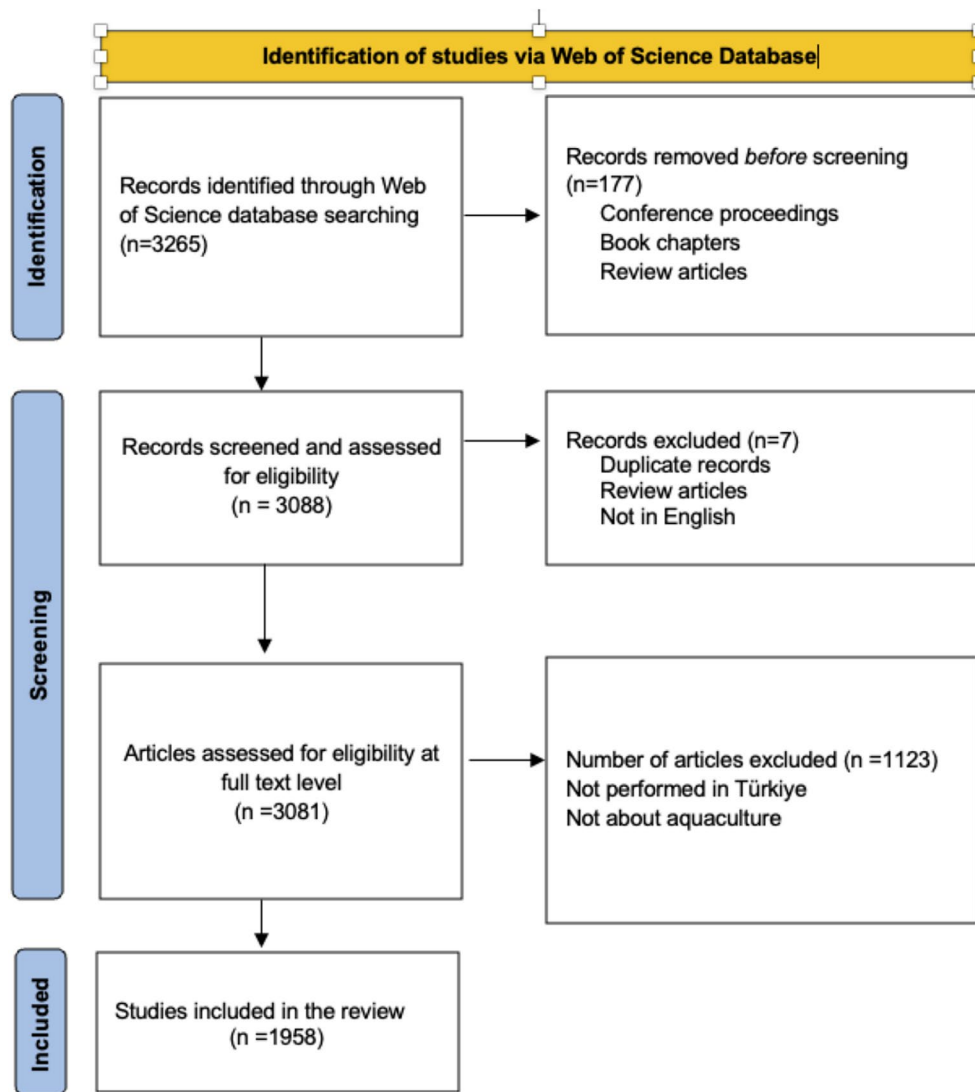


FIGURE 2 | PRISMA flow diagram for systematic review.

### 2.3 | Data Analysis

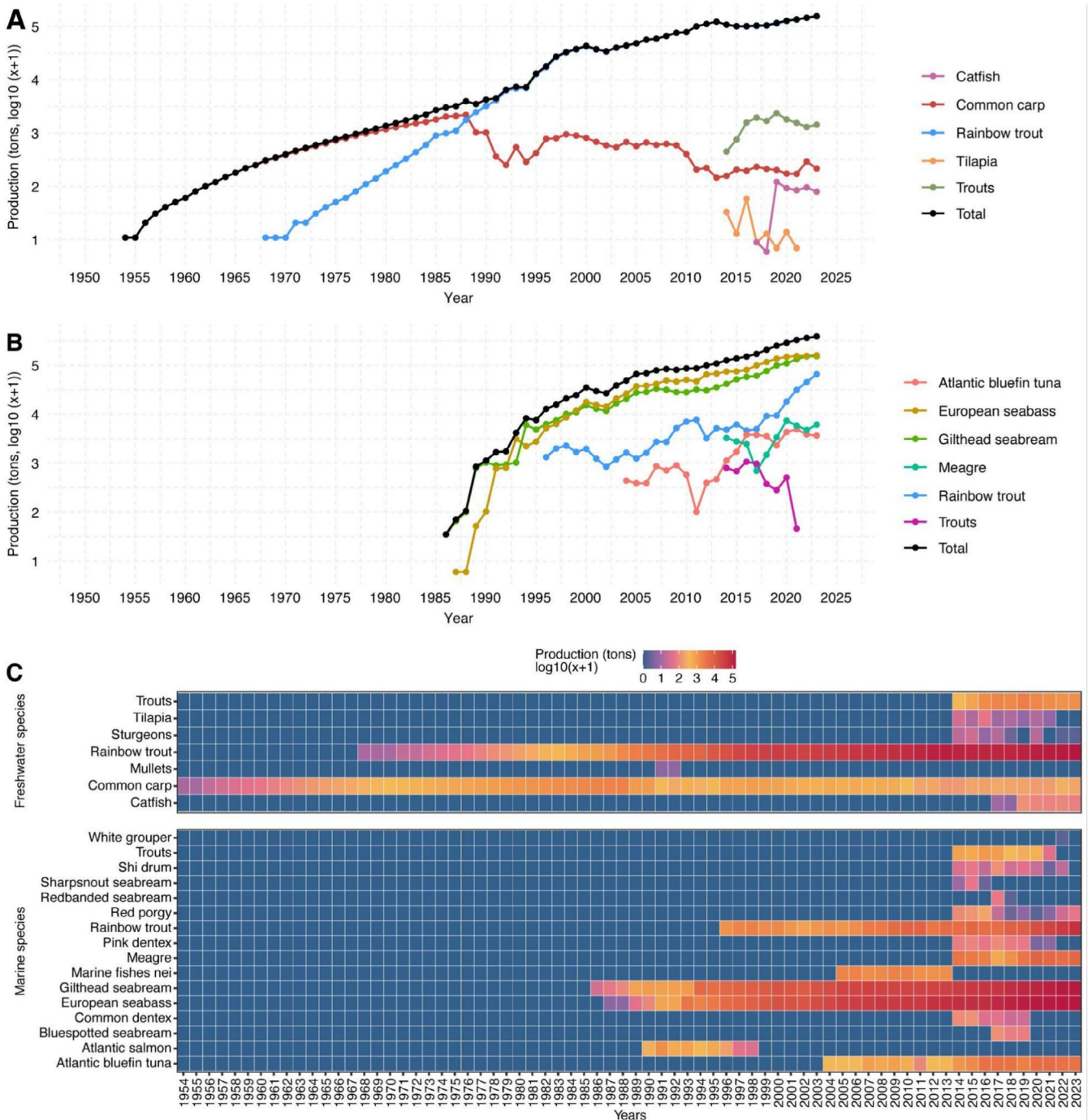
All data analyses were performed in R (ver. 4.4.1) [25], unless otherwise stated.

A scientometric quantitative analysis of the included publications and knowledge mapping [26] was performed using *the bibliometrix* package [27]. The collaboration network [28] was calculated using the Kamada-Kawai algorithm and visualized using *the igraph* package [29]. Data for word clouds were prepared and visualized using *the wordcloud* [30] and *tm* [31] packages. The functions of *tidyverse* [32] and *dplyr* [33] packages were primarily used for data cleaning and summarization processes. The *ggplot2* [34] was used for visualization.

### 3 | Overview of Finfish Aquaculture in Türkiye

The growth of aquaculture in Türkiye aligns with the worldwide trend. Rainbow trout, sea bass, and sea bream constitute the predominant share of overall aquaculture output, positioning Türkiye as the second-biggest aquaculture nation in Europe.

Finfish aquaculture in Türkiye began on a small scale in the 1950s, reaching 50 t of production by the 1960s through common carp (*C. carpio*) farming [35, 36]. During the same period, carp production saw substantial growth, surpassing 1000 t. In the late 1960s, small-scale production efforts initiated the farming of rainbow trout (*O. mykiss*) in freshwater environments [37]. During the mid-1980s, marine species such as sea bream (*S. aurata*) and sea bass (*D. labrax*) were introduced into the Turkish aquaculture sector [38]. The juvenile fish required for the culture were obtained from their natural habitats and reared in small wooden cages during the initial phases of sea bass and bream aquaculture. During the 1980s, carp production reached its maximum at 2000 t, while rainbow trout production approached 1000 t (Figure 3). The late 1980s “anchovy crisis” in Türkiye marked a turning point for Turkish aquaculture, bringing attention to its potential as a sustainable alternative to traditional fishing industries [39]. A significant milestone in Turkish aquaculture was a collaborative project with the Japanese government at the Central Fisheries Research Institute (SUMAE) in Trabzon-Türkiye, which successfully developed hatchery technology for the Black Sea turbot (*S. maximus*). Despite technological success,

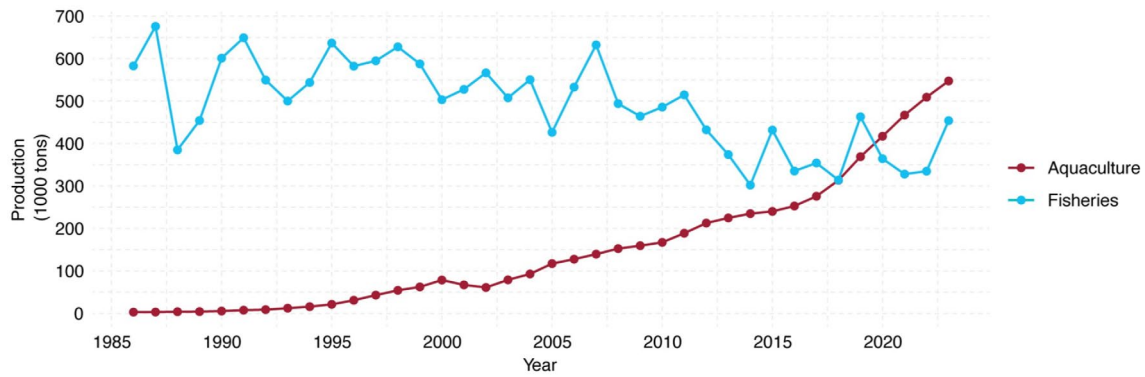


**FIGURE 3** | Growth of freshwater (A) and marine (B) cultured finfish species production from the 1950s to 2023 and heatmap of annual production of finfish species both in freshwater and marine (C). The data was obtained from the Turkish Statistical Institute (TUIK) and FAO statistics. Annual production values were  $\log_{10}(x+1)$  transformed for visualization. The names of the finfish species/groups listed here are presented as listed in TUIK and FAO statistics.

commercial production has not been achieved yet due to unsuitable water temperatures and a scarcity of land-based farm sites. Nevertheless, since 1998, SUMAE has continued to produce juvenile turbot for restocking purposes [40, 41].

The first attempts at rainbow trout and Atlantic salmon (*Salmo salar*) culture in the Black Sea were undertaken in the early 1990s. These species were initially considered promising candidates for large-scale aquaculture due to their high market

value and established farming techniques in other regions, notably Norway. The initial attempts at Atlantic salmon farming yielded a considerable production, reaching up to 1500t between 1990 and 1998 in the Black Sea, but the operations had to be discontinued because of the region's high summer water temperatures for sustainable salmon production (Figure 3). Drawing on the knowledge gained from Atlantic salmon production in 1996, Türkiye transitioned from Atlantic salmon to rainbow trout farming in marine environments. This shift

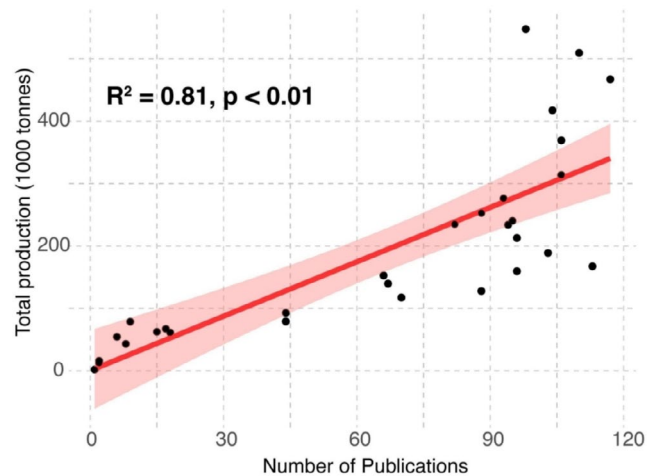


**FIGURE 4** | The growth comparison between finfish aquaculture and fisheries landing from 1986 to 2023 in Türkiye.

might also have been influenced by the increased availability of rainbow trout fingerlings compared to the limited availability of Atlantic salmon fingerlings in that period. In the same period, sea bream production increased significantly, rising from 10,000 to 30,000 t. Similarly, sea bass production increased from 15,000 to 50,000 t [15] (Figure 3). During this period, sea bass and sea bream farming was gradually transformed from capture-based aquaculture to hatchery-based aquaculture relying on seasonal juvenile production. To develop and establish marine aquaculture production, the Beymelek Lagoon Aquaculture Project was carried out in Antalya with cooperation between the Ministry of Agriculture and Rural Affairs and the United Nations Development Programme in 1988. In parallel with the governmental effort, numerous private enterprises made remarkable investments to increase fully independent marine aquaculture, resulting in the establishment of high-capacity sea bass and sea bream hatcheries and enabling the production of millions of juveniles in the following years.

At the beginning of the 2000s, a significant advancement in the industry was the introduction of bluefin tuna (*T. thynnus*) farming in the Mediterranean Sea, initiating a production of 400t, which subsequently increased to exceed 3000t in 2016 [15, 39] (Figure 3). The aquaculture sector experienced a remarkable decline during the national economic crisis in 2001–2002. Compensation began as the economy improved after 2003 (Figures 3 and 4), spurring rapid production growth supported by European Union (EU) membership developments and government subsidies [39].

Research and development activities in Turkish aquaculture by private companies, public research institutions, and universities also focused on new/alternative species for diversification in aquaculture, including Black Sea turbot, flounder (*Platichthys flesus*), sturgeon species, mullets (*Mugil cephalus* and *Liza aurata*), bluefin tuna, common dentex (*Dentex dentex*), red porgy (*Pagrus pagrus*), common pandora (*Pagellus erythrinus*), sharpnose sea bream (*Puntazzo puntazzo*), white grouper (*Epinephelus aeneus*), shi drum (*Umbrina cirrosa*), striped sea bream (*Lithognathus mormyrus*), meagre (*Argyrosomus regius*), greater amberjack (*Seriola dumerili*), brown meagre (*Sciaena umbra*), white sea bream (*Diplodus sargus*), two-banded sea bream (*Diplodus vulgaris*), blue-spotted sea bream (*Pagrus caeruleostictus*) and clownfish (*Amphipron ocellaris*) [20, 42–47]. Although these species possess value, consistent farming has not been sustained due to some factors such as insufficient market demand. Meagre



**FIGURE 5** | The Spearman correlation between aquaculture production (in tonnes) and the number of scientific studies on key species over time.

(*A. regius*) aquaculture, however, stands out with an average annual production of over 4000 t in the past decade (Figure 3).

Turkish aquaculture production has significantly expanded over the last decades, mirroring global trends and eventually surpassing fisheries production [22]. Over the past 20 years, total aquaculture production in Türkiye has increased tenfold, surpassing 500,000 t [15] (Figure 4). In 2020, for the first time, aquaculture production in Türkiye surpassed that of wild fisheries, signifying a notable milestone and underscoring the increasing significance of aquaculture in addressing global fish demand as traditional fisheries confront sustainability challenges (Figure 4). As of 2023, finfish aquaculture production in Türkiye reached 547,507 t, representing over half of the country's total fish production, as shown in Figure 4 [22]. Mariculture, especially farming of sea bass, sea bream, and rainbow trout, plays a key role in finfish production, contributing 390,780 t, or 71.3% of the total. Large rainbow trout, also known as Turkish salmon, showed remarkable growth, reaching 66,055 t, 31.18% increase from the previous year (Figure 3).

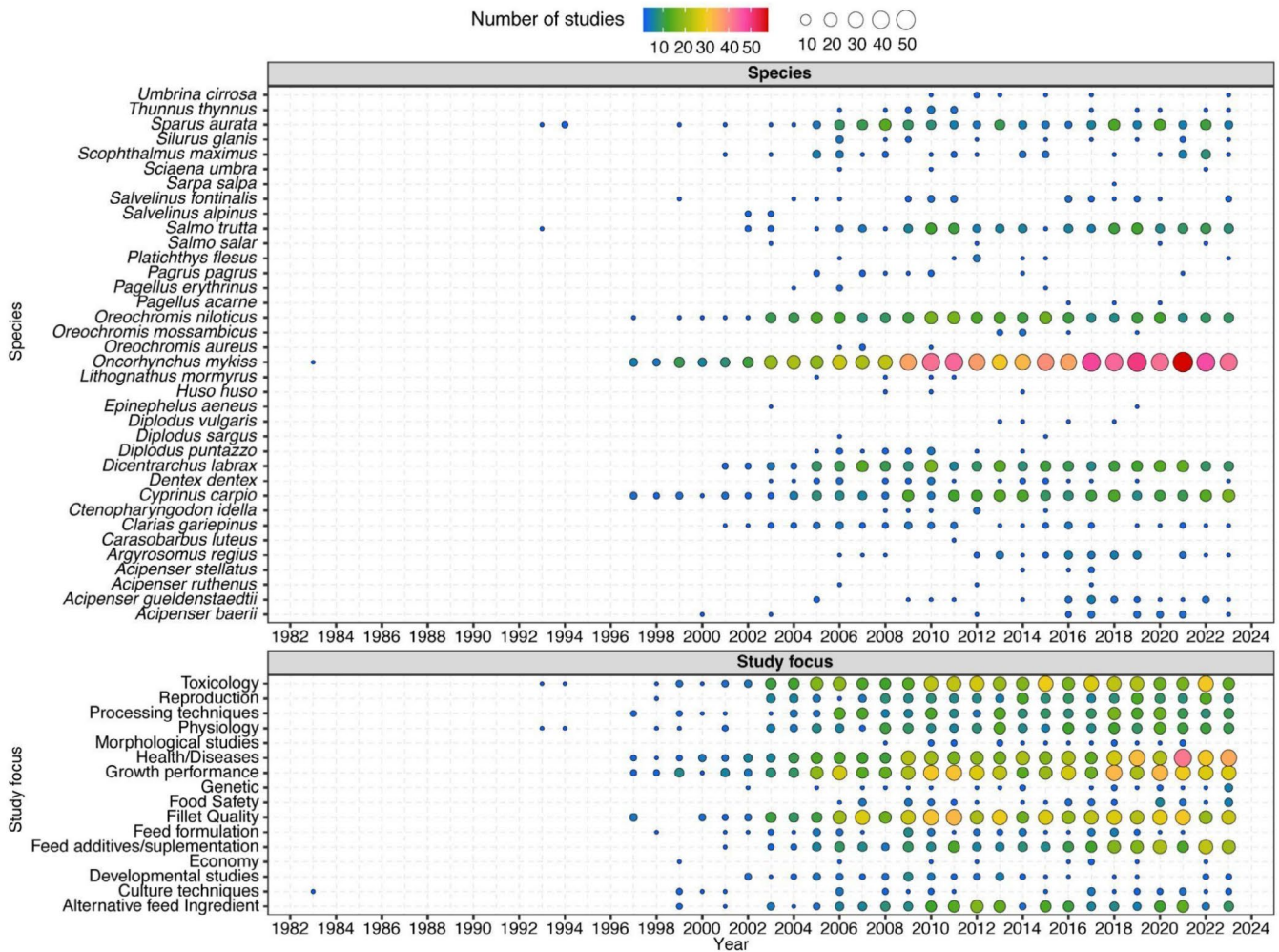
In the meantime, the aquaculture sector has experienced substantial growth due to technological advancements, government support, and scientific knowledge, establishing the country as a leading Mediterranean producer. Türkiye has emerged as a major producer of rainbow trout, sea bream, and sea bass, with

operations expanding to the Black Sea for the cultivation of rainbow trout (Turkish salmon). In Turkish aquaculture, intensive culture techniques are widely used, particularly for carnivorous fish species [48]. This growth and variety highlight an expanding global role in the aquaculture of Türkiye, fueled by higher production capacities and a broader selection of farmed species, shaped by market forces and environmental needs.

Since the 1980s, Türkiye has demonstrated significant advancements in scientific research, characterized by an increasing number of researchers and the establishment of new institutions driving scientific progress, especially throughout the 1990s. During this period, scientific studies focusing on species such as rainbow trout, sea bass, sea bream, and carp were prevalent, resulting in numerous published papers on these species. With the rapid expansion of the aquaculture sector, the significance of research has intensified and has played a critical role in supporting future developments in this relatively nascent food production industry [49]. The abundance of research on these species has significantly enriched aquaculture knowledge [50]. A significant increase in scientific research focused on recently cultivated species such as meagre has been observed in recent years. Figure 5 shows a strong correlation between publication numbers and

aquaculture production volumes. This relationship can be complex, as increased production may stimulate further research on these species, while the development of “know-how” in aquaculture techniques, driven by scientific inquiry, might, in turn, enhance production. On the contrary, some species, such as the Black Sea turbot, are currently only produced for stock enhancement due to inadequate farming conditions and water quality. Nevertheless, scientific research in this context may solve specific problems and make commercial production of these species possible. Research has been crucial in advancing the breeding of historically difficult to breed species [51].

The species with the most consistent and increasing research interest include rainbow trout, common carp, Nile tilapia (*Oreochromis niloticus*), brown trout (*Salmo trutta*), sea bass, and sea bream. These species have been subjected to a substantial number of studies, especially since 2000 onwards (Figure 6). Research activity showed a significant increase in the number of studies on these species, reflecting the growing global interest in aquaculture practices. There has been a significant increase in the number of studies across various research areas, particularly in terms of growth performance, filet quality, toxicology, and health/diseases (Figure 6).



**FIGURE 6** | Temporal distribution of the number of scientific articles by species and study focus from 1983 to 2023. The upper panel displays the number of scientific articles on various fish species, while the lower panel highlights the focus areas of these articles. Bubble sizes and colors represent the number of studies.

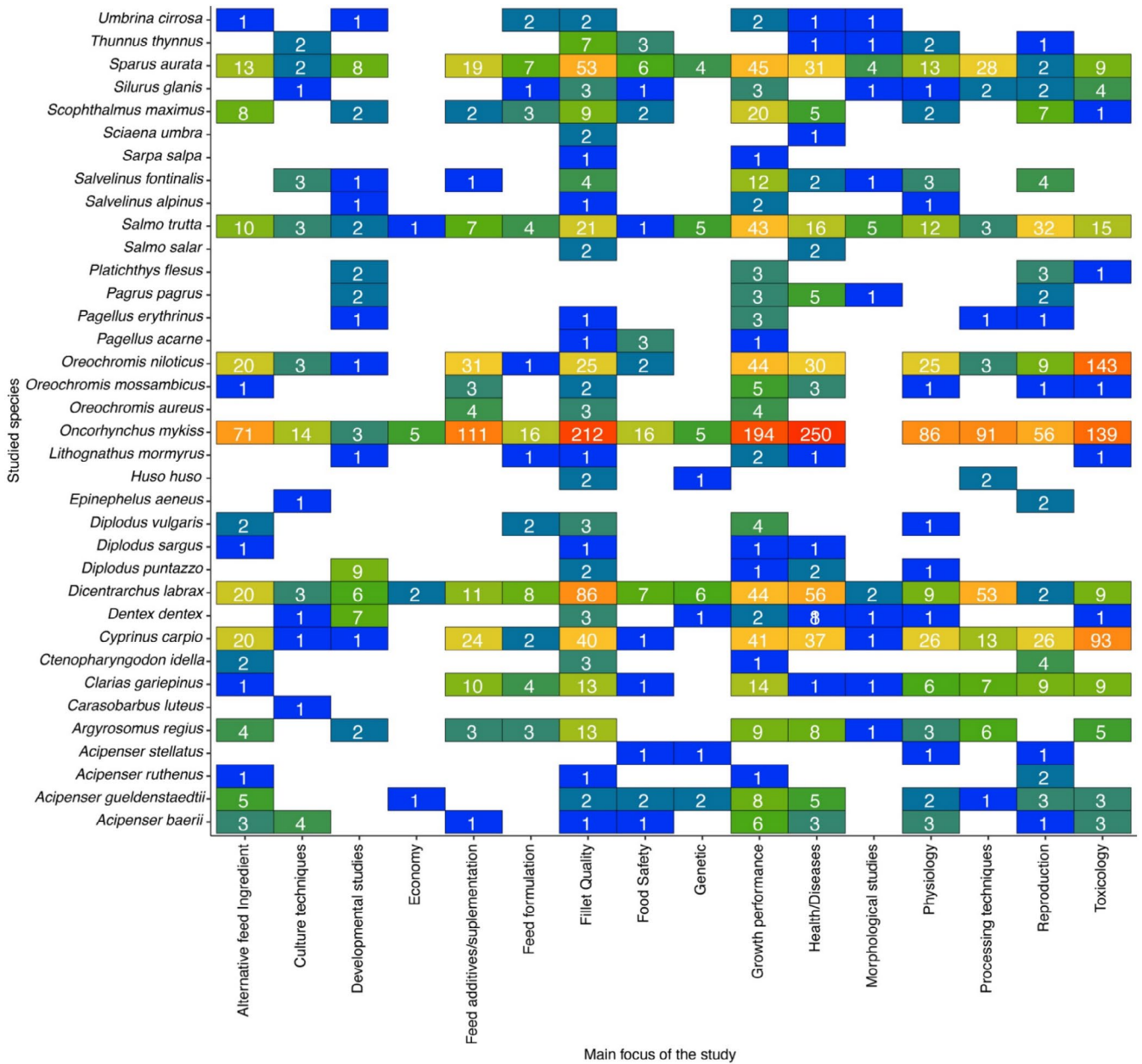
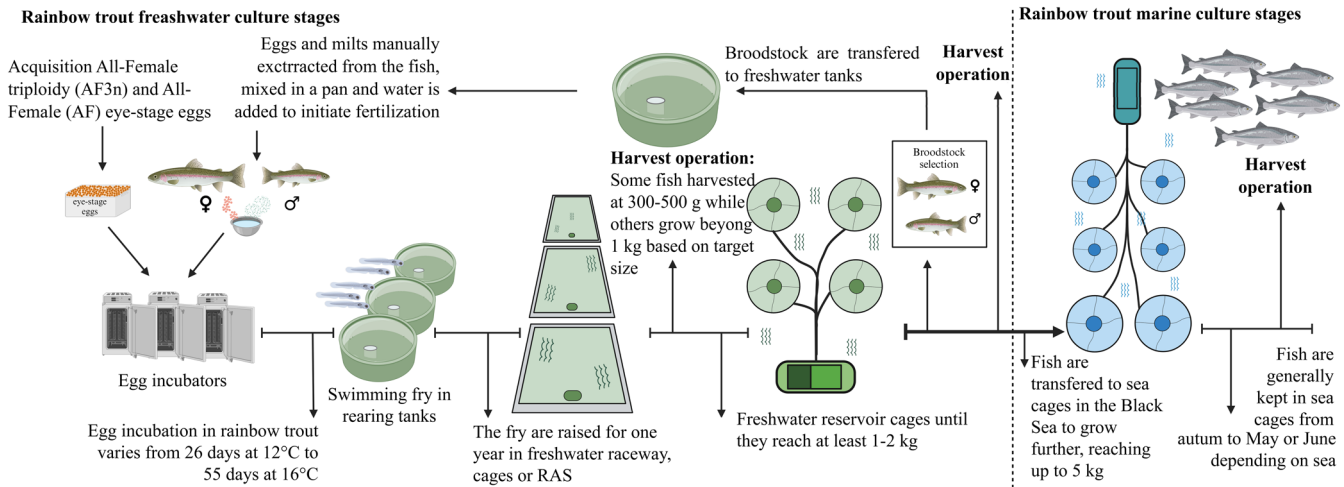


FIGURE 7 | Main focus of the scientific articles by species.

The main goal of most scientific studies in this field is to determine the most suitable species-specific culture conditions for sustainable and successful production. It is an undeniable fact that scientific research has contributed to the development of aquaculture production techniques and has played an important role in ensuring their sustainability. Information gathered from the systematically reviewed papers revealed that *O. mykiss* (rainbow trout) has been the most extensively studied species in Turkish aquaculture. Studies on this species predominantly focus on areas such as fish health and diseases (250 studies), fillet quality (212 studies), growth performance (194 studies), toxicology (139 studies), and feed additives/supplementation (111 studies) (Figure 7). In contrast, despite their high market value and increasing interest in aquaculture, sturgeons have attracted considerably less research effort, with comparatively few studies addressing their cultivation methods, nutritional needs, and health management.

#### 4 | Culture Techniques/Systems

In Türkiye, aquaculture includes a range of advanced systems and techniques that have driven rapid growth in the industry, especially in finfish farming. Freshwater production primarily relies on raceway systems and is widespread across the country [52]. Earthen pond aquaculture with saline water in the Aegean region began in the late 1980s, with a main focus on sea bass and sea bream. Small family-run farms use artesian well water, and ponds rely on aerators to maintain oxygen levels for optimal fish health and production [53]. Marine and inland cage systems are among the most significant drivers of recent expansion, which have played a pivotal role in boosting aquaculture production [54]. The initial cage farming applications in Türkiye involved frames made of iron or galvanized steel with wooden components, providing buoyancy through high-density foam or plastic drums [55]. Technological



**FIGURE 8** | Production process of large rainbow trout, starting in freshwater and harvested from either marine or freshwater cages.

advances have made it possible to build larger, more durable cages and improve farming production. In recent years, barge systems have made it possible to produce thousands of tonnes of fish in a single system, significantly reducing the demand for human labor [23]. The large-sized rainbow trout, called “Turkish salmon”, is cultured with the understanding that it is a process that undergoes several stages to guarantee optimization of growth and production. It starts in autumn when broodstock is chosen and continues with egg fertilization (Figure 8). Water temperature during the incubation of eggs and early development of fry seriously affects their survival [56, 57]. After hatching, the fry are reared in freshwater for approximately 1 year, reaching a weight of 300–500 g. Harvesting occurs at different stages depending on growth conditions and market demands; some fish are harvested at 500 g, whereas others are transferred to freshwater or sea cages for further growth [58]. In the Black Sea region, fish transferred to sea cages can reach over 5 kg [59]. The use of all-female triploid and diploid eggs, primarily imported at the eyed stage from the USA or EU but now also produced domestically, is common in these sea cage operations.

The rapid expansion of aquaculture is increasingly constrained by limited water resources, suitable sites, and the ecological carrying capacity of surrounding environments [60]. As a result, there is growing private investment in alternative production systems and novel techniques, which are critical for sustainable production. For instance, the applications of oxygen generators and liquid oxygen have been recently adopted by a number of rainbow trout farmers in flow-through ponds to ensure continuity of production during the summer months and marine finfish hatcheries to increase stocking densities [61]. Although conventional fish farming is expected to continue growing, innovative systems such as land-based recirculating aquaculture systems (RAS) and deep-sea aquaculture might play a significant role in future production growth. General progress in RAS technologies has fostered an increasing interest in salmon farming in onshore intensive tank production systems. There are ongoing initiatives to produce Turkish salmon using RAS, though these efforts are still in the pilot-scale phase. While these innovative systems have started to be implemented commercially, their widespread adoption remains limited due to the high initial capital

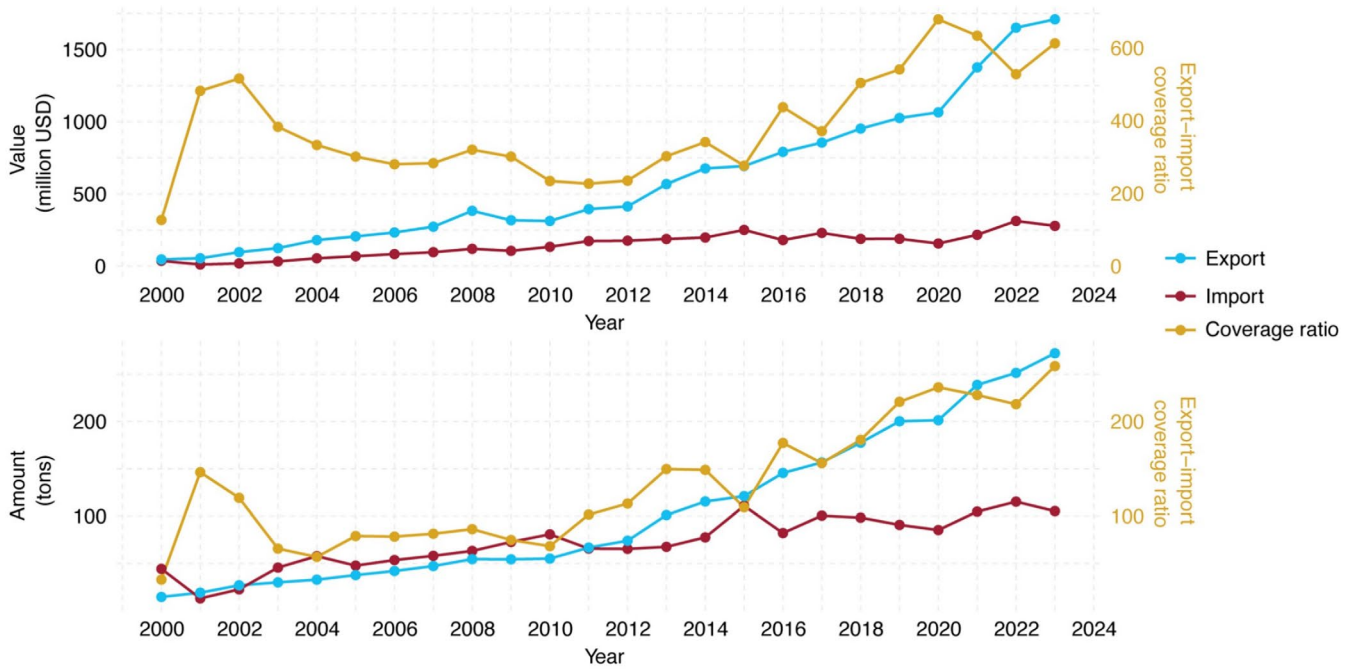
investment, technical challenges, and high operating costs, similar to the experience in European aquaculture. As an alternative to traditional aquaculture methods, the use of submersible cages in the Black Sea or innovative solar-powered circulation systems and deep-sea cage systems are examples. However, the application of such systems in Turkish aquaculture remains largely experimental at this stage [23]. Furthermore, biofloc technology and aquaponics demonstrate substantial potential for the future of Turkish aquaculture, enhancing sustainability through improved water quality and reduced environmental impact [62–64].

Despite implementing the current aquaculture systems to optimize farm management, aquaculture producers employ diverse innovative technologies, including automation of operations, gathering data via sensors and imaging, and analyzing this data to inform decision making through machine learning. However, there remains a need for additional technological applications in culture systems to measure the impact of aquaculture operations on environmental ecosystems, which can subsequently enhance aquaculture efficiency by minimizing inputs and losses.

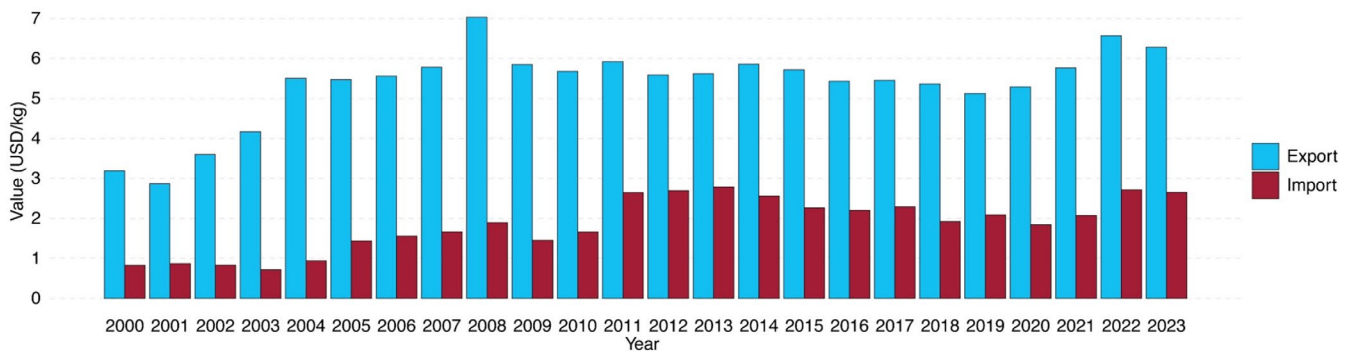
## 5 | Fish Feed

One of the most significant indicators of the rapid and secure progress of aquaculture in Türkiye is the development of the fish feed sector, which functions as a symbiotic partner in the industry. In the 1980s, less than a hundred companies produced several thousand tonnes of finfish [65], yet during the same period, only 134 t of fish feed were being produced [66], highlighting the limited feed availability to produce fish at that time. Challenges in sourcing essential raw materials initially made feed manufacturers hesitant to produce feed for finfish, pushing farmers to use poultry feed as an alternative feed for aquaculture [67]. The establishment of the first fish feed producer in Türkiye, Bilecik Feed Industry Company (Bilyem-Taş), in 1978 marked a major milestone for the industry. Building on this progress, Çamlı Feed (formerly Pınar Feed) began producing fish feed in 1987 and further advanced the industry by becoming the first Turkish company to adopt extrusion technology for fish feed production in 2000 (Bio Aqua) [68]. By 1998, there were nine fish feed factories





**FIGURE 11** | Total exported and imported fish by value (top), amount (bottom), and export-import coverage values by year (the value and amount were displayed on the left y-axis, while the export-import coverage ratios were presented on the right y-axis).



**FIGURE 12** | Annual comparative analysis of fish exports and imports from Türkiye, quantified by kilogram value.

nutrients also help lower rates of heart disease, stroke, and some cancers [77]. Factors like income, education, and cultural preferences influence consumption, with developed countries consuming up to 24 kg annually, while low-income nations consume as little as 10 kg [78].

Despite Turkey's extensive coastline and a growing aquaculture sector, fish consumption remains relatively low at 7.2 kg per capita, compared to world average [79, 80]. The low local consumption is an important challenge for the development of the international competitiveness of the aquaculture sector [81]. The low consumption is attributable to cultural, economic, and geographical factors. Turkish individuals exhibit a strong cultural preference for red meat and poultry, with fish often perceived as food reserved for exceptional occasions, particularly in inland regions where access to fresh fish is limited, making terrestrial meat products more readily available and economically viable. Turkish people generally prefer fresh fish over processed fish, even though processed fish products are available. Hence, fish consumption in Türkiye is

highly seasonal, with certain species like anchovy and bonito being available only at specific times of the year, contributing to fluctuating consumption patterns [78, 82]. Additionally, favorite fish like anchovy are relatively inexpensive and widely available in markets when in season, which makes them a preferred choice for many consumers seeking fresh and budget-friendly fish [83]. Living close to coastal areas is a key factor influencing fish consumption [84]. Indeed, fish consumption per capita was reported as 25 kg in the Black Sea Region, while it is notably lower, at just 0.5 kg in the southeastern part of Türkiye [85].

To increase fish consumption in Türkiye, certain policies, such as training, advertising, and different marketing strategies, can help increase the amount and frequency of fish consumption, especially among lower socioeconomic groups and for less-consumed fish species [86, 87]. Educational activities that promote proper fish processing techniques to reduce waste may also contribute to increased fish consumption [88]. Increasing awareness of the health benefits of eating fish and seafood can

also play a role in boosting fish consumption [89]. Moreover, as incomes and awareness levels rise, fish consumption in Türkiye could increase. NGOs and government agencies are running school campaigns to promote fish consumption, aiming to boost per capita intake by helping children become familiar with the taste of fish from an early age.

## 8 | Employment

Employment in the aquaculture sector has grown significantly, in parallel with the increase in the number of ventures and production volumes. The workforce experienced considerable growth over the years, expanding from 5100 employees in 2003 to 8500 employees by 2012 and further reaching 11,200 employees by 2022 [79]. Only in Muğla province, a total of 2127 individuals are employed in 327 fish farms, of which 24.8% are aquaculture engineers and technicians, while the remaining 75.2% consist of other staff. Hiring these technical professionals is essential for bridging the gap between the field and academic institutions, enabling direct knowledge and solution sharing from practical operations to universities and public research centers. This connection supports ongoing improvement and innovation in the industry [90]. A survey study reported that 355 individuals were employed across 18 fish feed factories in Türkiye, including 33 aquaculture engineers, 15 agricultural engineers, 8 chemists, 6 veterinarians, 5 technicians, and workers [91]. The number of fish feed factories has now risen to 29, with operations across 15 provinces (Figure 9). It is estimated that the number of employees has increased along with the increase in the number of factories and production volume [92].

## 9 | Bibliometric Mapping and Systematic Review of Current Research Activities in Turkish Aquaculture

An initial search of WoS yielded 3265 results. After excluding conference proceedings, book sections, and review articles, the number was narrowed down to 3088. Out of the 3088 articles screened for relevance to finfish aquaculture, 1123 were excluded. In total, 1958 scientific articles were published on cultured or candidate finfish species in Türkiye between 1983 and 2023. A rapid increase in the number of published articles has been observed in recent years. In the following years, an average of approximately 100 articles was published (Figure 13A). The articles were published in 292 distinct journals indexed in the WoS. Among these, the *Israeli Journal of Aquaculture-Bamidgheh* (149) is the leading journal with 150 articles, followed by the *Turkish Journal of Veterinary and Animal Sciences* (128), the *Turkish Journal of Fisheries and Aquatic Sciences* (108), and *Aquaculture Research* (97) (Figure 13B). The authors from 297 institutions contributed to these articles. Based on affiliations, Çukurova University is the top institution, with 272 articles, followed by Ege University (178), Atatürk University (170), and Istanbul University (139) (Figure 13C). Collaboration network analysis indicated that Çukurova University demonstrated the highest level of collaboration with other institutions, followed by Atatürk University and Çanakkale Onsekiz Mart University (Figure 13D). Based on the keywords used by the authors, rainbow trout (388 occurrences) and *O. mykiss* (207 occurrences)

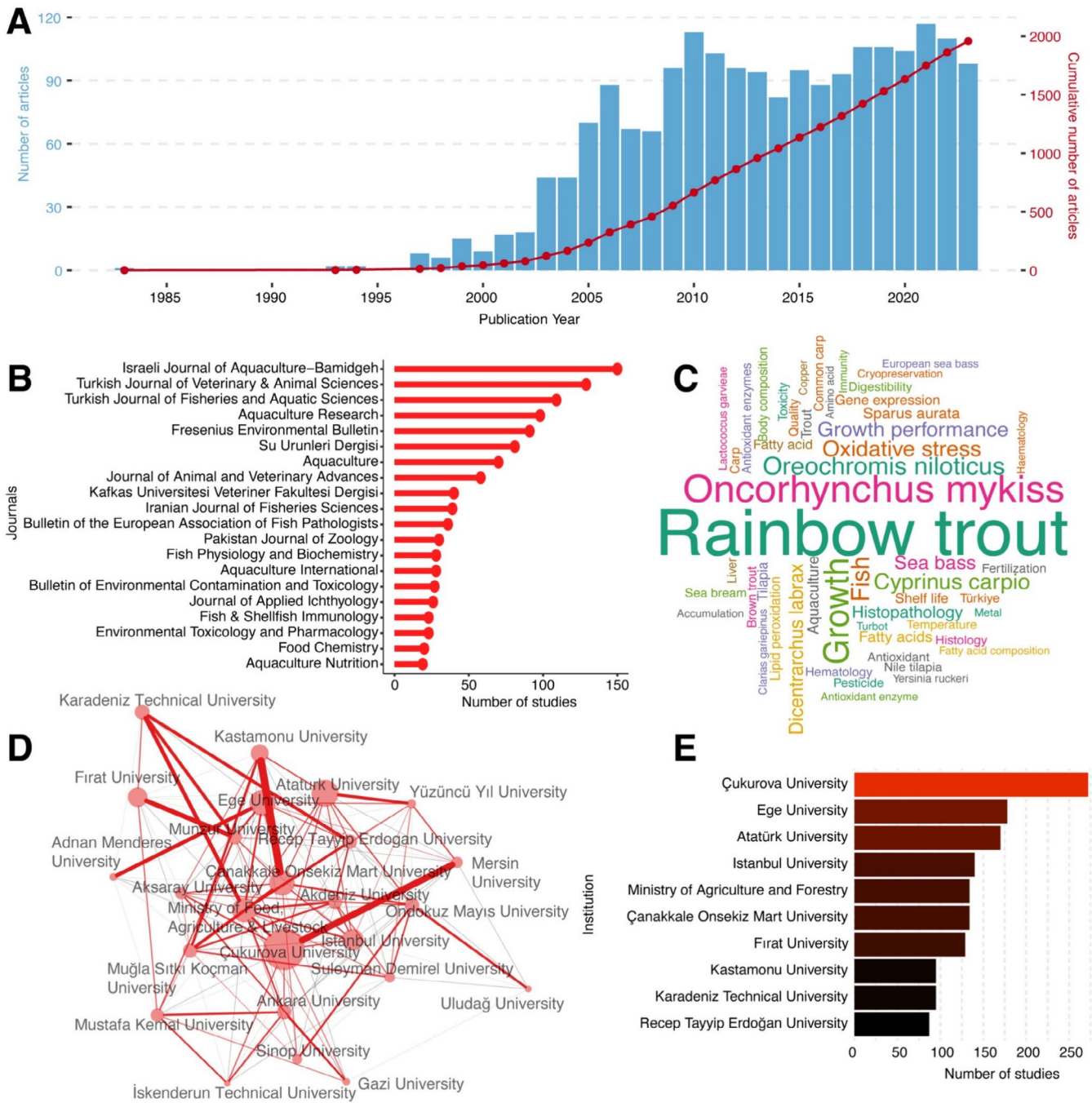
were the most frequently mentioned species names, highlighting the importance of this species in aquaculture research in Türkiye (Figure 13E). Other species, such as *O. niloticus* (107), *C. carpio* (94), *D. labrax* (77), and *S. aurata* (41), are also common, indicating a broader interest in diverse aquaculture species. The keyword “growth” (173 occurrences) indicated a significant focus on the growth performance of the cultured species. Oxidative stress (95), histopathology (57), gene expression (34), hematology (30), and toxicology (26) emphasize physiological and health-related studies, reflecting concerns regarding fish health and environmental stressors. Fatty acids (46), lipid peroxidation (33), and body composition (23) highlight the importance of nutritional studies, which are essential for optimizing fish diets and enhancing product quality (Figure 13E).

Studies on cultured species in Türkiye were conducted on 13 families of 36 species (Tables S1 and S2). A substantial number of studies have focused on Salmonidae (966), Cichlidae (249), Cyprinidae (222), Sparidae (217), and Moronidae (212) following in terms of research volume. At the species level, *O. mykiss* was the most researched species, with 808 studies (Figure 14).

## 10 | Aquaculture Development Opportunities and Technological Innovations

In Türkiye, the global trend was reflected, and production increased from a negligible amount of (2.6 thousand tonnes) in the early 1980s [65] to 556 thousand tonnes in 2023. The annual average increase for the last 23 years has been 26% [22], which is sound evidence that Turkish aquaculture production still has significant potential to grow. However, there is enormous growth potential; supplying more than the current demand may disrupt market equilibrium. Traditional Turkish aquaculture production (97%) predominantly relies on three major finfish species: rainbow trout, sea bass, and sea bream. There is an ongoing endeavor in Turkish aquaculture to diversify cultured species [22]. Although R&D initiatives supported by the state aim to incorporate omnivorous species into aquaculture, carnivorous species continue to dominate market preference. Turkish water resources exhibit considerable ecosystem diversity, which presents significant potential for various herbivorous and omnivorous species with differing environmental requirements. This habitat diversity would also facilitate the culture of different species in polyculture systems or integrated multi-trophic aquaculture systems.

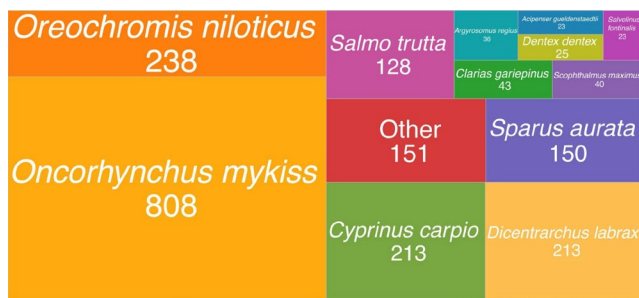
Currently, Turkish aquaculture production primarily relies on cages, raceways, and pond systems. However, these systems are arguably subjected to the matter of environmental carrying capacity in the near future. RAS might be a promising alternative for the Turkish aquaculture sector, particularly for hatcheries, and is supported through the Turkish government subsidies. Despite this support, RAS adoption remains limited due to high capital investment, high energy demands, and operational complexity [93–95]. Globally, RAS has shown mixed success, with more failures than large-scale commercial viability [96]. A key obstacle is the elevated operational expense, particularly energy use, which continues to be a major issue. To address this, the Turkish government offers subsidies for RAS projects that incorporate renewable



**FIGURE 13** | Time trend based on the number of scientific articles published over the years and cumulative number of scientific articles (A). The top journals publishing the articles (B). Word cloud showing the most commonly used keywords (C). Collaboration network among institutions (D). Institutions making the greatest contribution to cultured finfish research in Türkiye (E).

energy investments, enabling producers to reduce energy costs and enhance both economic viability and environmental sustainability. Significant progress has been made in the Turkish aquaculture sector, aligning with global trends aimed at enhancing efficiency, sustainability, and monitoring capabilities. One innovative area involves the use of pump systems in enclosed, tarp-wrapped cages for marine aquaculture, designed to pump cooler water from below the thermocline layer—especially in the Black Sea—to enable continuous trout production throughout the year. These systems can help reduce stress caused by high surface temperatures by pumping

cooler water from deeper layers, which in turn lowers the risk of temperature-related losses in trout farming. Recently, sea-water drawn via airlift pumps below the thermocline layer in cage systems was assessed and proved to be useful in the Black Sea during the summer months (Project No: TAGEM-15/AR-GE/22). This concept has great potential but has not yet been applied in commercial aquaculture. The development of mobile fish farms (aquaculture vessels) stands out as a possible innovation that offers flexible and sustainable solutions in the aquaculture field and allows fish farming in different environments. This method helps fish farming practices adapt to



**FIGURE 14** | The number of studies by species in Türkiye between 1983 and 2023. (The studies with multiple species and/or main focus included more than once).

changing conditions, increasing production and growth potential. Türkiye launched a mobile fish farm project with a capacity of 4800 t in 2010. The growth performance of rainbow trout in mobile fish farms was assessed during the summer months, and results proved that mobile fish farms could provide opportunities for offshore aquaculture [97].

Until the early 1990s, hand-feeding was a common practice in small-scale fish farms. With the growth of the aquaculture industry from small-scale operations to more technologically advanced modern facilities in the early 2000s, automatic feeders were introduced [98]. Barge systems are being used in cage farming operations for their efficiency in feeding and monitoring in the large-scale farms, particularly for marine aquaculture.

Compact autonomous environmental monitoring buoy systems for water quality monitoring are being implemented in cage systems in Türkiye. These systems are equipped with sensors to measure key environmental parameters such as temperature, oxygen, and salinity, enabling real-time monitoring and allowing farmers to respond swiftly to any adverse conditions that may arise. However, the sector still requires “know-how” transfers, such as the automation of triploidization processes applied in Norway, to further advance aquaculture practices. In addition, disseminating and investing in region-specific practices, such as monitoring fish feeding behavior with camera systems, are important to strengthen local practices and encourage innovation in the sector.

In recent years, machine learning applications have become globally preferred tools for solving problems with computer algorithms compared with environmental data modeling, as they focus on the highest success and economic performance with maximum data usage. Aquaculture production, similar to other animal husbandry practices, is influenced by multiple interconnected factors. These include environmental conditions, the species being farmed, type of aquaculture system, farm management practices, site-specific features, climate fluctuations, and the skill level of the workforce. Additionally, the sector faces unique challenges such as water quality fluctuations, climate change impacts, fishing pressure on wild stocks, and anthropogenic disturbances. Understanding how these elements interact is essential for optimizing productivity, ensuring sustainability, and improving the resilience of aquaculture systems. Given the complexity of aquaculture production and the multitude of

interacting factors influencing productivity, there is an increasing demand for advanced tools to enhance decision-making and optimize operations. In this regard, machine learning has proven to be a valuable tool in this context, enabling analysis of vast datasets, detection of trends, and enhancement of efficiency in aquaculture management. In Türkiye, recent studies have demonstrated the potential of machine learning in monitoring fish mortality and assessing environmental interactions at the laboratory scale [99]. Additionally, blood parameter monitoring has been reported as an effective method for evaluating fish physiology, welfare, health, responses to therapeutics, nutritional status, malnutrition, and responses to environmental stressors [100]. One of the biggest problems in aquaculture practices is the size variations in fish in a cage or pond to be harvested. It is well known that the harvest needs to be done at the most ideal size, and it is necessary to analyze the stock very well to ensure this. High accuracy size determinations have been managed with machine learning and artificial neural networks [99, 101, 102]. There is no question that artificial intelligence and machine learning solutions with innovative approaches will be used more frequently in Turkish aquaculture, basically to increase feed efficiency, monitor water quality, and monitor fish growth and size. For this, aquaculture producers must provide data for processing with new technologies, which could help decision makers determine the right decisions and strategies for the future.

Cultured fish constitutes an essential element of human nutrition and health, with its quality being significantly influenced by the manner of its processing. The market for cultured fish requires a substantial financial investment and is driven by consumer preferences. The initial stage of fish processing entails icing and chilling, with traditional freezing representing the most prevalent preservation method [103]. The welfare of fish is a significant concern for the industry, and novel commercial technologies such as electrical slaughtering are designed to achieve optimal product quality control, efficiency, and process safety [104, 105]. Fresh chilled and frozen fish have a longer shelf life, but further processing enhances their attractiveness and profitability. Conventional canned and smoked seafood products may not be sufficient to meet the demands of the market in the near future due to the rapidly evolving social and individual lifestyles of contemporary individuals. The consumption of ready-to-eat foods is an attractive option for individuals with high degrees of individualization, busy schedules, and family obligations [106, 107]. Accordingly, the sous-vide cooking method, derived from the French phrase “under vacuum,” involves sealing raw or partially cooked food in a plastic pouch and cooking it slowly in a water bath at temperatures between 65°C and 95°C for extended periods [108, 109]. This method was successfully applied to Turkish aquaculture products such as sea bass [110, 111] and rainbow trout [112, 113], which would further increase product diversity.

The by-products and waste materials generated by fish processing plants are employed in a variety of sectors, including aquaculture, agriculture, pharmaceuticals, and food [114, 115]. Türkiye, with a substantial amount of aquaculture products, is likely to utilize such by-products in the manufacture of a range of products, including protein hydrolysate, fish oil, fish sauce, fish gelatine, fish collagen, and enzymes derived from viscera more soon.

## 11 | Challenges

### 11.1 | Fish Feed Ingredients

In aquaculture, fish feeds are generally classified according to the life stages of fish, including larvae or hatchery, pre-growth, and growth and broodstock feeds. For early development stages of marine finfish species, live feeds including rotifers (*Brachionus plicatilis* and *Brachionus rotundiformis*) and *Artemia* sp. with different origins and sizes are used with the incorporation of algae species including *Chlorella* sp., *Nannochloropsis* sp., *Nannochloris* sp., *Isochrysis* sp., and *Tetraselmis* sp. [61]. A dependency on foreign countries for live feed enrichment products is one of the main challenges of marine finfish hatcheries. High-quality marine origin ingredients ranging from 65%–72% are only used for the early growth phase, but their dietary levels are remarkably reduced for the grow-out stage [92]. Over the past decades, the use of fish meal in aquaculture has steadily increased to 78% by 2019 [116]. Turkish aquaculture largely relies on global marine ingredients with 195,000t of imports in 2022 and is significantly affected by the changes in market dynamics [92, 98]. In diets currently used in Turkish aquaculture, marine proteins, constituting 10%–30% of grow-out diets, have increasingly been replaced by terrestrial animal protein sources, comprising 10%–50%, and vegetable proteins, accounting for 10%–30% [92, 98]. Similarly, dietary marine oils (3%–5%) have been largely substituted with aquaculture by-product oils (8%–10%) and vegetable oils (5%–8%) [92]. One circular approach to reducing marine ingredients is by-product fish meal and fish oil produced by the conversion of fish processing residues. In 2023, approximately 7500t of fish meal and 5.5t of fish oil were produced [117]. Carbohydrate sources are wheat and rarely corn with dietary incorporation at around 10% [98].

Domestic fish meal and fish oil production are 48,000 and 27,300t, respectively [70], too short to meet the requirement. Although dietary inclusion levels of fish meal vary depending on the species and developmental stages, an average incorporation rate of 28%–30% is observed. Based on this assumption, approximately 210,000t of fish meal are needed to produce 880,000t of fish feed in 2023. To meet this demand, Türkiye imported about 153,000t of fish meal in 2023, valued at \$255 million [92]. Despite a significant reduction in dependence on marine protein and oils during the last two decades, there is still a huge foreign dependency on proteins of oil-bearing seeds, corn, and wheat gluten, as well as feed additives [92, 98]. In 2022, the importations of soybean products and corn were 3.47 and 2.98 million tonnes, respectively. The import of feed additives was also substantial, totaling 703,315t. Another notable point is the import of 491,068t of sunflower meal. Moreover, attempts are being made to assess alternative animal-based feed ingredients, such as insect meal and poultry by-product meal, to diversify protein sources and reduce reliance on traditional imports [118–120]. The overall import volume of feed ingredients reached 12.75 million tonnes, while exports totaled 2.94 million tonnes during the same period [22]. Despite the unknown net amounts of the ingredients used in fish production, the Turkish fish feed industry is facing a significant dependence on imported feed ingredients, a situation that threatens the sustainable growth of the aquaculture sector.

### 11.2 | Finfish Health

Diseases remain one of the most significant constraints to sustainability and profitability. As aquaculture expands and intensifies globally, the risk of disease outbreaks grows due to higher stocking densities, environmental stress, and the increased movement of fish across regions. Diseases threaten fish health and the economic stability of the sector at a global level. In parallel with the growth of the aquaculture sector in Türkiye, it confronts similar challenges. Therefore, research on fish diseases has also increased, and in particular, the need for effective management strategies with accurate diagnosis has been emphasized. The growing interest in fish diseases demonstrates that as the sector of aquaculture progresses, there is an increasing necessity to address issues surrounding infectious diseases.

Historically, disease outbreaks in Turkish aquaculture were poorly documented, with more emphasis given to increasing fish production rather than dealing with health challenges. In the early 1980s, as aquaculture practices continued to develop, the first significant records of fish diseases emerged, primarily focusing on bacterial and parasitic infections. The first studies on fish diseases in Türkiye dealt with freshwater fish parasites and were carried out in the 1970s [121]. During the initial decades of aquaculture development, bacterial diseases, particularly those caused by *Aeromonas hydrophila*, were identified in the early 1980s [122]. Viral diseases such as Lymphocystis disease and Cyprinid herpesvirus 1 (Carp pox) were also observed in the early 1990s. In a short time, diseases spread across the nation where fish were cultivated owing to uncontrolled egg and fish transfers. Since the early 1990s, the number of researchers in the field of fish diseases, including bacterial, viral, parasitic, and fungal infections, has risen, leading to the identification of novel disease agents [123]. The quantity of fish diagnostic laboratories has increased at universities and research institutions, and a national reference laboratory for fish diseases was established in Izmir. Since then, the quality and quantity of research articles on the fish diseases area have increased.

Fish, being poikilotherms, are unable to regulate their body temperature and are highly sensitive to changes in the aquatic environment. Changes in water temperature, particularly those caused by global climate change, cause stress in fish and increase their susceptibility to infectious diseases. Therefore, fish losses due to infectious diseases can be reduced by improving water quality parameters, reducing handling stress, using high-quality feed with immune boosters, and culturing genetically disease-resistant strains. When fish get sick, farmers promptly administer any available antibiotics, disregarding the underlying cause of the disease. In such instances, mortality often cannot be avoided as the cause of death may not be bacterial, or even if it is, the bacteria may exhibit resistance to the antibiotics administered [124]. Although preventing non-prescription antibiotics is necessary in solving this problem, antibiotics should not be prescribed without accurately diagnosing the disease. Regardless of the use of antibiotics, fish should be made available for human consumption after the withdrawal period has concluded.

When antimicrobials are used inappropriately, bacteria can gain resistance to used antimicrobials. Antimicrobial resistance in

aquaculture has emerged as a pressing global concern, posing threats to both human health and the sustainability of the aquaculture industry [125]. Extensive use of antibiotics, either for the prevention or growth promotion of aquaculture, has contributed to resistant strains in aquatic environments. These bacteria could then be transferred to humans upon the consumption of infected aquatic food, thus challenging the treatment of bacterial infections and perhaps threatening public health [124].

Increasing antibiotic resistance makes alternative treatment methods necessary. In addition, the limited treatment options for viral infections require supportive feeding strategies and ideal production conditions. Therefore, innovative management approaches are being adopted throughout the country. Vaccination has emerged as a proactive strategy, significantly reducing the incidence of certain bacterial and viral diseases in Türkiye. However, the vaccination process remains challenging, costly, and labor-intensive, often requiring skilled personnel to administer vaccines effectively. The introduction of semi-automated machines (fish vaccinators) is beginning to enhance the vaccination process, improving efficiency and consistency. Alternative therapeutic options such as bacteriophages [126], antimicrobial peptides [127], probiotics, and feed additives [128] are being experimentally employed to prevent/treat bacterial fish diseases in Türkiye.

The EU adopted and implemented a series of acts, regulations, and directives aimed at regulating the use of antibiotics. Antimicrobial resistance poses a significant global health threat, making it harder to fight bacterial diseases in people and animals, as in farmed fish. The new Regulation (EU) 2019/6 of the European Parliament and of the Council on Veterinary Medicinal Products, replacing Directive 2001/82/EC, establishes rules concerning the marketing, manufacturing, import, exportation, supply, distribution, control, and use of animal medicines. It covers veterinary medicinal products manufactured in factories or in a form that requires a factory process and is intended for sale. These rules also apply to active substances used as building blocks in animal medicines. The new Regulation (EU) 2019/4 on Medicated Feed contains rules and standards with veterinary drugs that have been put in place to protect the effectiveness, accessibility, and availability of antibiotics. A series of annexes indicate: (i) Specific requirements for feed business operators; (ii) List of antimicrobial active substances; (iii) Specific labeling requirements; (iv) Permitted tolerances for the compositional labeling of medicated feed or intermediate products; (v) Information to be included in the veterinary prescription for medicated feed. Article 14 (6) of Regulation (EC) No. 47/2009 covers the classification of EU pharmaceutically active substances and their maximum residue limits (MRL). All the fish farmers and agencies should follow these regulations and directives to have sustainable and environmentally friendly aquaculture.

A SWOT analysis was conducted to elucidate the key actions that should be considered for sustainable aquaculture [129]. These include establishing a balance of authority through laws, diversifying and training personnel, and creating a fish disease database to control the spread of pathogens. Therefore, it is crucial to increase domestic production of hatchery eggs and juveniles to reduce reliance on foreign sources and promote healthy

growth within the sector. The development of vaccinations for bacterial, viral, and parasitic diseases becomes a must to minimize antibiotic use, protect aquatic environments, and ensure fish production sustainably.

The integration of molecular tools for rapid pathogen detection and characterization is important for early identification and control of outbreaks [130]. International cooperation can play an important role in monitoring and managing the spread of pathogens across borders. Aquaculture and fisheries in the Republic of Türkiye are governed by Fisheries Law No. 1380, which came into effect on March 22, 1971. Detailed guidelines concerning protection, production, and management related to fishery resources are given in this law. This law emphasizes the importance of environmental protection measures, the monitoring of fish health and disease conditions, and the implementation of disease control protocols to safeguard both aquaculture and natural fish populations.

The law, which was amended twice in 2007 and 2009 to comply with EU legislation, assigns the Ministry of Agriculture and Forestry the task of conducting research and monitoring fish health. This task includes the identification and management of diseases that may affect both cultured and natural fish populations. The Veterinary Control Research Institutes and Fisheries Research Institutes, affiliated with the Ministry of Agriculture and Forestry, carry out research related to fish health, such as diagnosis of diseases, control, and residual analysis. Diagnosis and treatment services are provided to the farmers upon request. These institutes have established a strong network throughout Türkiye.

A notifiable fish disease was documented in cultured fish in Türkiye [131], while most of them remain unreported. To prevent notifiable fish diseases, the following measures must be implemented: The prevention of notifiable fish diseases addresses a multi-faceted approach that includes biosecurity measures, regular monitoring, and timely response in the case of disease outbreaks. Basic biosecurity practices that will prevent the transmission of diseases include the movement control of fish and equipment, disinfection, and complete quarantine procedures for new stock coming onto the farm. Specific pathogen-free fish stock can effectively prevent notifiable fish diseases by reducing the likelihood of introducing harmful pathogens into aquaculture systems. Regular health checks, water quality checks, and optimum environmental conditions are necessary to reduce the stress factor that makes fish susceptible to infection. Education of farm personnel in the early symptoms of disease would help institute containment measures, such as the urgent isolation of infected tanks. Adherence to local regulations and the prompt reporting of any notifiable diseases to relevant authorities are crucial for coordinated actions to protect farmed and wild fish populations from severe disease impacts.

### 11.3 | Fish Seed Quantity and Quality

Selective breeding programs in European aquaculture began in the 1970s, starting with Atlantic salmon and later expanding to species such as rainbow trout and sea bass. Initially, the main

goal was to improve growth. However, over time, other traits like feed conversion rate, filet yield, and disease resistance were added, with the help of genomic and marker-assisted selection [132, 133].

By 2021, Türkiye produced 1.35 billion rainbow trout eggs across 670 hatcheries, with 95% concentrated in 190 operations. Marine aquaculture in Türkiye grew substantially, with 30 hatcheries producing 1.11 billion juveniles by 2023. Seven of these facilities utilize RASs, while the rest rely on flow-through systems. Marine aquaculture in Türkiye boasts a 95% production success rate, driven by the adoption of modern technologies [134]. Although Türkiye has developed significant expertise in seed production, genetic selection remains underutilized. European aquaculture research includes numerous breeding programs across the region, particularly for species such as rainbow trout, sea bass, and sea bream [135]. In Türkiye, only two marine fish hatcheries applied genetic selection, compared to eight each in Greece and France [136].

The Turkish government has recently funded selective breeding research, with projects focusing on trout [137], as well as sea bass and carp. A National Fisheries Gene Bank has also been established for preserving genetic materials for future research [138]. Rainbow trout, commonly cultured in small-scale family-run fish farms and sea cages in the Black Sea, are used for Turkish salmon production in sea cages. There are not enough hatcheries to meet the demand for the fingerlings of those farms. To address this need, over the past decade, the import volume of trout eggs has increased from approximately 1000 to 30,000 kg, with the value rising from \$160,000 to \$6 million [22]. There is a clear need for the production of high-quality juveniles with superior genetic traits to ensure better performance (i.e., growth, disease resistance, feed efficiency) and compatibility in the world market. To reduce the export dependence on trout eggs, a state hatchery should be established with close collaboration with the private sector.

In addition to initiatives aimed at improving seed quality, the Turkish government has made substantial progress in restocking national waters with species such as carp, turbot, sturgeon, and trout. In 2023, among other species, approximately 54 million juvenile common carp, raised in government-run hatcheries, were released into lakes and rivers in 2023 to support fisheries and populations that had been reduced [44, 79].

#### 11.4 | Legislation and Regulatory Issues

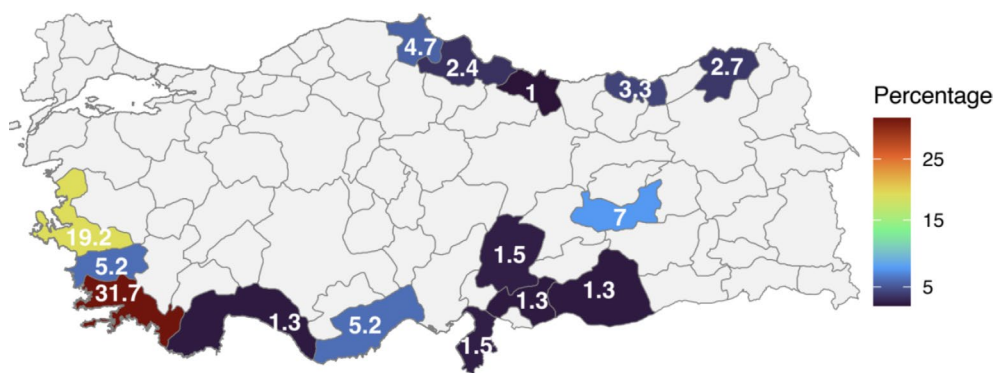
The legal regulations and reforms introduced to promote the growth of aquaculture in Türkiye play a crucial role in supporting the sector's sustainable development. The Fisheries Law of 1971 was the first to define responsibilities related to aquaculture practices [139–141], while subsequent amendments in 2007 aimed to align with EU directives, particularly concerning site selection criteria. The environmental regulations enacted in 2007 aimed to protect water quality from aquaculture related pollution by employing the trophic index to assess the risk of eutrophication [142]. Revisions made in

2009 further emphasized the importance of fish welfare and monitoring aquaculture farms. The aquaculture sector, which implements strategies focused on data-driven environmental site selection, is primarily regulated by the Ministry of Agriculture and Forestry [142]. The legal framework governing marine aquaculture in Türkiye is overseen by the Ministry of Agriculture and Forestry, including specific regulations like Aquaculture Regulation No. 25507, which sets standards for the establishment and management of aquaculture facilities [44]. Collectively, these laws are aimed at supporting the sustainable growth of aquaculture while ensuring environmental protection and food safety.

Carrying capacity, site selection, and marine spatial planning are critical for ensuring the sustainability of the aquaculture sector [44]. However, inadequate spatial planning and site selection regulations have been identified as significant challenges [140, 142]. These deficiencies have likely caused environmental degradation, social conflicts, and inefficiencies in production, harming sector development [129]. Better guidelines for site selection and carrying capacity estimation may support the development of aquaculture farms in more suitable locations while minimizing environmental and socio-economic impacts. A comprehensive regulatory framework may also support the effective management of aquaculture activities, particularly in terms of environmental protection and sustainability [141]. Deficiencies in legislation hinder the growth and development of the sector, threaten the ecological sustainability of the industry, and lead to conflicts with marine area users. Various measures have been taken to solve these problems. For example, the establishment of the General Directorate for Fisheries and Aquaculture has improved governance and coordination within the aquaculture sector [140]. Simplifying project approval and licensing procedures, along with stringent monitoring to prevent unlicensed expansions, remains essential [142]. The implementation of marine spatial planning can help to balance the location, type, and intensity of aquaculture activities, thereby mitigating conflicts and minimizing adverse impacts [143]. Consequently, for the sustainability of this sector, it is important that aquaculture regulations are aligned with broader environmental policies and that environmental impact assessment processes are effectively implemented [141].

#### 11.5 | Climate Change and Water Stress

In aquaculture, the effects of climate change are multifaceted, encompassing an increase in water temperature concomitant with a decrease in dissolved oxygen concentrations. Rising surface seawater temperatures have already been observed since 1970, with the highest increase recorded in the Black Sea [144, 145]. This phenomenon could significantly affect the production of key species such as rainbow trout, sea bass, and sea bream, which constitute the backbone of the aquaculture industry. Moreover, the insufficiency of freshwater resources to meet the water demand has already been experienced and is anticipated to increase in numerous river basins across Türkiye [146, 147]. Inland aquaculture, which necessitates abundant clean freshwater, is one of the areas most affected by these



**FIGURE 15** | Distribution of finfish aquaculture production by province in Türkiye, highlighting provinces contributing 1% or more to the national aquaculture output [157].

changes. Reduced and erratic rainfall is causing surface and groundwater resources to deplete in major production areas, increasing the risk of production failures. Changes in water availability caused by climate change make it more important to find innovative aquaculture technologies, such as oxygenation [61] and RAS, that can reuse water and make aquaculture less reliant on freshwater sources outside of aquaculture [148].

The carbon footprint per kg of farmed fish changes depending on the species and culture methods (1.8–15 kg CO<sub>2</sub>e/kg) but the average values have been reported to be close to those attributed to poultry and pigs, whereas they are much lower than the values associated with small and large cattle farming [149–152]. Aquaculture of filter feeders and macroalgae is more sustainable, as evidenced by their lower carbon footprint values, which range between 0.01 and 0.95 kg CO<sub>2</sub>e/kg [153, 154].

Limited effort has been devoted to investigating the carbon emissions of aquaculture practices in Türkiye. In studies of rainbow trout cultured in the cage and flow-through systems, the cage system has a smaller carbon footprint (1.13 kg CO<sub>2</sub>e/kg) compared to the flow-through system (1.78 kg CO<sub>2</sub>e/kg) [152, 155]. The carbon footprint values of European sea bass and meagre reared in earthen ponds show significant disparities between species and production seasons, with values ranging from 2.49–3.40 kg CO<sub>2</sub>e/kg for European sea bass and 1.91–2.36 kg CO<sub>2</sub>e/kg for meagre [155]. It should be underlined that these findings do not include the emissions arising from post-harvest transportation and processing. The choice of transportation modalities is also critical to mitigate emissions. Since the dominant share of Turkish aquaculture exports is directed to European countries, the utilization of maritime and road transport will be advantageous in terms of achieving less CO<sub>2</sub> emissions.

In addition, the carbon footprint associated with the compound diet and electrical energy used during the production process exerts a significant impact on the total emission values pertinent to aquaculture [155, 156]. Fish feed factories are predominantly located in the Aegean Region (Figure 9), which produces a substantial amount of aquaculture products (Figure 15). The geographical proximity of fish feed factories to production sites in Türkiye presents potential advantages regarding the sustainability metrics of marine fish products. The more scattered production sites across the territory of Türkiye, especially in the

Black Sea region for rainbow trout, may inadvertently lead to higher carbon emissions due to the distance between feed factories and production areas.

## 11.6 | The Covid-19 Pandemic

During the Covid-19 pandemic, the Turkish aquaculture market experienced noticeable price increases in farmed fish, driven by rising costs of inputs such as feed, electricity, and fuel, and a reduction in trade volume [158, 159]. The sector faced challenges such as high financial leverage and reliance on foreign manufacturing costs, which need to be addressed to ensure long-term sustainability [160]. The majority of Turkish aquaculture farms reported financial losses due to the pandemic, with land-based aquaculture systems being particularly affected. The loss of market and customers was a significant issue, especially for land-based farmers [161]. Contrary to the negative responses, the economic records of the aquaculture companies showed a remarkable increase in profitability in 2020, achieving the highest levels in the last 12 years [160]. The Turkish aquaculture industry also managed to sustain its growth, with production increasing by an average of 11.3% annually from 2020 to 2022, as farmers did not reduce production as a mitigation measure [161]. The government played a key role by providing financial support to fish farms, compensating for export losses, and implementing measures to prevent job losses, such as banning employee dismissals for a period [87]. These measures significantly contributed to the absence of job losses in the aquaculture sector [161]. Additionally, the pandemic has helped cushion some of the economic impact by driving a shift toward frozen and processed seafood. The pandemic has highlighted the need for better preparation and support for small-scale producers to increase the sector's resilience to future unexpected crises [161].

## 12 | Conclusion

This comprehensive review outlines the Turkish aquaculture sector, which has demonstrated substantial growth in recent decades, establishing itself as a significant contributor to both European and global markets. Through a comprehensive analysis of industry dynamics, this review underscores the pivotal role of species like rainbow trout, sea bass, and sea bream, which have leveraged Turkish geographical and environmental diversity for

production gains. These advancements contribute to both national food security and global seafood supply. The systematic review underscores the critical importance of research and development, as evidenced by the increase in publications on key species. However, the industry continues to face sustainability challenges, particularly in sustainable feed production, disease control, and environmental impact mitigation. Addressing these issues will necessitate ongoing research and development, particularly in feed innovation and disease prevention, to enhance resilience against environmental stresses and support long-term sustainability. It is essential to increase domestic production of alternative feed ingredients with balanced high protein contents from plant-based proteins, insects, algae, and aquaculture by-products to reduce the reliance on imported feed ingredients. The development of selective breeding programs with a focus on traits like disease resistance, feed efficiency, growth rate, and resilience against increased water temperatures is highly critical to improve fish seed quality. Although legislative reforms have promoted sustainable growth, further efforts are essential, particularly in site selection and carrying capacity assessment, to minimize environmental impacts and conflicts with other marine users. Continued emphasis on research and development is crucial for Türkiye to maintain its competitive advantage.

Future directions for Turkish aquaculture must focus on the integration of advanced technologies, such as machine learning for management and real-time monitoring systems, to optimize production efficiency and minimize resource consumption. Expanding the use of RAS could help mitigate climate-induced stress and improve resource efficiency. However, despite its advantages, RAS implementation remains limited by high operational costs, energy consumption, and the requirement for advanced expertise, which may hinder widespread adoption in Türkiye. Efforts should be directed toward improving cost efficiency, access to renewable energy sources, and providing technical training to enhance commercial-scale operations' viability. Additionally, reducing dependence on imported eggs, particularly for rainbow trout, will be vital for ensuring the industry's independence and long-term sustainability. With the implementation of targeted strategies, Turkish aquaculture is well-positioned to meet rising global demand, contributing to food security and economic growth both domestically and internationally.

#### Author Contributions

**İlhan Aydın:** writing – review and editing, writing – original draft, conceptualization, visualization, data curation, supervision, methodology, investigation. **Rafet Çağrı Öztürk:** conceptualization, writing – original draft, writing – review and editing, data curation, formal analysis, validation, methodology, investigation. **Orhan Tufan Eroldoğan:** conceptualization, writing – original draft, writing – review and editing. **Murat Arslan:** conceptualization, writing – original draft, writing – review and editing. **Yahya Terzi:** writing – original draft, writing – review and editing, data curation, visualization, software, formal analysis, methodology, investigation. **Sevdan Yılmaz:** writing – review and editing. **Gürkan Diken:** writing – review and editing, writing – original draft, visualization. **Önder Yıldırım:** writing – original draft, writing – review and editing, visualization. **Türker Bodur:** visualization, writing – review and editing, writing – original draft. **Nejdet Gültepe:** writing – review and editing. **Ömer Alper Erdem:** writing – review and editing. **Ece Evliyaoğlu:** writing – review and editing. **Ömerhan**

**Dürrani:** writing – review and editing, visualization. **Sinem Gülen:** writing – review and editing. **Esin Batır:** writing – review and editing. **İlhan Altınok:** writing – review and editing, supervision. **Hüseyin Sevgili:** conceptualization, writing – original draft, writing – review and editing.

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#### Conflicts of Interest

The authors declare no conflicts of interest.

#### Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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### Supporting Information

Additional supporting information can be found online in the Supporting Information section.