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web: www.seruvenyayinevi.com
e-mail: seruvenyayinevi@gmail.com

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INTERNATIONAL COMPILATION OF RESEARCH AND STUDIES IN THE FIELD OF AQUACULTURE SCIENCES

Editor

Prof. Dr. Ayşe Gül Harlıoğlu

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Chapter 1

SPORT FISHING IN TÜRKIYE: CURRENT STATUS AND COMPETITIONS

Aytaç Özgül[1]

1 Ege University, Faculty of Fisheries, Department of Fishing and Seafood Processing Technology. Orcid: 0000-0001-7706-9012

Introduction

With the sustainable use of natural resources and the increasing emphasis on environmental awareness, the consideration of recreational activities within ecosystem-based approaches has gained importance. Sport fishing, or recreational fishing, is a significant recreational activity in which individuals engage in fishing not for commercial profit or subsistence purposes, but for leisure, sport, and interaction with nature. A fundamental principle of sport fishing is that the captured aquatic organisms are not commercially exploited. Rather, this activity is primarily based on personal satisfaction, sporting experience, and environmental awareness. According to the Food and Agriculture Organization of the United Nations (FAO), sport fishing is defined as a fishing activity that does not constitute an individual's primary source of livelihood or nutrition and in which the catch generally does not enter commercial circulation; moreover, FAO emphasizes that such activities should be conducted in accordance with sustainable fisheries principles (FAO, 2012). The sustainability dimension of sport fishing is frequently highlighted in the literature, particularly due to its contribution to the conservation of fish stocks and the continuity of aquatic ecosystems through "catch and release" practices (Arlinghaus et al., 2016). This approach elevates sport fishing beyond a purely individual hobby and integrates it into the broader framework of ecosystem-based management.

Sport fishing competitions can be defined as organized and regulated forms of recreational fishing conducted within a framework of specific rules and limitations. These competitions allow participants to demonstrate their fishing techniques and strategic skills, while simultaneously incorporating elements of sporting competition and environmental awareness. Such events are non-commercial in nature and are organized in accordance with relevant legal regulations, thereby exhibiting a structure compatible with sustainable fisheries principles. Indeed, the approaches adopted by the Food and Agriculture Organization of the United Nations (FAO) and the International Confederation of Sport Fishing (CIPS) emphasize that sport fishing competitions should be conducted in a manner consistent with fish welfare, the conservation of fish stocks, and ecosystem-based management principles. In this context, contemporary sport fishing competitions have evolved beyond being purely competition-oriented events and have become multidimensional, sustainability-based organizations that incorporate catch-and-release practices and methods contributing to scientific data generation ((Arlinghaus et al., 2016; CIPS, 2020; FAO, 2012).

Within this framework, modern sport fishing competitions are structured around specific organizational and operational components. Competition duration, target fish species, permitted equipment, scoring criteria, as well as officiating and monitoring mechanisms constitute the core elements of these events. Competitions held in marine and freshwater environments, and organized in various formats such as shore-based or boat-based fishing, may use fish weight, length, number, or species diversity as determinants in scoring systems. In recent years, the increasing use of electronic measurement systems, photographic documentation methods, and practices that prioritize the live release of captured fish back into the water have enhanced the transparency and enforceability of competitions, while also strengthening their alignment with sustainable fisheries objectives (FAO, 2012; Toner, Whoriskey, & Harrod, 2014).

2. Sport Fishing Competitions Around the World

Sport fishing competitions worldwide have become prominent international recreational activities that integrate individual technical proficiency with environmental awareness within the broader framework of recreational fisheries (Cooke & Cowx, 2004). These competitions are conducted in both freshwater and marine environments through diverse organizational models, and their implementation is guided by a combination of international standards and region-specific regulatory frameworks.

At the global level, the regulation, standardization, and organization of sport fishing competitions are primarily overseen by international and national institutions, including confederations, federations, and organizing committees. Key global organizations include the International Game Fish Association (IGFA), the International Sport Fishing Confederation (CIPS), and the Food and Agriculture Organization of the United Nations (FAO), alongside regionally and nationally focused institutions such as the American Sportfishing Association, the Federation of European Anglers, the Japan Sport Fishing Association, and the New Zealand Big Game Fishing Association.

The International Game Fish Association (IGFA) establishes technical benchmarks related to international record certification, scoring systems, and standardized regulations for rods, reels, and fishing lines. In addition, IGFA actively promotes ethical angling practices and catch-and-release principles, thereby contributing to the sustainability of fish stocks (IGFA, 2023). The International Sport Fishing Confederation (CIPS) organizes world and continental championships, ensures the harmonized application of competition standards across participating countries, and prioritizes fish welfare and ecosystem-based management approaches (CIPS, 2020). FAO supports the global implementation of sustainable recreational fisheries by publishing guidelines that emphasize environmental responsibility and long-term resource conservation. Complementing these efforts, national federations and local angling clubs organize domestic tournaments and ensure their alignment with international norms (Fig.1). Collectively, these institutions facilitate the fair, transparent, and sustainable conduct of sport fishing competitions at multiple governance levels (Arlinghaus et al., 2016).

At the local scale, while international standards provide the overarching framework for competition design, regional legislation and conservation measures remain binding in practice. In Europe, freshwater and marine championships organized by international federations and angling clubs exhibit variation in competition formats, scoring systems, and sustainability measures in response to geographical and ecosystem-specific conditions (World Fly Fishing Championships, 2025). Consequently, the organizational structure of sport fishing competitions worldwide is shaped by the interaction between global standards and local governance, resulting in events that are measurable, equitable, and environmentally responsible (Table.1).

North America hosts some of the most developed and commercially visible sport fishing competition structures. Major tournaments such as the Bassmaster Classic, FLW Tour, and the Jacksonville Kingfish Tournament enable participants to demonstrate advanced technical skills through scoring systems based on fish weight, length, and species composition (Arlinghaus et al., 2016). Catch-and-release practices are widely implemented in these events, and extensive sponsor-supported media coverage contributes to high participation rates and public visibility (Arlinghaus et al., 2016). In Mexico and the Caribbean region, the Bisbee's Black & Blue Marlin Tournament represents a globally recognized offshore competition targeting pelagic species. Offering substantial prize incentives and attracting international participation, this tournament contributes to marine conservation through the systematic application of catch-and-release protocols and sustainable fishing practices (Bisbee's Black & Blue Tournament, 2025).

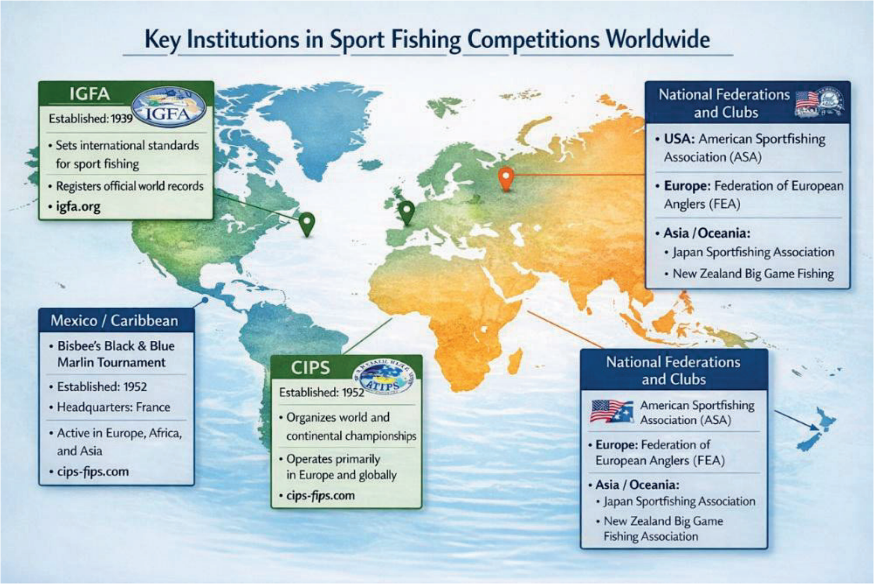

Figure 1. Key Institutions in Sport Fishing Competitions Worldwide

In Europe, sport fishing competitions are predominantly organized by federations and angling clubs and are conducted in accordance with CIPS regulations. Events such as the World Fly Fishing Championships and the Balaton Carp Cup encompass both freshwater and marine fisheries and focus on species including carp, trout, and pike. These competitions emphasize ethical angling behavior, species diversity, and environmental stewardship within their scoring and evaluation systems (FAO, 2012; Pitcher & Hollingworth, 2002).

Competitions in Asia and Oceania combine traditional angling practices with modern competitive formats. In Japan, fly fishing tournaments emphasize technical precision, skill refinement, and specialized equipment use, whereas offshore competitions in Australia and New Zealand—such as the Moreton Bay Classic—primarily target large pelagic species and employ photographic documentation alongside catch-and-release practices to enhance monitoring and sustainability outcomes (Toner et al., 2014; Arlinghaus et al., 2016).

Table 1. Overview of Major International Sport Fishing Tournaments

Region	Major Tournaments	Target Species	Competition Structure	Technical & Sustainability Features
North America	• Bassmaster Classic; FLW Tour • Jacksonville Kingfish Tournament	Bass; walleye; king mackerel; cobia	Professional, sponsor-driven leagues	Weight/length-based scoring; advanced angling techniques; mandatory catch-and-release (Arlinghaus et al., 2016)
Mexico / Caribbean	• Bisbee's Black & Blue Marlin Tournament	Marlin; pelagic species	International offshore competition	High participation; catch-and-release protocols; sustainable offshore fisheries management (Bisbee's Black & Blue Tournament, 2025)
Europe	• World Fly Fishing Championships; • Balaton Carp Cup	Carp; trout; pike; marine species	Federation-based (CIPS standards)	Species-diversity scoring; ethical angling; ecosystem-oriented regulations (FAO, 2012; Pitcher & Hollingworth, 2002)
Asia	• Japan Fly Fishing Championships	Trout; freshwater species	Club- and federation-organized	Precision gear; technique-based evaluation; sustainability-focused practices (Toner et al., 2014)
Oceania	• Moreton Bay Classic; • NZ Big Game Fishing	Tuna; marlin; pelagic species	Federated offshore tournaments	Photographic verification; large-species targeting; data-oriented catch-and-release (Arlinghaus et al., 2016)

3. Sport Fishing and Competitions in Türkiye

Türkiye exhibits substantial geographical suitability for the organization of sport fishing competitions in both marine and freshwater environments, attributable to its location bordered by seas on three sides and its extensive network of lakes, reservoirs, and river systems. This diverse hydrological structure provides a wide range of ecological settings conducive to the development of recreational and competitive sport fishing activities.

Sport fishing competitions conducted in Türkiye operate within a well-defined legal and regulatory framework established under Law No. 1380 on Fisheries and its associated secondary legislation. These regulations comprehensively govern target species, fishing seasons and closed periods, permitted fishing gears, as well as minimum size and catch quotas, thereby ensuring that competitive fishing activities are aligned with principles of sustainable resource use and conservation. Within this legislative context, the Communiqué on the Regulation of Amateur Fisheries No. 6/2 (Communiqué No. 2024/21) formally defines sport fishing as an individual angling activity conducted in accordance with rules set by sport fishing federations and grounded in core principles such as minimizing harm to captured fish and ensuring their release back into the aquatic environment in a healthy and viable condition (BSGM, 2025). Accordingly, sport fishing competitions in Türkiye are organized by amateur angling associations or federations, subject to prior authorization from the General Directorate of Fisheries and Aquaculture.

Furthermore, catch-and-release practices constitute a central component of sport fishing competitions in Türkiye and are actively promoted by angling clubs and tournament organizers. These practices are widely recognized as effective management tools that contribute to the conservation of fish stocks, the maintenance of population structures, and the long-term sustainability of aquatic ecosystems (Ateşşahin & Cilbiz, 2023).

The legal and institutional framework governing sport fishing activities in Türkiye is established and implemented by the General Directorate of Fisheries and Aquaculture (BSGM), which is responsible for issuing official permits and enforcing regulations through communiqués and related legislative instruments. Although detailed information on the first officially documented sport fishing competition in Türkiye remains limited, existing literature and records from angling associations suggest that shore-based and boat-based fishing competitions held in the Istanbul Strait in the early 1980s represent the emergence of modern sport fishing practices in the country (Ateşşahin & Cilbiz, 2023).

Sport fishing tournaments in Türkiye are primarily organized through local associations, angling clubs, and national federations. Within this structure, the Turkish Angling Federation (Türkiye Olta Balıkçılığı Federasyonu, TOBF) plays a key coordinating role by organizing national-level tournaments and ensuring that competitive events are conducted in accordance with internationally recognized standards. At the regional level, institutions such as the Istanbul Sport Fishing Association and the Izmir Sport Fishing Club coordinate competitions held in both freshwater and marine environments across the Marmara and Aegean regions, while actively implementing catch-and-release practices and environmental protection measures.

In addition to these organizations, numerous local associations and clubs—including the Çanakkale Fishing Association, Mersin Sport Fishing Club, and Seferihisar Fishing Club—are involved in the organization of regional tournaments and the supervision of participant compliance with competition rules. Across all levels of competition, internationally aligned scoring systems, referee oversight, and environmental guidelines are applied, with participants evaluated based on criteria such as fish weight, species diversity, or length measurements. In recent years, growing interest among youth and amateur anglers, together with the increasing adoption of catch-and-release practices and ecosystem-based management principles, has contributed to Türkiye's rising prominence as a regional center for sport fishing and competitive angling activities (Ateşşahin & Cilbiz, 2023).

3.1 An Overview of Major Sport Fishing Competitions in Türkiye

Sport fishing competitions in Türkiye are organized and supported by a diverse range of institutional actors, including federations, non-governmental organizations, academic communities, local governments, and private sector stakeholders. Each of these actors plays a distinct role in the development, coordination, and long-term sustainability of competitive recreational fishing activities.

The Amateur and Sport Fishing Federation (ASOF) represents a significant institutional initiative toward the formalization and structured governance of sport fishing in Türkiye. The federation focuses on establishing standardized competition regulations, strengthening coordination among local clubs, and fostering institutional linkages with international sport fishing organizations.

At the core of competitive activity, Amateur Anglers and Wildlife Conservation Associations serve as the primary organizers of sport fishing competitions across the country. Numerous associations operating in different provinces—particularly those based in Çanakkale, İzmir, Istanbul, Antalya, and Ankara—regularly organize shoreline angling, carp fishing, and pike fishing tournaments. These organizations play a critical role not only in sustaining recreational fishing practices but also in embedding environmental awareness and conservation principles within competitive frameworks.

In recent years, University Sport Fishing Clubs have emerged as increasingly influential actors, particularly in promoting youth participation in sport fishing competitions. Established within university settings, these clubs organize technically focused tournaments—mainly targeting carp and pike species—alongside educational and training-oriented activities aimed at improving angling skills and fostering ecological awareness among students.

Local governments and municipalities also contribute significantly to the organization of sport fishing competitions, often integrating such events into local festivals and community celebrations. Municipal support typically encompasses logistical assistance, prize provision, and promotional activities. In regions such as Beyşehir and Eğirdir, municipality-supported competitions have additionally contributed to regional tourism development, underscoring the broader socio-economic potential of sport fishing events.

Finally, private sector and sponsor-supported organizations, particularly companies engaged in the production and marketing of fishing equipment, provide sponsorship for selected competitions, thereby enhancing organizational quality and visibility. Although sponsor-driven events remain relatively limited in Türkiye, they represent a growing potential for the professionalization and further institutional development of sport fishing competitions. In this context, the main sport fishing competitions held in Turkey, both in inland waters and along our coasts, can be listed as follows (Fig.2).

1. Istanbul International Pike Fishing Competition (IIPFC): Organized by the Istanbul Amateur and Sportive Angling Association (İSOBDER) at Lake Terkos, this international sport fishing competition brings together both amateur and professional anglers. Participants are evaluated based on the largest and the highest number of pike caught. All captured fish are measured and subsequently released (Catch & Release). The 2025 edition, held for the fourth time, attracted participants from various provinces in Turkey and abroad. The competition is regarded as a significant platform for promoting sport angling culture, facilitating knowledge exchange, and enhancing environmental awareness.

2. Istanbul Surf Casting / Fishing Competition: Conducted at Semizkumlar Beach in collaboration with Silivri Municipality and Istanbul Surf Casting Sports Club, this international sport fishing event emphasizes shore-based fishing techniques (surf casting). Both amateur and professional anglers are evaluated according to the size and number of fish caught. The sixth edition in 2025 hosted approximately 100 participants from domestic and international locations. Captured fish were measured and released, aligning with environmental sustainability principles. The competition traditionally promotes sport angling culture, encourages the exchange of experience, and supports the integration of nature with recreational activity.

3. Çanakkale Shore Angling Competition: Held at Karabiga İğdelik Beach under the coordination of the Biga Amateur Sportive Anglers Association and Karabiga Municipality, this national competition fosters competitive surf casting. The seventh edition in 2025 attracted amateur and professional anglers from across Turkey. Scoring is based on the number and size of fish caught within a designated period. The event emphasizes not only sporting success but also social interaction, experience sharing, and environmentally conscious participation. Awarded participants enhance the prestige of this sporting platform.

4. International Kocaeli Surfcasting Fishing Competition: Organized by the Kocaeli Sportive Angling Sports Club with the support of Kocaeli Metropolitan Municipality, this international surfcasting event takes place at Kandıra Uzunkum Beach. Competitors participate in two stages to capture either the largest or the highest number of fish, with awards across multiple categories including “Overall Ranking,” “Countries,” “Women,” “Big Fish,” and “Sector.” The competition is recognized internationally for its prestige and provides both competitive and collegial environments.

5. Izmir Sea Bass Fishing Competition (Mordoğan Sea Bass Fishing Competition): Held at Mordoğan Kocakum Beach, Karaburun, Izmir, this traditional event unites amateur and professional fishing enthusiasts. Organized by Karaburun Municipality under the motto “We say crisp to simit, sea bass to friendship,” the competition allows participants to showcase sea bass fishing skills, enjoy immersive nature experiences, and strengthen social bonds. The 2025 edition marked the 14th occurrence. Throughout the event, rods are cast into the sea, top performers are recognized, and social activities complement the competition.

6. Tuna Master: One of Turkey's most established sport fishing competitions targeting large pelagic species, Tuna Master commenced in the mid-2000s along the Izmir coasts. The Alaçatı (Çeşme) edition has been held uninterruptedly for approximately 20 years, with a Seferihisar–Teos Marina edition added more recently. Both events occur in September in the Aegean Sea under International Game Fish Association (IGFA) rules. Due to the sensitivity of tuna stocks, competitions adhere to strict permitting processes, referee supervision, and catch-and-release practices, integrating competitive elements with sustainable fishing principles.

7. Big Fish Turkey: Initiated in 2007, this long-running offshore sport fishing tournament primarily targets bluefin tuna and other large pelagic species. Held annually off Çeşme, Izmir, the multi-day event includes briefings, fishing days, and award ceremonies. Following the "Catch-Release-Sustain" principle, the tournament promotes sustainable fishing practices, hosts participants from Turkey and Europe, and contributes to the institutionalization of sport fishing in the country.

8. Didim Offshore Sport Fishing Competition: Conducted annually in the Gulf of Güllük, off Didim, Aydın, this tournament began in 2019 and is open to both amateur and experienced anglers. Participants demonstrate technical skills in offshore conditions within designated rules and timeframes. Pelagic and demersal species are targeted, with evaluations based on size, species, and capture technique. The competition encourages ethical and sustainable fishing through catch-and-release practices while supporting regional marine tourism.

9. Bodrum International Sport Fishing Tournament: This recreational fishing competition, open to international participants, is held in Bodrum and surrounding waters. Since the early 2000s, the event has been organized under varying formats, allowing both amateur and experienced anglers to participate. Competitions follow catch-and-release practices, ethical fishing guidelines, and sustainability principles. The tournament reinforces Bodrum's maritime culture and contributes socially and economically to the region.

10. Mediterranean Surfcasting Tournament: Organized by the Mediterranean Surf Casting Amateur and Sportive Anglers Association (A.S.C), this shore-based competition is primarily conducted along the coasts of Adana (Yumurtalık) and Mersin (Silifke). Since 2018, the tournament has generally been held in October or November, with participants competing to catch the largest or most fish. Open to both amateur and professional anglers, awards are presented to top performers.

11. ASOF Turkey Sportive Carp Fishing Competition: Held at Bolu Gölköy Dam Lake by the Amateur and Sportive Angling Federation (ASOF), this competition aims to institutionalize carp fishing in Turkey. First organized in 2021, the event follows national legislation and federation rules, emphasizing minimum size requirements, ethical angling, and catch-and-release practices. The competition highlights participants' technical skills and seeks to protect fish stocks, raise environmental awareness, and promote sustainable fishing.

12. National Pike Fishing Competition: Organized by the Akyazı Hunting, Shooting, and Fishing Sports Club Association (AKDER), this is one of Turkey's most prestigious pike fishing events. The 17th edition evaluates participants in both the "most fish caught" and "largest fish caught" categories. Generally held in natural locations such as Lake Sapanca, the tournament allows participants from different provinces to demonstrate technical skills while promoting social interaction and awarding top performers.

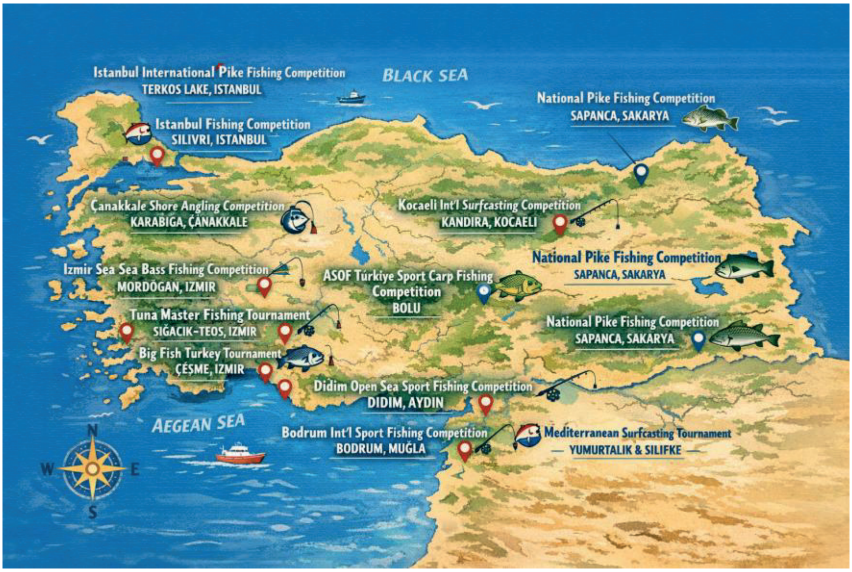

Figure 2. Major Sport Fishing Competitions in Türkiye

4. Conclusion and Recommendations

Within the scope of this study, sport fishing competitions were examined in terms of their conceptual framework, global practices, and the current situation in Turkey. The analysis indicates that these competitions function not only as competitive events but also as important mechanisms for fostering environmental awareness, promoting recreational use of aquatic resources, and supporting local development. Despite the country's abundant natural water resources and growing interest in amateur angling, sport fishing competitions in Turkey are predominantly organized on a local and voluntary basis. While this approach encourages broad participation and flexibility, it also presents structural challenges related to standardization and long-term sustainability, as organizational quality, measurement and scoring systems, and environmental oversight vary considerably across events. To enhance the effectiveness and sustainability of sport fishing competitions, it is recommended that standardized national competition guidelines be established and disseminated, training programs for refereeing and measurement procedures be implemented, and catch-and-release practices be widely adopted to prioritize fish welfare and stock conservation. Furthermore, fostering institutional collaboration among universities, non-governmental organizations, and local authorities, as well as designing competitions to generate scientific data, would strengthen both the organizational quality and the broader ecological and socio-economic contributions of these events.

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Chapter

2

Codium spp. AS EMERGING FUNCTIONAL INGREDIENTS FOR FOOD AND ANIMAL FEED[1]

Derya Güroy[2]

Esra Keskin Uzel[3]

1 Ministry of Agriculture and Forestry, 2nd Regional Directorate, Yalova Directorate of Nature Conservation and National Parks, Türkiye ORCID ID: 0009-0009-9896-920X

2 Department of Food Processing, Armutlu Vocational School, Yalova University, Yalova, Türkiye ORCID ID: 0000-0002-8254-1403

3 Department of Aquaculture, Graduate School of Education, Yalova University, 77200 Yalova, Türkiye ORCID ID: 0009-0009-9896-920X

1. Introduction

Global population growth, depletion of natural resources, and climate change make the search for sustainable food sources imperative. Considering Türkiye's current water resource potential, advancing the aquaculture sector and increasing seafood consumption are of significant importance in the context of evolving global conditions. In this context, marine biomass resources—particularly seaweeds—have emerged recently as promising alternatives for sustainable food systems (Khan et al., 2024). Seaweeds are regarded as environmentally friendly biomass sources due to their rapid growth rates, the lack of requirement for arable land, and their relatively low environmental footprint (Pessarrodona et al., 2024).

Uncontrolled use of water resources, unplanned industrialization, pollution from industrial effluents, and the extensive use of fertilizers and insecticides in agriculture have degraded water quality in freshwater and coastal ecosystems, leading to ecosystem damage and biodiversity decline (Kargın & Bilgüven, 2018). As of 2021, approximately 828 million people worldwide faced hunger, and around 3.1 billion people were unable to afford a healthy diet in 2020 (FAO, 2022). As the food sector has not expanded in proportion to global population growth, there is increasing interest in alternative resources to ensure sustainability. Algae, cultivated for millennia, have the potential to alleviate challenges associated with meeting the nutritional needs of a growing population (Diaz et al., 2023; García-Vaquero & Hayes, 2016).

Macroalgae (multicellular seaweeds) are rich in nutrients and contain biologically active constituents that may confer health benefits (Frazzini & Rossi, 2025; Lee et al., 2024). Key compounds include sulfated polysaccharides, phenolic compounds, pigments (chlorophylls, carotenoids, and phycobiliproteins), and dietary fiber (Mishra & Saini, 2024). In the food industry, these compounds are increasingly utilized for their antioxidant, anti-inflammatory, antimicrobial, and immunomodulatory properties, and their use as natural additives in functional food formulations is expanding (Gengatharan et al., 2025; Matos et al., 2024).

The concept of functional foods refers to the use of ingredients that provide specific health benefits beyond basic nutrition. Bioactive components derived from seaweeds hold substantial potential in this field. For instance, fucoidans from brown macroalgae (Phaeophyceae) and agaroid derivatives from red macroalgae (Rhodophyta) have broad functional applications (Asanka Sanjeewa et al., 2021; Nagahawatta et al., 2023). In parallel, green macroalgae (Chlorophyta) have attracted increasing attention recently because many species are rich in soluble fiber, protein, chlorophyll, and bioactive polysaccharides (Cadar et al., 2025; Xu et al., 2023).

Macroalgae are commonly categorized into three major groups based on pigmentation: brown algae (Phaeophyceae), red algae (Rhodophyta), and green algae (Chlorophyta). Green macroalgae are widely distributed in tropical and temperate seas, with genera such as *Ulva* (sometimes cited as *Enteromorpha* in older literature), *Chaetomorpha*, and *Codium* belonging to this group. These algae are notable for both their nutritional value and biological activities (Cadar et al., 2025; Xu et al., 2023). In particular, the antioxidant capacity of sulfated polysaccharides from green algae has been linked to mechanisms such as iron chelation and hydrogen peroxide scavenging (Nurkolis et al., 2023).

Among green macroalgae, the genus *Codium* stands out for its biochemical richness and adaptive traits across varying environmental conditions. *Codium* species are widely distributed globally and can occur in coastal waters as epiphytic or epilithic life forms. High chlorophyll content, sulfated galactans, certain phenolic compounds, and soluble dietary fiber have been reported in *Codium* spp. (Meinita et al., 2022). Moreover, extracts from *Codium* species have been associated with antioxidant, anti-inflammatory, antibacterial, and potential anticancer activities in various studies (Figueroa et al., 2022). These properties support the prospect of using *Codium* spp. as raw materials in the cosmetic, food, and pharmaceutical industries. Additionally, processed *Codium* biomass has been reported to provide environmental benefits, including supporting soil ecosystems and enhancing soil water-holding capacity (Martins et al., 2024).

This chapter examines the biochemical characteristics of Codium seaweeds and evaluates their potential for use in the production of functional foods or dietary supplements.

2. The Genus *Codium*: General Characteristics, Morphology, and Distribution

Codium is a genus of marine macroalgae within the phylum Chlorophyta (green algae) and the family Codiaceae. The genus is characterized by a siphonous thallus organization (aseptate, multinucleate, tubular structures). Thalli of *Codium* species typically exhibit a spongy texture and contain a reticulate medulla formed by the entanglement of branched tubular filaments. This siphonous architecture may develop as mat-like flattened forms in some species, whereas others show spherical or erect morphologies. Thalli are usually dark green, and the absence of calcification contributes to their distinctly soft texture.

The genus *Codium* is distributed widely across temperate and tropical seas. Species such as *Codium fragile*, *C. tomentosum*, *C. vermilara*, and *C. cylindricum* are among the representatives reported from different geographic regions. Many *Codium* species play an essential role as primary producers in coastal ecosystems and contribute substantially to biomass formation (Meinita et al., 2022). However, some species are also recognized as invasive in regions where they have been introduced. Notably, *C. fragile*, native to the Pacific Ocean, has been transported to the Atlantic Ocean and the Mediterranean Sea and has exhibited invasive characteristics in these areas (Meinita et al., 2022). Its rapid growth capacity and competitive ability may alter local ecosystem dynamics.

In the Mediterranean and along the coasts of Türkiye, several *Codium* species have been recorded. In particular, *C. fragile* has been reported from Turkish coasts (including the Aegean Sea and Marmara-connected areas). Keskinkaya et al. (2020) and Üstünada et al. (2011) reported collecting *C. fragile* specimens from the Çanakkale coastline, supporting its presence in Turkish waters. Native species like Codium bursa also exist in the Mediterranean. The spherical form of *C. bursa* is considered characteristic of Mediterranean macroalgal flora and has also been observed along Turkish coasts. In general, *Codium* species grow attached to rocky substrates or as epiphytes on other surfaces. They are reported to tolerate variability in seawater temperature and can occur from intertidal zones to deeper waters.

Morphologically, *Codium* species are recognized by their velvety softness. This trait is associated with the lack of calcium deposition in the extracellular matrix and distinguishes them from calcifying green algae. The syphons contain cytoplasmic fluid and numerous nuclei, allowing the thallus to function as a “single giant cell”. This unusual organization may support rapid repair after damage and regrowth from fragmented parts. Members of the genus are commonly referred to as “dead man’s fingers”, particularly *C. fragile*, reflecting the branched, finger-like thallus morphology.

From an ecological perspective, *Codium* species have been reported to be relatively tolerant of salinity and temperature fluctuations. Some species may proliferate rapidly under elevated nutrient conditions (eutrophication), leading to increased abundance in coastal areas affected by urban or agricultural discharges. Seasonal *Codium* blooms have also been reported in organically enriched bays along the Aegean and Mediterranean coasts of Türkiye. Beyond ecological importance, the genus *Codium* has gained economic attention; recently, its nutritional and pharmacological potential has increasingly been addressed in scientific studies (Meinita et al., 2022).

3. Nutritional Composition and Key Nutrients

Marine macroalgae, including *Codium* spp., are characterized by distinctive nutritional profiles. In general, they are known for high carbohydrate content (particularly dietary fiber), moderate protein levels, and low lipid content (Meinita et al., 2022). Among green seaweeds, *Codium* species are notable for their high carbohydrate fraction. In a study on *Codium fragile* collected from Turkish coasts, carbohydrates accounted for approximately 58% of dry weight, with 17% crude fiber and 41% soluble sugars within the total carbohydrate fraction (Yucetepe et al., 2024). These findings indicate that *Codium* species are rich in dietary fiber and soluble carbohydrates and may therefore represent a suitable resource for functional food applications. Similarly, nutrient profiling of *C. fragile* from the northern coast of Chile reported 13.7% protein and a low lipid content (1.5%), supporting its high-carbohydrate/low-fat composition (Ortiz et al., 2009). For *Codium tomentosum* harvested from the Portuguese coast, total sugars ranged from 14.4% to 23.8% (Rodrigues et al., 2015). In the same study, the relatively high total phenolic content further suggested biological value. Collectively, these data highlight *Codium* spp. as an important carbohydrate source with relevance to both nutritional and biotechnological applications. The high carbohydrate proportion is attributed mainly to cell-wall polysaccharides (e.g., sulfated galactans, arabinans). These complex polysaccharides may function as dietary fibers and exert prebiotic effects in the gastrointestinal tract.

Protein content in seaweeds varies substantially among taxa. Red seaweeds show the widest range, with protein values reported between 0.67% and 45.0% dry weight, followed by green seaweeds (3.42–29.80%) and brown seaweeds (5.02–19.66%) (Cherry et al., 2019). In general, algal protein content may exceed that of some foods, such as egg (~13%), oats (~13.5%), and wheat (~15%), and can be comparable to high-protein sources such as soy (~38.6%) and chicken breast (~31%) (Wu et al., 2023). Certain marine-derived bioactive peptides have been reported to exhibit high antioxidant potential (Ngo & Kim, 2013). For *Codium* spp., protein values commonly fall within ~3–16% dry weight. For instance, protein contents of 11–18% have been reported for *C. tomentosum*, whereas *C. fragile* is often reported around 10–11% (Ortiz et al., 2009; Meinita et al., 2022). In contrast, a *C. fragile* sample from Turkish coasts showed a protein level of 4.6% (Yucetepe et al., 2024). Such discrepancies may reflect seasonal variability, local nutrient conditions, sampling location, and methodological differences. Beyond quantity, protein quality is also important: the presence of essential amino acids, such as lysine, suggests that Codium may be a promising plant-based protein contributor (Ortiz et al., 2009).

Seaweeds generally contain low amounts of lipids, and this applies to *Codium* as well. For *C. fragile*, total fat has been reported at approximately 1% (Yucetepe et al., 2024), while many *Codium* species do not typically exceed 1–3% total lipids on a dry-weight basis (Ortiz et al., 2009). Overall, total lipid levels in seaweeds are often reported to be below 4% of dry weight (Sohrabipour, 2019). Despite low total fat, seaweeds can contain valuable polyunsaturated fatty acids (PUFAs). In *Codium* spp., palmitic acid (C16:0) is commonly the dominant saturated fatty acid, and oleic acid (C18:1) is often the dominant monounsaturated fatty acid. Essential fatty acids such as α-linolenic acid (C18:3, omega-3) have also been detected (Costa et al., 2025; Khotimchenko, 2003; Meinita et al., 2022).

A substantial part of the macroalgal lipid fraction consists of phospholipids and glycolipids, within which biologically relevant PUFAs can occur. These include omega-3 (e.g., eicosapentaenoic acid, EPA) and omega-6 fatty acids (e.g., linoleic and arachidonic acids) (Rajapakse & Kim, 2011). In green seaweeds, PUFA levels have been reported to range between 21.5% and 49.5%, with α-linolenic acid frequently identified as a predominant PUFA (Goecke et al., 2010; Schmid et al., 2014). Moreover, numerous fatty acids with unusual chain lengths and structural features have been reported in some *Codium* species (Aliya & Shameel, 1993; Dembitsky & Hanus, 2003). These characteristics support the potential of *Codium* spp. as a resource for functional foods and biopharmaceutical applications.

Mineral content and ash yield represent another key nutritional feature of *Codium*. Dried seaweeds may leave a high ash fraction, indicating mineral richness. For *C. fragile*, an ash content of 36% has been reported (Yucetepe et al., 2024). Macroalgae can selectively absorb minerals from seawater and accumulate nutritionally essential macro- and microelements (Cabrita et al., 2016). *Codium* spp. are often rich in sodium (Na), potassium (K), calcium (Ca), and magnesium (Mg) (Meinita et al., 2022). For example, the tropical species *C. iyengarii* has been reported to contain high potassium levels (Rizvi & Shameel, 2004). In a *C. fragile* sample from Turkish coasts, magnesium and potassium contents were reported at approximately 10 mg/g and 0.7 mg/g, respectively (Yucetepe et al., 2024). Variations among species and regions may depend on salinity, temperature, and nutrient availability. When properly processed and consumed, macroalgae such as *Codium* may represent valuable sources of minerals such as calcium and iron. Macroalgal mineral content can be comparable to or higher than that of terrestrial plants and may contribute to daily mineral requirements (Rupérez, 2002). Accordingly, some green seaweeds have been suggested as calcium-rich alternatives for supplementation, and meaningful calcium and magnesium levels have also been reported for *Codium* (Yucetepe et al., 2024; Wong & Cheung, 2000).

Vitamins and trace elements are also critical nutritional constituents of seaweeds. *Codium* spp. may contain vitamins A, C, and E as well as specific B-group vitamins. Trace elements essential for human health—such as iodine, iron, zinc, copper, manganese, and selenium—have also been detected in *Codium* species (Seo et al., 2019; Meinita et al., 2022). For instance, *C. fragile* has been reported to contain notable amounts of iron (Fe) and zinc (Zn) on a dry-weight basis (Yucetepe et al., 2024). However, seaweeds may also accumulate undesirable heavy metals, such as arsenic and cadmium, in the seawater. Therefore, seaweeds intended for food use should be sourced from controlled waters and regularly monitored through appropriate analyses.

Overall, *Codium* spp. offer a favorable ingredient profile characterized by high dietary fiber and mineral content, moderate protein levels, and low total lipids. Their amino acid composition, vitamins, and trace elements further enhance nutritional value. This rich dietary composition forms a key basis for the potential use of *Codium* as a functional food ingredient and as a dietary supplement component.

4. Secondary Metabolites: Phenolic Compounds and Sterols

Seaweeds are not only sources of macronutrients and minerals but are also rich in so-called secondary metabolites, which may exert a range of biological effects relevant to human health. Within this context, the genus *Codium* displays a noteworthy profile of bioactive constituents, particularly phenolic compounds and sterols.

Phenolic compounds (polyphenols): *Codium* species can contain various phenolic compounds that are also commonly found in terrestrial plants. In marine environments, algae may synthesize phenolic metabolites as part of protective responses to factors such as ultraviolet radiation, oxidative stress, and grazing pressure. Studies quantifying total phenolic content (TPC) in *Codium* have reported notable values. For example, the aqueous extract of *C. tomentosum* exhibited a TPC of approximately 32.3 mg gallic acid equivalents (GAE)/g (Hafez et al., 2022), which is comparable to the phenolic levels reported for many terrestrial fruits and vegetables. The same study also looked at the total flavonoid content (TFC), which showed that C. tomentosum had about 4.5 mg of catechin equivalents per gram. Flavonoids are phenolic bioactives that can contribute to antioxidant capacity, and their presence in *Codium* may be linked to stress-response and defense mechanisms.

To characterize the phenolic profile, Hafez et al. (2022) analyzed the extracts using high-performance liquid chromatography (HPLC) and reported the presence of multiple phenolic constituents in *C. tomentosum*, including gallic acid, catechin, methyl gallate, caffeic acid, syringic acid, ferulic acid, vanillin, p-coumaric acid, rutin, ellagic acid, naringenin, daidzein, quercetin, cinnamic acid, apigenin, kaempferol, and hesperetin. This extensive list highlights the diversity of polyphenols present in *Codium*. Antioxidant compounds typically associated with terrestrial plants—such as daidzein (an isoflavone) and apigenin (a flavone)—were reported at relatively high levels in the *C. tomentosum* extract (approximately 791 μg/g and 225 μg/g, respectively). The occurrence of phenolic acids with potent antioxidant properties, such as gallic acid and ellagic acid, is also noteworthy. Overall, such a phenolic signature is considered to contribute substantially to the antioxidant potential of *Codium* (Hafez et al., 2022; Tanna et al., 2018). Given their redox properties, phenolics may neutralize reactive species and help mitigate oxidative damage, thereby supporting protection against oxidative stress.

Sterols: *Codium* species are also of interest as sources of sterols (phytosterols). Several sterol derivatives that are not always common in green algae have been isolated from *Codium*. In a comprehensive analysis of three *Codium* species, Aliya and Shameel (1993) reported the presence of eight different sterols, including ergosterol, ostreasterol, clerosterol, decortinone, decortinol, and isodecortinol, as well as cholesterol derivatives (cholesteryl acetate and cholesteryl galactoside). The detection of ergosterol—typically abundant in fungi—is particularly notable. Decortinone and decortinol are sterols associated with *Codium decorticatum*, from which their nomenclature derives. Sterols are integral structural components of algal cell membranes and contribute to the regulation of membrane fluidity and permeability. From a nutritional perspective, certain phytosterols are known to reduce intestinal cholesterol absorption and lower circulating LDL-cholesterol levels, suggesting that *Codium* sterols may warrant investigation for potential hypocholesterolemia effects. Moreover, phytosterols may also exhibit anti-inflammatory properties. For instance, fucosterol, commonly reported in brown algae, is recognized for its anti-inflammatory and antioxidant activities (Meinita et al., 2021, 2022). Although *Codium* species more frequently contain ergosterol-related derivatives rather than fucosterol, the potential pharmacological relevance of these sterols remains of interest.

In addition to phenolics and sterols, *Codium* may produce other secondary metabolite classes, including terpenoid compounds (notably diterpenes) and pigments (chlorophyll derivatives and carotenoids). However, within the scope of this section, phenolic compounds and sterols represent the two most prominent groups. These metabolites are thought to underpin key functional attributes of *Codium*, such as antioxidant, anti-inflammatory, and antimicrobial properties. While phenolics may contribute to sensory qualities such as taste and color in foods, sterols are often considered in dietary supplements due to their potential roles in cholesterol metabolism.

In summary, *Codium* spp. are characterized by substantial phenolic content and a distinctive sterol composition, alongside other secondary metabolite classes such as terpenoids and pigments. From a functional perspective, these constituents have been widely investigated as potential contributors to oxidative stress modulation and inflammation-related pathways. However, the relevance of these compounds for health-orientated applications ultimately depends on evidence of bioactivity from experimental models. Therefore, the following section focuses on the antioxidant and anti-inflammatory activities reported for *Codium* extracts and purified fractions.

5. Antioxidant and Anti-Inflammatory Effects

Building on the bioactive composition outlined above—particularly phenolics, sterol derivatives, and sulfated polysaccharides—recent studies have evaluated *Codium* extracts and purified fractions for antioxidant and anti-inflammatory activities. Evidence has primarily been generated using chemical antioxidant assays (e.g., DPPH, $ABTS^{+}$, FRAP), cell-based inflammation models (e.g., cytokine release and adhesion molecule expression), and selected in vivo studies. While these findings provide mechanistic and proof-of-concept support, translation to human health outcomes requires standardized preparations and well-controlled clinical trials.

Antioxidant capacity of *Codium* extracts is commonly assessed using DPPH, $ABTS^{+}$, and FRAP assays. For instance, the aqueous extract of *C. tomentosum* showed a DPPH scavenging activity with an IC_{50} of 75.3 µg/mL, while the positive control ascorbic acid exhibited an IC_{50} of ~22.7 µg/mL (Hafez et al., 2022). Although less potent than ascorbic acid, the extract demonstrated meaningful antioxidant capacity comparable to many botanical extracts. The reported positive correlation between total phenolic content and antioxidant activity further supports the contribution of phenolics to the overall effect. Additionally, *C. tomentosum* (with higher phenolic content) showed a lower IC_{50} than the tested red alga (*A. fragilis*), reinforcing the role of phenolics (Hafez et al., 2022).

Beyond phenolics, sulfated polysaccharides may also contribute to antioxidant effects. In a Chilean study, sulfated polysaccharides isolated from *C. bernabei* exhibited DPPH and $ABTS^+$ radical-scavenging capacity and a positive FRAP response (Figueroa et al., 2022). Given the role of oxidative stress in chronic disease pathways, these findings support the functional-food relevance of *Codium*.

Anti-inflammatory potential has been investigated using cellular inflammatory markers. In *C. decorticatum*, solvent-fractionated extracts were compared, and the dichloromethane fraction was reported to strongly suppress IL-8 release in human endothelial cells stimulated with LPS and TNF-α, while also reducing E-selectin expression (Zbakh et al., 2020). These results indicate that constituents derived from Codium can influence inflammatory pathways, at least in experimental settings. Mechanistically, specific sterols (e.g., ergosterol-related compounds) and selected flavonoids have been reported to interfere with inflammation-associated signaling cascades such as NF-κB.

Reported bioactivities of *Codium* extracts and purified compounds extend beyond antioxidant/anti-inflammatory effects and include immunomodulatory, anticoagulant, antitumor, antiviral, antibacterial/antifungal, anti-obesity, and anti-angiogenic actions (Meinita et al., 2022). For example, partially sulfated polysaccharides have been associated with anticoagulant effects (Li et al., 2015), and sulfated polysaccharides from *C. fragile* were reported to attenuate weight gain in high-fat diet-fed mice (Kolsi et al., 2017). However, translation of these findings to humans requires standardized extracts, robust dose–response data, and clinical trials.

6. *Codium* as a Functional Food: Uses and Applications

The rich composition of Codium spp.—including high dietary fiber and mineral content, as well as bioactive constituents such as phenolic compounds, sterols, and sulfated polysaccharides—supports their consideration within the functional food concept. "Functional foods" are commonly defined as foods that provide health-related benefits beyond basic nutrition or that support specific physiological functions. In this context, Codium has attracted attention due to (i) phenolic fractions associated with antioxidant and anti-inflammatory activity, (ii) polysaccharides that may modulate immune responses, and (iii) sterol profiles that may be relevant to lipid metabolism. These features make Codium relevant to both traditional dietary practices and modern food design.

6.1 Traditional consumption and cultural uses

From a traditional perspective, Codium is recognized as a "sea vegetable", particularly in East Asian cuisines. Several green seaweeds have been consumed for centuries in Asia, and Codium fragile is among the species reported for use in traditional foods. As noted by Moreira et al. (2022) and Pereira (2016), *C. fragile* has been used as food in China, Korea, and Japan. It may be incorporated into dishes such as miso soup in Japan and consumed as fresh salads or pickled products in Korea. Moreover, cultural beliefs regarding the health-supporting nature of seaweeds have encouraged the use of C. fragile in dried and powdered forms, added to teas, soups, and related preparations (Kim et al., 2023). These practices have also inspired modern research exploring potential health-related effects linked to Codium bioactives.

6.2 Modern food applications: product development examples

In contemporary food technology, seaweeds are increasingly used to enhance nutritional value, provide natural additives, and improve shelf life. Within this trend, Codium can be utilized both as a direct food ingredient and as an extract-based functional additive.

(i) Gourmet and direct consumption: Codium is increasingly featured in culinary applications as part of the "sea vegetables" concept. In Mediterranean gastronomy, C. fragile has been reported as an ingredient valued for its distinctive marine flavor and soft texture, often paired with seafood dishes (Naff, 2025). Such uses support the acceptance of Codium as a direct food component.

(ii) Natural preservative/shelf-life extension: Owing to phenolics and related antioxidant constituents, Codium extracts have been investigated as natural preservatives with the potential to slow lipid oxidation and reduce microbial load. Hafez et al. (2022) applied *C. tomentosum* extract to sea bass fillets and reported reduced microbial counts and delayed oxidative deterioration. These findings indicate that Codium extracts may serve as natural alternatives to reduce reliance on synthetic additives.

(iii) Fortification and delivery systems (encapsulation): Another modern direction involves integrating Codium extracts into food matrices through controlled delivery strategies. Costa et al. (2025) incorporated *C. tomentosum* extract into yoghurt using phospholipid-based nanoparticles (phytosomes) to enhance nutritional and functional properties. Such carrier systems are increasingly considered valuable tools to improve bioactive stability and potential bioavailability while managing sensory attributes (e.g., taste and odor) during product development.

6.3 Commercial outlook and key constraints

Despite its recognition in traditional diets, standardized products explicitly marketed as "Codium" remain relatively limited in the dietary supplement and functional food markets. In practice, many products are labeled under broad terms such as "seaweed/kelp", often as multi-species mixtures, which complicates Codium-specific standardization and efficacy assessment. Therefore, product development requires robust species authentication, raw material quality control, batch-to-batch compositional consistency, and regular monitoring of safety parameters (e.g., iodine, sodium, and heavy metals).

Key constraints for broader use of Codium in functional foods include (i) sensory impacts such as taste/odor and salinity, (ii) stability of bioactives during processing, (iii) variability in bioavailability, and (iv) risks linked to mineral and heavy-metal accumulation depending on the harvesting environment. Accordingly, successful implementation typically depends on optimized harvesting strategies, effective processing methods, standardized extraction protocols, and, where appropriate, advanced formulation approaches such as encapsulation.

7. Dietary Supplement Production and Processing Pathways

To translate *Codium* biomass into functional foods and dietary supplements, integrated strategies are required across raw material quality, processing technology, standardization, and safety.

7.1 Raw material sourcing, authentication, and pretreatment

Biomass should be sourced from clean waters, harvested under controlled conditions, and handled under hygienic conditions. Species-level authentication (morphological + molecular when possible) is recommended because composition varies among *Codium* spp. Importantly, preservation approaches used for analytical sampling (e.g., formalin in some studies) do not apply to food-grade production and should be clearly distinguished from industrial processing.

7.2 Drying and milling

Controlled drying (e.g., moderate-temperature oven drying) limits microbial spoilage and improves stability. Freeze-drying is advantageous for heat-labile constituents but may be cost-prohibitive. Dried biomass can be milled to powders for direct use or further extraction.

7.3 Extraction strategies

Extraction depends on the target fraction: hydroalcoholic systems for phenolics; apolar solvents for lipophilic constituents; and hot-water extraction and ethanol precipitation for polysaccharides, followed by purification if needed (Figueroa et al., 2022). Fractionation studies (e.g., stepwise polarity extraction) highlight that bioactivity can be fraction-dependent, supporting marker-based standardization (Zbakh et al., 2020). In this context, a study conducted by Keskin Uzel (2025) treated *Codium* samples with the proteolytic enzyme bromelain and subsequently fermented them using baker's yeast. The results showed that these processes markedly increased the bioactive constituent content of *Codium*; notably, the combined enzyme + fermentation approach yielded the highest total phenolic content and antioxidant capacity. These findings suggest that enzymatic and fermentative pretreatments, in addition to conventional extraction strategies, may enhance the recovery of functional compounds from *Codium*.

7.4 Green extraction: subcritical water (SWE)

SWE can reduce the use of organic solvents and enable recovery of both phenolic and polar constituents. *C. tomentosum* has been evaluated using SWE, with potential advantages in time and sustainability (Costa et al., 2025).

7.5 Concentration and powdering

Extracts are concentrated (vacuum evaporation) and converted into stable powders (spray drying with carriers such as maltodextrin). Polysaccharide-rich fractions are often freeze-dried to preserve structural integrity (Figueroa et al., 2022).

7.6 Formulation and encapsulation

Encapsulation can mitigate taste/odor issues and improve stability and potential bioavailability. Phytosome-based incorporation of *C. tomentosum* extract into yoghurt is an example of advanced delivery design (Costa et al., 2025). Capsules remain the most common supplement format for standardized powders/extracts.

7.7 Clinical evidence, safety, and health claims

Human clinical evidence remains limited; thus, safety assessment is essential. Routine monitoring of iodine, sodium, and heavy metals in both raw material and final products is required. Regarding marketing claims in the EU, health claims are governed through authorization and the EU Register of Nutrition and Health Claims, and any *Codex-related* claim should be checked against the register and applicable rules.

8. Use of Codium in Animal and Fish Feed

Seaweeds have long been used not only as food for humans but also as feed additives for animals. In agriculture and livestock farming, seaweeds are incorporated into feed formulations to leverage their nutritional value and biological effects (Morais et al., 2020). Although studies on the role of Codium and similar green algae in animal feeding remain limited, broader seaweed research provides valuable insights.

Seaweeds have been used as feed supplements by coastal farmers for centuries. In coastal areas like Iceland and Britain, adding dried seaweed powder to cow and sheep feed has been a traditional practice. This helps meet livestock's mineral needs, as seaweeds are rich in elements such as salt, iodine, selenium, and cobalt. These minerals are essential for animal health, influencing fertility and thyroid function (Makkar et al., 2016).

Regarding Codium species specifically, while there are few reports of direct incorporation into livestock feed, the general effects of green algae powders have been studied. Recently, the use of green seaweeds (Chlorophyta), particularly species of the genera Ulva and Codium, as natural sources of protein, minerals, and bioactive compounds in poultry feed has increased. For instance, studies have shown that adding 3% Ulva lactuca improves breast muscle development and carcass yield in broilers (Wells et al., 2016). However, Codium species, particularly those with high salt retention capacity, may cause digestive issues and stunted growth if consumed in high quantities without desalting (Morais et al., 2020). Therefore, removing the sodium chloride content is a crucial step before incorporating Codium into animal feeds. Park et al. (2024) developed a desalting protocol for human consumption that could also be applied in animal feed production. In conclusion, green seaweeds show promise as feed additives for poultry, and Codium species can be utilized in this context if properly processed.

Ruminant animals (e.g., cows, sheep) tend to respond well to seaweed supplementation because their rumens contain microbial communities that help break down algae. Recent studies, particularly on red algae such as *Asparagopsis*, have highlighted its potential to reduce methane emissions in cattle (Roque et al., 2021). However, this finding does not apply to Codium species. Generally, green algae are more digestible than brown algae because they do not contain phenolic polymers (e.g., polyphenolic fucoidans) or lignification, which hinder digestion (Cotas et al., 2020). Therefore, when Codium is mixed with dry forage and hay, it can provide some protein and also contribute vitamins and minerals. However, there are currently no studies on such applications in ruminants.

Aquafeeds: In aquaculture, the use of seaweeds as a natural additive or alternative source of protein and carbohydrates in fish feed is becoming increasingly important. In this context, Codium has been investigated in some studies. For example, adding 5% *C. fragile* to young abalone (a type of shellfish) diet has been reported to improve growth performance and shell color development (Zhang et al., 2010).

Green algae, including Codium, can also provide carotenoid pigments for aquatic animals. As Codium's dominant pigment is chlorophyll, it is not expected to change the flesh color of fish like salmon. However, green algae in fish feeds can improve fish health. Some studies have shown that fish fed diets containing seaweed have better immune parameters and increased disease resistance. Accordingly, Keskin Uzel (2025) reported that Codium extracts exhibited in vitro antibacterial activity against two important aquaculture pathogens, Aeromonas hydrophila and Yersinia ruckeri. This finding suggests that Codium supplementation may provide bioactive compounds capable of directly supporting disease resistance in fish. Furthermore, algal polysaccharides have been reported to have an immunostimulatory effect in fish. The sulfated polysaccharides present in Codium are of particular interest in this regard because these compounds may strengthen the mucus structure of fish, preventing pathogen adhesion or increasing stress tolerance through their antioxidant effects (Yang et al., 2019).

In practice, brown algae powders like *Ascophyllum nodosum* are commonly added to fish feeds at small amounts (1-2%), and these components are widespread in commercial feeds. Although Codium is not yet widely used, some integrated multi-trophic aquaculture systems (IMTA) grow algae alongside fish in the same ponds, which are then cyclically reintroduced into the fish feed. Codium species are potential candidates for this concept (Kang et al., 2008).

Poultry: The use of seaweed in poultry feeds can impact performance and carcass quality. Additionally, adding algae to the diets of laying hens can increase the iodine content of eggs. As iodine-rich algae, Codium could be utilized for this purpose.

Pet Food: Recently, algae have also found their place as natural mineral and omega-3 sources in pet foods. Some premium dog food products now list "kelp powder" (seaweed powder) as an ingredient. While Codium is not typically included, green algae can be added to these mixtures. These additives are often marketed for reducing plaque (due to iodine) or improving coat health (Gawor and Jank, 2023).

Although Codium and similar algae have versatile potential in animal feed, careful formulation is required. Their advantages include the improvement of animal health and product quality due to their high nutritional and bioactive content. Potential drawbacks include their high salt content and some animals' unfamiliarity with their taste and odor. Therefore, Codium must undergo proper processing (e.g., desalting, drying, and grinding) before being used in animal feeds. With dosage adjustments, it can be safely incorporated into animal diets. As future research clarifies the specific benefits of Codium for various animals, its use in the livestock sector is likely to increase.

9. Conclusions and Recommendations

Codium spp., a group of green macroalgae, stand out among marine biomass resources due to their unique morphology, broad geographic distribution, and rich nutritional and bioactive composition. Depending on species and environmental conditions, *Codium* can contain high levels of dietary fiber—particularly sulfated polysaccharides—along with meaningful amounts of protein, diverse vitamins and minerals, and notable levels of phenolic compounds and sterols. Collectively, these characteristics position *Codium* beyond a traditionally consumed sea vegetable and support its candidacy for functional food and nutraceutical development (Figueroa et al., 2022; Meinita et al., 2022; Ortiz et al., 2009; Zbakh et al., 2020).

Current evidence indicates that *Codium* extracts and purified fractions may exhibit antioxidant and anti-inflammatory activities, as well as a broader spectrum of bioactivities, including immunomodulatory, anticoagulant, anti-obesity, and antitumor effects. However, a substantial portion of this evidence derives from in vitro assays and animal models. Therefore, well-designed human studies are required to clarify clinical efficacy and safety. Priority should be given to controlled clinical investigations assessing the impact of *Codium*-based products on oxidative stress biomarkers, inflammatory parameters, lipid profile (LDL/HDL), glucose metabolism, and selected immune indicators. Such data are essential to support scientifically substantiated health claims and responsible market introduction.

To enable safe and effective industrial translation of *Codium*, progress is required in the following areas:

1. **Standardization and quality assurance:** Marker compounds (e.g., total phenolic content or defined polysaccharide fractions) should be identified to ensure batch-to-batch compositional consistency, with minimum target levels defined and verified. In addition, routine monitoring and traceability should address iodine, sodium, and potential heavy-metal accumulation (e.g., As, Cd, Pb, Hg).

2. **Regulatory compliance:** Regulatory frameworks governing seaweed-based products—such as novel food approval pathways, labelling requirements, and health claim authorization—may strongly influence market entry. Manufacturers should proactively align product development and documentation with the regulations of target markets (e.g., EU, USA).

3. **Sustainable sourcing and cultivation:** Uncontrolled harvesting from natural stocks may disrupt ecological balance. Accordingly, controlled cultivation strategies (e.g., sea farms, recirculating aquatic systems, and IMTA concepts) should be developed to secure a year-round, clean biomass supply. In regions where certain *Codium* species are considered invasive (e.g., *C. fragile* in specific Mediterranean contexts), managed harvesting and valorization may reduce environmental pressure while creating economic value.

4. **Processing technologies to enhance bioavailability:** Processing routes such as fermentation, enzymatic hydrolysis, and other biotechnological approaches can improve bioavailability and may strengthen antioxidant and antimicrobial properties (Matos et al., 2024; Offei et al., 2018; Siddik et al., 2023; Wang et al., 2025). Optimizing such processes for *Codium* is likely to increase effectiveness in both functional food and feed additive applications.

5. **Consumer acceptance and communication:** The success of functional products depends on consumer adoption. Therefore, managing sensory attributes (taste/odor) through formulation strategies (e.g., capsule formats, flavor masking, encapsulation) and providing clear guidance on safe use are essential. In particular, transparent communication regarding iodine content is advisable, especially for individuals with thyroid-related conditions.

Given the environmental advantages of seaweed production—low land and freshwater requirements, rapid growth, and high biomass yields—green macroalgae such as *Codium* occupy a strategic position for sustainable food-system innovation (Holdt and Kraan, 2011; Marques et al., 2022; L. Zhang et al., 2022). In conclusion, *Codium* spp. provide a multidisciplinary platform for research and application across food technology, animal nutrition, and health-related fields. Translating this potential into practice will require coordinated collaboration among food engineers, aquaculture specialists, microbiologists, biochemists, medical researchers, and public health stakeholders. Effective networks linking universities, producers, and field-level actors (farmers and aquaculture enterprises) will facilitate the safe and sustainable transition of *Codium* "from the laboratory to the table."

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Chapter 3

FACTORS AFFECTING MEAT YIELD IN TROUT

Sinan ÖZCAN[1]

Ebru İfakat ÖZCAN[2]

1 Öğr. Gör.; Munzur University, Pertek Sakine Genç Vocational School. sinanozcan@munzur.edu.tr ORCID No: 0000-0003-2975-698X

2 Prof. Dr.; Munzur University, Pertek Sakine Genç Vocational School. ebruozer@munzur.edu.tr ORCID No: 0000-0003-2017-6647

INTRODUCTION

Trout farming is one of the fastest-growing production lines in the aquaculture sector, both globally and in Turkey. *Oncorhynchus mykiss* (rainbow trout), in particular, can be raised in both freshwater and marine environments thanks to its high tolerance to cold water conditions, rapid growth performance, high-quality meat structure, and adaptability (Gjedrem and Robinson, 2014). Trout production in Turkey has increased rapidly since the 1970s and now accounts for a large portion of total aquaculture production.

Meat yield is one of the most important performance criteria determining economic profitability in fish farming. Meat yield is a broad concept that encompasses not only the amount of muscle tissue in the fish but also the processable fillet ratio, muscle quality, fat distribution, and consumer acceptance (Johnston, 2011). Fish with higher meat yields reduce production costs and increase operating efficiency by utilizing feed more efficiently. Therefore, identifying the factors that determine yield is critical for improving aquaculture practices. The factors affecting meat yield in trout are multidimensional. Genetic makeup has a significant impact on growth rate, biochemical properties of muscle tissue, fat distribution, and fillet yield. Thanks to selective breeding programs, annual increases in growth performance of 1–2% have been achieved, and these improvements have positively impacted fillet yield (Yáñez et al., 2014; Gjedrem, 2012). Studies conducted in Turkey have also revealed that different genetic lines exhibit significant differences in productivity and growth. Nutritional factors are also critical in determining meat yield. When the protein, fat, carbohydrate, vitamin, and mineral levels required by the fish are not met, growth performance decreases and muscle development remains inadequate (NRC, 2011; Jobling, 2016). Domestic studies have shown that the optimum protein/energy ratio in trout nutrition directly affects both growth performance and fillet yield. Furthermore, functional feed additives (probiotics, prebiotics, herbal extracts) are known to contribute to more effective muscle tissue formation by increasing digestive enzymes (Ringø et al., 2018; Yıldız and Şener, 2003).

Environmental factors are among the most important factors limiting productivity in aquaculture. Parameters such as water temperature, dissolved oxygen level, and ammonia and nitrite concentration have a direct impact on fish metabolism, appetite, and growth rate (Wedemeyer, 1996; Bjørnsson et al., 2001). Studies conducted in Türkiye have shown that high water quality and appropriate stocking density are critical for productivity. Excessive stocking density creates behavioral stress, fin injuries, competition, and growth retardation, thereby negatively affecting meat yield (Ellis et al., 2002). The physiological state, age, sex, hormonal balance, and annual biological cycle of the fish are also important biological factors affecting meat yield. During the breeding season, due to the shift of energy toward gonadal development, the muscle percentage in females may decrease, which can lead to differences in fillet yield (Barton, 2002; FAO, 2020). Young fish have a faster growth rate and more efficient feed utilization; however, determining the optimal slaughter time is essential for economic efficiency. Studies conducted in Turkey show that slaughter weight significantly affects the muscle/bone ratio and fillet quality. Diseases and health management are also a direct determinant of yield. Numerous studies have demonstrated that parasitic and bacterial diseases reduce growth performance and therefore limit muscle development (Austin and Austin, 2016; Tavares-Dias and Oliveira, 2017). Good water quality management, vaccination programs, and regular health checks throughout production are essential for high yield (Robb, 2008). Pre-harvest practices are the final stage that determines meat quality and workable yield. Pre-slaughter fasting time, slaughtering technique, and storage methods directly determine fillet yield by affecting muscle pH, rigor mortis duration, and textural properties (Olsen et al., 2006). When all these factors are considered together, it becomes clear that meat yield in trout is not merely a biological parameter, but rather the combined result of multidisciplinary processes such as nutritional science, water quality management, genetic improvement, disease control, and production techniques (Table 1). Therefore, efforts to increase meat yield must be approached with a holistic approach.

Table 1. Main Factors Affecting Meat Yield in Trout

Factor Category	Effect Mechanism	Sample Findings	References
Genetic	Muscle development capacity, growth rate, FCR	10–25% increase in growth through selection	Gjedrem (2012); Yáñez et al. (2014)
Feeding	Protein/energy balance, amino acid profile	Optimum growth with 40% protein	NRC (2011)
Environmental Conditions	Water temperature, O_2 level, ammonia	Maximum growth at 12–16 °C	Bjørnsson et al. (2001)

Factor Category	Effect Mechanism	Sample Findings	References
Stock Density	Stress, competition, behavioral pressure	Decrease in growth with increasing density	Ellis et al. (2002)
Physiology	Age, sex, hormonal status	Optimum cut: 250–350 g	FAO (2020)
Diseases	Metabolic suppression, decreased appetite	*Y. ruckeri* reduces growth	Austin and Austin (2016)
Harvesting Methods	pH, rigor mortis, tissue integrity	Low stress → high quality	Olsen et al. (2006); Robb (2008)

1. GENETIC FACTORS

1.1 Differences Between Species and Genetic Lines

Genetic variation in trout is one of the most important variables affecting growth rate and muscular development. Rainbow trout (*Oncorhynchus mykiss*) is the dominant species in global production due to its high adaptability to culture conditions (Gjedrem, 2012).

Differences of up to 10–25% have been found between different genetic lines in terms of growth rates, FCR values, and fillet yield (Yáñez et al., 2014). Some studies conducted in Türkiye also indicate significant yield differences among genetic lines.

1.2 Selective Breeding Programs

The primary goal of selective breeding programs is to increase growth rate, feed efficiency, and fillet yield. Breeding programs conducted on commercial lines in Norway, Canada, and Chile indicate that annual genetic improvement in growth is on the order of 1–2% (Gjedrem and Robinson, 2014). While data on selection studies in Turkey are limited, studies conducted in the private sector and universities are reportedly promising.

1.3 Genetics–Nutrition Interactions

Genetic makeup determines a fish's feed utilization capacity and the efficiency with which it converts protein into muscle (Johnston, 2011). Some lines are reported to respond more quickly to high-protein feeds and have more uniform muscle fiber development (Tocher, 2015).

2. NUTRITION AND FEED FACTORS

2.1 Feed Composition

Protein

Protein is the fundamental building block of muscle tissue. The optimum crude protein level for trout is reported to be 38–45% (NRC, 2011). Similarly, domestic studies have shown that protein levels around 40% increase both growth performance and fillet yield.

Fat and Carbohydrate

A balanced energy/protein ratio is critical for meat yield. Excess fat energy can lead to fatty liver and low muscle yield (Jobling, 2016). Long-chain fatty acids such as EPA and DHA are reported to improve muscle fatty acid composition and tissue health (Tocher, 2015).

Vitamins and Minerals

Antioxidants such as vitamin C, vitamin E, and selenium support growth by reducing muscle breakdown (Table 2) (NRC, 2011). Studies in Turkey show that mineral deficiencies negatively affect growth and meat yield.

Table 2. Effect of Nutrients on Growth and Meat Yield in Rainbow Trout

Nutrient	Recommended Level	Effect on Meat Yield	Description
Crude Protein	38–45%	Increases	A key component of muscle synthesis
Crude Fat	12–18%	Increases when balanced	Excess fat → fatty liver
Carbohydrate	10–20%	Limited effect	Excess fat can lead to fatty liver
Omega-3 (EPA+DHA)	≥1.5%	Increases	Excess fat can lead to fatty liver
Vitamin C	50–100 mg/kg	Increases	Improves muscle fatty acid profile
Vitamin E	150–200 mg/kg	Increases	Antioxidant defense

Nutrient	Recommended Level	Effect on Meat Yield	Description
Probiotics	Varies depending on the type	Increases	Digestive enzymes and immunity are supported

2.2 Feeding Strategies

Feeding frequency, ration size, and feeding method are critical practices that affect growth rate.

- Underfeeding → reduced growth,
- Overfeeding → fat gain and loss of productivity,
- Optimal feeding → increased muscle mass (Jobling, 2016).

2.3 Functional Feed Additives

Probiotics and prebiotics have been reported to enhance growth and immunity (Ringø et al., 2018). Probiotic use in Turkey has also been shown to positively affect growth and feed utilization in trout (Yıldız and Şener, 2003).

3. ENVIRONMENTAL FACTORS

3.1 Water Quality

Parameters such as water temperature, dissolved oxygen, pH, ammonia, and nitrite directly affect growth metabolism (Wedemeyer, 1996).

- Optimal temperature: 12–16°C
- Oxygen level: ≥ 7 mg/L
- Ammonia (NH_3): < 0.02 mg/L

3.2 Stocking Density

Excessive stocking density increases stress hormones in fish, increases competition, and suppresses growth (Ellis et al., 2002). Local studies have indicated that fish reared at optimal densities have higher fillet yields.

3.3 Environmental Stress Factors

Water-related stress affects hormone levels in the long term, slowing muscle development (Barton, 2002). Prolonged stress has been shown to increase protein catabolism.

4. PHYSIOLOGICAL FACTORS

4.1 Age and Weight

Growth is faster in young individuals; however, optimal slaughter weight is important for economic yield. The optimal slaughter weight in Turkey has frequently been reported to be 250–350 g.

4.2 Sex

In females, muscle percentage may decrease during the reproductive period as energy is directed towards gonadal development. Males generally achieve higher fillet yields (FAO, 2020).

4.3 Hormonal Regulation

IGF-1, growth hormone, and thyroid hormones are known to play a critical role in muscle development (Johnston, 2011).

5. DISEASES AND HEALTH MANAGEMENT

5.1 Parasitic and Bacterial Diseases

Pathogens such as *Ichthyophthirius multifiliis*, *Aeromonas spp*., and *Flavobacterium psychrophilum* negatively affect growth (Austin and Austin, 2016). *Yersinia ruckeri* infection, in particular, is known to cause significant economic losses in Turkey

5.2 Vaccination and Water Hygiene

Appropriate vaccination programs reduce mortality rates and improve growth performance. Regular water disinfection positively affects yield (Tavares-Dias and Oliveira, 2017).

6. HARVEST AND PROCESSING PRACTICES

6.1 Starvation Period

A 12–24-hour fasting period before slaughter improves meat quality by reducing digestive residues (Robb, 2008).

6.2 Slaughtering Techniques

Minimizing fish stress during slaughter positively affects rigor mortis, pH, and muscle structure (Olsen et al., 2006).

6.3 Storage Conditions

When the cold chain is not maintained, muscle structure deteriorates rapidly and the byproduct ratio increases. This reduces economic yield.

7. RECOMMENDATIONS FOR INCREASING MEAT YIELD

- Expanding genetic selection programs
- Improving feed quality and optimizing protein/energy ratio
- Monitoring water quality with automated systems
- Implementing optimum stocking densities
- Regular vaccination and health checks
- Adopting low-stress harvesting methods

CONCLUSION

Meat yield in rainbow trout (*Oncorhynchus mykiss*) is determined by the combined influence of numerous interconnected factors, including genetics, nutrition, environmental parameters, stocking density, physiological structure, health management, and harvesting techniques. This study comprehensively evaluated each of these factors based on literature reviews and scientific data. Overall, the findings demonstrate that increasing trout meat yield is possible not with a single method but with a holistic culture strategy.

Genetic factors are critical to meat yield. Selection programs have been shown to significantly increase growth performance over the years, and this increase is directly reflected in muscle development, feed conversion ratio

(FCR), and fillet yield (Gjedrem, 2012; Yáñez et al., 2014). Studies conducted in Turkey also indicate that the productivity of different genetic lines varies, and that appropriate line selection significantly impacts production success. These findings highlight the need for breeders to prioritize family lines that are not only fast-growing but also possess high muscle mass and appropriate body composition.

Nutritional factors are among the most flexible and manageable factors determining meat yield. Meeting the optimal protein-energy ratio, amino acid balance, fat source, and micronutrient requirements of trout increases the efficiency of muscle synthesis and, consequently, the muscle percentage in fillets (NRC, 2011; Jobling, 2016). Local studies reveal that protein levels (38–45%), in particular, play a critical role in yield, and that improper formulations significantly reduce growth performance. Furthermore, probiotics, prebiotics, and functional feed additives have been shown to positively impact yield by increasing digestive enzyme activity (Ringø et al., 2018; Yıldız and Şener, 2003).

Environmental conditions, particularly water temperature and dissolved oxygen levels, are parameters that directly determine the physiological performance of fish. Exceeding the optimal temperature range (12–16°C) causes significant reductions in growth rate (Bjørnsson et al., 2001). Elevated levels of ammonia, nitrite, and similar toxic compounds negatively impact meat yield by creating stress and metabolic stress. In this context, water quality problems, observed in many farms in Turkey, are among the most important causes of low yields.

Stock density is one of the most frequently studied yield determinants in the literature. Production above optimal densities increases competition among fish, decreases appetite due to elevated stress hormones, and decreases growth performance (Ellis et al., 2002). This leads to a decrease in muscle percentage in fillets, increased fat content, and deterioration of marketable product quality.

Physiological factors cannot be ignored either. The age, maturity, sex, and seasonal cycle of the fish create significant changes in yield. It is expected that meat yield will decrease in females, particularly during the breeding season, as energy is directed towards gonadal development rather than muscle development (Barton, 2002; FAO, 2020). Therefore, proper slaughter planning is a critical aquaculture decision for both economic and quality reasons.

Diseases and health management are also among the most important factors limiting yield. Parasitic and bacterial infections suppress muscle development by causing loss of appetite, metabolic stress, and tissue degeneration (Austin and Austin, 2016; Tavares-Dias and Oliveira, 2017). In Turkey, *Yersinia ruckeri*, *Lactococcus garvieae* and parasitic infestations are known to cause significant production losses. Therefore, regular water quality control, vaccination programs, quarantine practices, and early detection methods are essential.

Harvesting techniques are the final stage determining final yield and quality. Pre-slaughter fasting time, stress levels, and slaughter methods directly impact final yield by affecting muscle pH, rigor mortis and fillet visual/textural characteristics (Olsen et al., 2006; Robb, 2008). Therefore, low-stress harvest protocols must be implemented.

When all factors are considered together, the most effective strategy for increasing meat yield in trout is a holistic production model that integrates genetic breeding, proper feed formulation, water quality management, optimal stocking density, disease control, and appropriate harvesting techniques. A significant portion of yield differences among producer enterprises, particularly in Turkey, stem from differences in these management factors.

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Chapter

4

UNMANNED SURFACE VESSELS FOR INLAND WATER MONITORING

Semih Kale[1,2]

1 Çanakkale Onsekiz Mart University, Faculty of Marine Sciences and Technology, Department of Fishing and Fish Processing Technology, 17020, Çanakkale, Türkiye
2 Çanakkale Onsekiz Mart University, Faculty of Marine Sciences and Technology, Department of Aquaculture Industry Engineering, 17020, Çanakkale, Türkiye, semihkale@comu.edu.tr, ORCID: https://orcid.org/0000-0001-5705-6935

Introduction

Unmanned Surface Vessels (USVs), also referred to as Autonomous Surface Vessels (ASVs), are crafts designed to operate on the water's surface without the need for an onboard human crew. Growing interest in unmanned surface vehicles and autonomous vessels has led to extensive research, driven by their promising uses in naval operations, maritime, riverine, and lake-based industries, as well as environmental monitoring applications (Castano-Londono et al., 2024). These vehicles may function under remote human supervision or in a fully autonomous mode using pre-programmed mission parameters, sensor feedback, and onboard decision-making algorithms. Peeters et al. (2020) noted that a USV integrates sensor suites, propulsion systems, communication units, and control architectures into a compact hydrodynamic platform that can perform missions ranging from data acquisition and navigation to cargo transport. These systems often combine multiple layers of autonomy, enabling them to sense environmental variables, interpret data in real time, and make navigational decisions without continuous human intervention.

USVs can be categorized based on their control architecture (Danilin et al., 2021):

(i) *Remotely Operated Surface Vehicles (ROSVs)*, which rely on direct control from a shore-based or ship-based operator.
(ii) *Semi-Autonomous USVs*, which execute pre-defined tasks autonomously but still allow for human intervention.
(iii) *Fully Autonomous USVs*, capable of mission planning, decision-making, and dynamic re-tasking using artificial intelligence (AI) and machine learning (ML) algorithms.

The development of USVs reflects broader advancements in robotic sensing, marine autonomy, and mechatronic engineering. Their increasing sophistication is enabling new paradigms in data-driven water resource management, environmental monitoring, and sustainable logistics. The concept of unmanned or automated marine vehicles dates back to military research in the mid-20th century. Early designs focused primarily on mine countermeasures and surveillance operations, particularly within naval defense programs. However, as robotic technology matured, the potential for civil and scientific applications became apparent. By the early 2000s, commercial and academic institutions began adapting these technologies for environmental purposes. The emergence of miniaturized sensors, high-efficiency electric propulsion systems, and real-time data telemetry catalyzed the transition of USVs from experimental platforms to operational environmental monitoring tools (Verberght & Van Hassel, 2019).

Recent developments have focused on inland and nearshore operations, where navigation complexity is heightened by confined spaces, variable currents, and signal interference. For example, Peeters et al. (2019) developed a scale-model unmanned inland cargo vessel that demonstrates the feasibility of autonomous navigation in restricted waterways. The prototype incorporated a 360°-steerable propulsion system and hierarchical control architecture capable of executing maneuvers with precision. This represented an essential step toward sustainable inland logistics and monitoring applications. As USV design evolved, the systems began incorporating modular payloads, allowing a single vessel platform to perform multiple environmental functions, such as water sampling, bathymetric mapping, and pollution tracking, by swapping sensors as needed. This modularity underpins the modern conceptualization of USVs as multi-mission robotic platforms.

The growing importance of USVs arises from the convergence of technological innovation, environmental necessity, and economic efficiency. USVs represent a fusion of robotics, computer vision, and marine engineering. Their ability to integrate multiple sensors, including LiDAR, sonar, and environmental probes, facilitates real-time monitoring of aquatic systems. The inclusion of artificial intelligence enables adaptive control, allowing USVs to respond dynamically to unexpected changes such as current shifts, debris, or floating vegetation (Cheng et al., 2021). Recent work by Yin et al. (2022) demonstrates the use of deep learning for shoreline detection, improving navigation in complex inland environments. The fusion of AI-based perception with traditional control systems is critical for safe, fully autonomous operations in rivers and lakes, where visual and acoustic interferences are common.

Inland water systems, including rivers, lakes, reservoirs, and estuaries, are vital to ecosystems, agriculture, and human livelihoods. Monitoring these systems is essential for water quality management, flood control, ecosystem health, and climate adaptation. Traditional monitoring approaches often rely on stationary sensors or human-operated boats, which are limited by cost, safety concerns, and spatial coverage. USVs overcome these limitations by enabling persistent, autonomous, and wide-area surveillance. Chensky et al. (2021) showed that an ultra-small catamaran-type USV equipped with solar panels and Li-ion batteries could autonomously map up to 15 km^2 of lake surface per day. Such capabilities make USVs invaluable for long-term environmental observation without human presence.

In addition to environmental and technical benefits, USVs offer substantial economic advantages. Operating without onboard crew reduces labor costs, fuel consumption, and logistical complexity. Moreover, USVs minimize human exposure to hazardous or remote environments, such as polluted waters, storm-affected regions, or flood zones. This enhances safety while maintaining operational efficiency (Karetnikov et al., 2017).

The evolution of USVs aligns with the global transition toward smart, networked environmental monitoring. They can be integrated into Internet of Things (IoT) architectures, where multiple autonomous vessels communicate with satellites, buoys, or unmanned aerial vehicles to form cooperative sensing networks. Such multi-agent systems enable adaptive sampling, dynamically adjusting monitoring strategies based on real-time feedback from the environment (Zhao et al., 2023). Additionally, USVs can serve as data collection intermediaries between underwater sensors and cloud-based analytics, effectively bridging the "data gap" in aquatic IoT systems. Their ability to gather and transmit multi-modal environmental data is essential for modern digital twin approaches in water management, which rely on continuous input from real-world sensors to maintain accurate simulation models. The integration of USVs into decision support systems (DSS) enables real-time visualization, forecasting, and resource allocation for hydrological management authorities, contributing to data-driven policy-making.

Globally, water resource degradation and climate-induced stressors are increasing. Inland waters are under threat from industrial effluents, agricultural runoff, eutrophication, and sedimentation. The deployment of USVs offers a way to augment existing monitoring networks and improve the spatial and temporal granularity of environmental data. For example, the European Union's Water Framework Directive (WFD) emphasizes continuous monitoring of surface water quality parameters. USVs offer an efficient means of compliance with such policies by automating repetitive data collection tasks, thus freeing human operators for higher-level analysis. Furthermore, in developing regions where infrastructure is limited, low-cost USVs such as those designed by Temilolorun & Singh (2024) provide scalable tools for community-level water management, aquaculture, and early-warning systems for contamination events.

The use of USVs in inland water monitoring can be conceptualized within three operational frameworks:

(i) *Exploratory Missions*: Mapping and surveying unknown or changing aquatic environments, including bathymetry and shoreline evolution.
(ii) *Monitoring Missions*: Repetitive, scheduled collection of environmental data such as turbidity, nutrient concentrations, or algal blooms.
(iii) *Response Missions*: Rapid deployment for pollution spills, flood assessment, or search and rescue operations.

Each framework requires varying levels of autonomy, communication infrastructure, and regulatory compliance. Integrating these into a cohesive operational model demands collaboration among engineers, hydrologists, ecologists, and policymakers. USVs represent a technological and operational revolution in inland water monitoring. Their versatility, autonomy, and scalability make them indispensable tools for sustainable management of aquatic resources. As technological advancements continue, particularly in autonomy, AI, and energy efficiency, USVs are poised to become integral components of global environmental observation networks.

Overview of Inland Water Monitoring Challenges

Inland waters, encompassing rivers, lakes, reservoirs, wetlands, and estuaries, are among the most dynamic and critical ecosystems on Earth. They serve as sources of drinking water, irrigation supply, biodiversity reservoirs, and industrial inputs, while also acting as sinks for urban and agricultural pollutants. Effective monitoring of these systems is therefore a cornerstone of sustainable water management, environmental protection, and climate adaptation strategies. However, monitoring inland waters is inherently complex due to the spatial and temporal variability of hydrological and biogeochemical processes, the heterogeneity of pollution sources, and the limitations of conventional monitoring methods. The transition to autonomous and unmanned monitoring systems such as USVs arises primarily from the need to address these challenges with greater precision, coverage, and cost-efficiency (Chensky et al., 2021).

USVs used in inland water monitoring face a range of challenges that can be broadly categorized under several key themes. The high spatial and temporal variability of inland water systems, difficulties related to accessibility and operational safety, and the technical limitations of traditional monitoring technologies represent some of the primary challenges. In addition, hydrological complexity and continuously changing environmental dynamics, along with economic and logistical constraints, can significantly affect the efficiency of USV-based monitoring efforts. Issues related to data quality and standardization, as well as institutional and regulatory barriers, further limit effective implementation. All of these factors become even more complex when combined with the impacts of climate change and emerging environmental pressures. These challenges can be categorized as follows:

(i) Spatial and temporal variability in inland water systems
(ii) Accessibility and safety challenges
(iii) Limitations of traditional monitoring technologies
(iv) Hydrological complexity and environmental dynamics
(v) Economic and logistical constraints
(vi) Data quality and standardization challenges
(vii) Institutional and regulatory barriers
(viii) Climate change and emerging environmental pressures

One of the fundamental challenges in inland water monitoring is capturing spatiotemporal variability. Water bodies are influenced by diverse, interrelated processes, including rainfall, runoff, sediment transport, evaporation, and human activities, that fluctuate on scales from hours to seasons. Traditional monitoring relies on fixed-point stations, which provide high-frequency but spatially limited data. This approach is insufficient for characterizing the heterogeneity of large river basins or lake systems. As a result, important events such as episodic pollution discharges, sediment plumes, or algal blooms may go undetected between sampling intervals (Zhao et al., 2023). Furthermore, many inland waters, especially shallow rivers and reservoirs, exhibit strong vertical and horizontal gradients in temperature, dissolved oxygen, and nutrient concentrations. Manual sampling at multiple depths and locations is both labor-intensive and dangerous, particularly in high-flow or contaminated environments. The mobility and autonomy of USVs directly address this issue. Unlike static sensors, USVs can systematically traverse the water surface, adapt their paths based on real-time data, and map spatiotemporal dynamics with high resolution. For example, Cheng et al. (2021) highlighted that inland waterways present significant GPS denial and multipath interference challenges that hinder conventional sampling but can be mitigated through multi-sensor fusion and intelligent navigation systems onboard USVs.

Another critical obstacle in inland water monitoring is physical accessibility. Remote or hazardous locations, such as flooded zones, contaminated industrial canals, and narrow riverine channels, are difficult or unsafe for manned operations. For instance, traditional sampling in polluted or hypoxic waters can expose researchers to chemical, biological, and physical hazards, while small boats risk capsizing in turbulent flows. In regions such as Southeast Asia and sub-Saharan Africa, where inland water networks are extensive but infrastructure is limited, regular manual sampling is often infeasible. Low-cost, modular USVs offer a scalable alternative for data collection in such environments (Temilolorun & Singh, 2024). Safety risks are also associated with extreme weather events, floods, high winds, or debris-laden waters, which can make fieldwork dangerous. Automated USVs, equipped with obstacle avoidance systems and self-righting hulls, can operate safely under such conditions without endangering human operators (Tran et al., 2021).

Historically, inland water monitoring has relied on a combination of manual sampling, fixed-station sensors, and remote sensing techniques. While these approaches have contributed significantly to water management, they each exhibit substantial limitations: (i) manual sampling, (ii) fixed sensor stations, and (iii) satellite and aerial remote sensing. Manual sampling provides high analytical accuracy but is spatially sparse and temporally discontinuous. It cannot capture rapid fluctuations in dynamic systems such as tidal estuaries or urban rivers. Fixed sensor stations offer continuous monitoring but are limited to specific locations and are prone to fouling, vandalism, and calibration drift. Their installation and maintenance are expensive, particularly in developing regions. Satellite imagery suffers from limited temporal resolution, atmospheric interference, and inability to detect subsurface parameters such as dissolved oxygen or nutrient concentrations while providing large-scale coverage.

The introduction of USVs bridges the gap between these methods by providing mobile, autonomous, and near-real-time data acquisition. As Chensky et al. (2021) demonstrated, autonomous catamaran-type vessels can execute hydroacoustic mapping, water quality sampling, and visual inspections simultaneously, offering multi-dimensional environmental datasets unattainable by stationary or remote sensing methods.

Inland water systems exhibit a wide range of hydrodynamic and ecological interactions that complicate monitoring efforts. These include (i) stratification and mixing in lakes and reservoirs, (ii) sediment resuspension and nutrient cycling in rivers, (iii) biological processes such as algal bloom formation or microbial activity, and (iv) anthropogenic influences, including agricultural runoff, wastewater discharge, and dam operations. Each of these processes varies across space and time, requiring flexible, adaptive monitoring strategies. USVs are particularly suited to such tasks because their onboard sensors and control algorithms can be dynamically reconfigured in response to changing conditions.

Moreover, confined inland waterways, unlike open seas, are characterized by complex boundary interactions such as reflections, multipath interference, and turbulence induced by banks and obstacles. Cheng et al. (2021) and Yin et al. (2022) both emphasized that these factors degrade GPS signals and hinder optical and acoustic sensors, posing unique challenges for navigation and data quality. Overcoming these requires advanced simultaneous localization and mapping (SLAM) and sensor fusion techniques, which are now being incorporated into next-generation USVs.

From a practical perspective, monitoring programs are often constrained by budget limitations and limited technical capacity. Deploying and maintaining large networks of sensors is financially burdensome, while human resources for fieldwork are often scarce. This is especially true in developing nations, where environmental agencies may lack the funding and expertise for continuous water monitoring. The operational efficiency of USVs makes them an attractive alternative. Once deployed, they can autonomously navigate predefined routes, collect and transmit data, and even return to charging stations. A solar-powered USV, such as the one developed by Chensky et al. (2021), demonstrated several days of continuous operation without external energy input that significantly reducing operational costs. In addition, traditional survey vessels require trained crews, fuel, and safety infrastructure, all of which contribute to the carbon footprint of environmental monitoring. Autonomous USVs mitigate these concerns through electrification, miniaturization, and renewable energy integration, aligning with global sustainability objectives.

The reliability of water quality data depends on sensor calibration, data validation, and quality assurance. Variability in sensor accuracy and environmental interference often complicate the interpretation of long-term datasets. Fixed sensors, for instance, may experience biofouling, accumulation of microorganisms and algae on sensor surfaces, which alters readings. USVs can mitigate this by incorporating self-cleaning mechanisms, redundant sensors, and adaptive calibration routines based on environmental feedback. However, as USVs integrate heterogeneous sensors (e.g., LiDAR, sonar, chemical probes), the challenge of data standardization becomes more acute. Harmonizing multi-modal datasets for cross-comparison or integration with satellite data requires robust data fusion and interoperability frameworks. Efforts such as the USVInland dataset (Cheng et al., 2021) are critical steps in standardizing perception and mapping data for inland waterways.

Beyond technical limitations, institutional and regulatory challenges pose significant obstacles to inland water monitoring innovation. Many national water authorities rely on legacy protocols that were developed before autonomous platforms existed. These often lack clear standards for USV deployment, data validation, and liability. According to Nzengu et al. (2021), existing maritime regulations explicitly assume the presence of a crew for navigation and emergency procedures, rendering autonomous operations noncompliant in many jurisdictions. This regulatory gap delays the adoption of USVs for routine monitoring, even when the technology is mature. Moreover, inter-agency data-sharing frameworks are often fragmented, leading to redundancy and inefficiency. Integrating USV-based monitoring into national water information systems will require not only technological but also institutional innovation, including harmonized standards and cross-sectoral collaboration.

Climate change introduces new and exacerbating challenges for inland water monitoring. Rising temperatures, altered precipitation patterns, and increased extreme weather events drive changes in water availability, quality, and ecosystem structure. Monitoring these impacts requires high-frequency, long-term, and spatially extensive datasets which traditional monitoring infrastructures cannot provide effectively. For instance, extreme flood and drought cycles necessitate rapid deployment of adaptive monitoring systems that can collect data in real time under variable hydrological conditions. USVs are ideally positioned to meet this demand. Their autonomous navigation allows for flexible response to hydrological extremes, while modular sensor systems enable detection of emerging parameters such as microplastics, dissolved greenhouse gases, and harmful algal toxins. The integration of these capabilities represents a paradigm shift from reactive to proactive water management.

Inland water monitoring is constrained by a complex interplay of environmental dynamics, technical limitations, logistical barriers, and institutional inertia. These challenges have historically led to data scarcity, spatial bias, and limited predictive capacity in hydrological management. USVs directly address these constraints by offering autonomous, adaptable, and scalable monitoring solutions. They bridge the gaps between stationary, manual, and remote sensing techniques, while enhancing safety and cost efficiency. However, realizing their full potential requires parallel advances in data standardization, regulatory frameworks, and technological integration.

Relevance of USVs in Modern Hydrological and Environmental Studies

Unmanned Surface Vehicles (USVs) have become central to the transformation of inland and coastal water monitoring, bridging the technological gap between traditional field surveys and the demands of high-resolution, real-time environmental data acquisition. The need for such systems arises from the growing importance of freshwater resources and the challenges posed by pollution and climate variability (Brierley & Harper, 1999; Anonymous, 2004; Akın & Akın, 2007).

Kale (2020a) emphasizes that the potential of USVs for environmental monitoring lies in their ability to collect spatiotemporally dense datasets for parameters such as water temperature, turbidity, dissolved oxygen, and nutrient levels without endangering human operators. This advantage is particularly critical in hazardous or inaccessible zones, such as acid mine lakes, extreme weather environments, or regions with logistical restrictions. Moreover, as Kale (2020b) and Demetillo & Taboada (2019) detail, hybrid-controlled USVs can perform sampling and mapping tasks in conditions that would render traditional manual operations impossible, such as at night or in polluted or shallow areas. Similarly, Yaakob et al. (2012) demonstrated that autonomous USVs enhance operational safety while maintaining accuracy in real-time monitoring of aquatic environments.

Beyond operational safety, the technology also enables broader scientific applications. Over the past two decades, hydrological and environmental sciences have undergone a paradigm shift driven by the fusion of robotics, remote sensing, and data analytics. Traditional methods of aquatic monitoring, based on manual sampling and fixed stations, are increasingly supplemented or replaced by autonomous robotic platforms, particularly USVs. These platforms provide scientists with the unprecedented ability to collect high-resolution, real-time, multi-parameter datasets across large spatial domains and extended temporal scales. The integration of USVs into hydrological research has accelerated due to three converging trends:

(i) Technological maturity in sensors, navigation, and AI
(ii) Urgent environmental pressures arising from water pollution, eutrophication, and climate-induced hydrological change
(iii) Policy demands for sustainable water management under frameworks such as the EU Water Framework Directive (WFD) and the UN Sustainable Development Goals (SDG 6: Clean Water and Sanitation).

USVs are no longer experimental tools but essential instruments for integrated water resource management, ecosystem modeling, and climate adaptation studies (Chensky et al., 2021). Their applications now span limnology, hydrodynamics, pollution tracking, aquatic ecology, and sediment transport modeling, fields traditionally constrained by spatial and temporal data scarcity.

Hydrological systems are characterized by spatial complexity and temporal variability, making comprehensive data collection challenging. Traditional approaches rely on fixed monitoring stations, manual sampling campaigns, or aerial remote sensing, each of which presents limitations in frequency, coverage, and resolution. USVs offer a transformative solution by functioning as mobile sensor networks that can autonomously traverse riverine or lacustrine environments. Equipped with multiparameter probes, echo sounders, LiDAR, and cameras, they enable continuous profiling of water quality, flow velocity, and bathymetry (Cheng et al., 2021). For instance, Peeters et al. (2019) designed an unmanned inland vessel with fully steerable propulsion that can maneuver precisely in narrow waterways, paving the way for automated flow mapping and sediment sampling in confined hydrological settings (Peeters et al., 2019). Similarly, the VIAM-USV2000, designed by Tran et al. (2021), demonstrated the ability to collect hydrological data while avoiding dynamic obstacles in dense river systems, thus providing real-time flow and turbulence information crucial for hydraulic modeling (Tran et al., 2021). Such data directly support the calibration and validation of hydrodynamic models (e.g., SWAT, HEC-RAS, Delft3D), which require dense, accurate, and continuous input datasets to predict flow, sediment transport, and contaminant dispersion.

Inland waters are under increasing pressure from eutrophication, heavy metal contamination, and emerging pollutants such as pharmaceuticals and microplastics. Continuous, spatially resolved data are essential for detecting pollution sources and assessing ecological health. USVs enable real-time water quality monitoring by integrating multi-sensor payloads capable of measuring:

(i) Temperature, conductivity, dissolved oxygen (DO)
(ii) pH, turbidity, chlorophyll-a
(iii) Nitrate, phosphate, and ammonia concentrations
(iv) Hydrocarbon and heavy metal traces via fluorometric sensors

The sustainable management of water resources requires continuous and spatially representative monitoring of water quality. Conventional water quality assessment methods are largely based on manual sampling and laboratory analysis, which are time-consuming and labor-intensive. In recent years, USVs have emerged as an effective alternative for water quality monitoring, offering increased operational efficiency and enhanced spatial data coverage. Many researchers reported that USVs have been used for water quality monitoring (Kaizu et al., 2011; Siyang & Kerdcharoen, 2016; Bin Mat Idris et al., 2016; Shuo et al., 2017; Balbuena et al., 2017; Cao et al., 2018; Melo et al., 2019; Madeo et al., 2020; Xing et al., 2020; Arko et al., 2020; Chang et al., 2021; Dsouza et al., 2021; Ansari et al., 2022; Setiawan et al., 2022). Duran & Sönmez (2025) provide a comprehensive review of USV-based water quality monitoring systems, highlighting the technical capabilities of these platforms in terms of sensor integration, hull design, energy management, communication infrastructure, and control stations. Their study emphasizes that key water quality parameters, such as pH, temperature, turbidity, dissolved oxygen, and electrical conductivity, can be measured in real time using integrated sensor modules mounted on USVs. Furthermore, the authors report that catamaran-type hull designs are particularly advantageous due to their superior stability and payload capacity, enabling the deployment of multiple sensors simultaneously. Similarly, Cao et al. (2018) developed an autonomous USV designed for water quality monitoring applications, demonstrating the advantages of mobile sensing platforms over stationary monitoring systems. In their study, the USV autonomously navigates predefined routes while collecting water quality data, which are transmitted wirelessly to a control station for real-time visualization and analysis. This approach enables rapid assessment of large water bodies and provides higher spatial resolution compared to fixed monitoring stations. The review by Duran & Sönmez (2025) synthesizes findings from such application-oriented studies and concludes that USV-based monitoring systems offer significant advantages in terms of cost efficiency, operational flexibility, and user safety. When evaluated together with experimental implementations such as that of Cao et al. (2018), these findings suggest that USVs have strong potential to become standard tools for future water quality and environmental monitoring applications.

A key example is the solar-powered catamaran-type USV developed by Chensky et al. (2021), which autonomously monitored water quality across 15 km^2 of lake surface per day, transmitting live data via GSM to a control center. This platform provided critical insights into diurnal and spatial patterns of water quality variations (Chensky et al., 2021). Furthermore, Temilolorun & Singh (2024) proposed a low-cost twin-hull USV for aquaculture applications that utilized ROS (Robot Operating System) and Extended Kalman Filter

(EKF) sensor fusion for enhanced localization and stability in shallow ponds. This design democratized access to automated monitoring tools for small-scale farmers in developing regions (Temilolorun & Singh, 2024). Such innovations illustrate how USVs contribute to both scientific research and practical water resource management, bridging the gap between academic data collection and operational decision support.

Modern hydrological and ecological models, such as Water Quality Analysis Simulation Program (WASP), MIKE 21, and EcoHydro models, require high-resolution spatial datasets for parameterization. Traditionally, such data have been sparse, leading to uncertainty in model predictions.

USVs fill this gap by providing dense spatial datasets that improve the calibration of models related to:

(i) Nutrient cycling and eutrophication dynamics
(ii) Sediment resuspension and deposition
(iii) Riverine mixing and pollutant dispersion
(iv) Aquatic ecosystem metabolism and primary productivity.

Cheng et al. (2021) emphasized that the USVInland dataset, collected over 26 km of diverse inland water scenes, provides critical benchmarks for testing perception and mapping algorithms, directly supporting model-data fusion in hydrology. These datasets improve the robustness of Simultaneous Localization and Mapping (SLAM) and flow-field reconstruction algorithms used in environmental simulations (Cheng et al., 2021). Moreover, integration with remote sensing platforms (UAVs and satellites) creates multi-scale datasets, enabling hierarchical modeling of catchment processes, from local hydrodynamics to basin-scale hydrology.

In addition to physical and chemical monitoring, USVs are increasingly used for biological and ecological investigations. Equipped with underwater cameras, sonar imaging, and eDNA (environmental DNA) samplers, they allow scientists to assess:

(i) Fish and plankton distribution
(ii) Benthic habitat structure
(iii) Vegetation dynamics
(iv) Invasive species detection.

These functions are crucial in ecosystems experiencing rapid anthropogenic change. For example, autonomous USVs operating in wetlands can monitor the expansion of invasive aquatic weeds such as Eichhornia crassipes (water hyacinth) and correlate these data with nutrient enrichment levels. Furthermore, by integrating hydroacoustic mapping with environmental sensors, USVs enable comprehensive habitat classification, supporting conservation and restoration efforts under global biodiversity frameworks such as the Convention on Biological Diversity (CBD).

USVs also play a vital role in disaster risk reduction and climate resilience. Floods, dam failures, and pollution spills require rapid assessment of hydrological conditions to inform emergency response. Manned surveys in such situations are often unsafe due to high velocities, debris, and contamination. Autonomous USVs can be deployed within minutes to:

(i) Measure flood depth and flow velocity
(ii) Map debris and obstacles
(iii) Track pollutant dispersion (e.g., oil spills or chemical leaks)
(iv) Monitor post-disaster water quality.

For instance, Karetnikov et al. (2017) predicted that unmanned river vessels would become essential to inland navigation within five years, primarily due to their potential to reduce human exposure to hazardous conditions and enhance logistical safety during extreme events (Karetnikov et al., 2017). As climate extremes intensify, integrating USVs into flood monitoring networks will enable real-time hydrodynamic modeling and rapid damage assessment, contributing directly to adaptation and resilience planning.

The relevance of USVs extends beyond technical and scientific domains into policy and governance. Their ability to deliver transparent, verifiable environmental data aligns with international efforts to achieve SDG 6 (Clean Water) and SDG 13 (Climate Action). Policy-driven applications include:

(i) Continuous compliance monitoring under the EU Water Framework Directive (WFD)
(ii) Support for Integrated Water Resource Management (IWRM) programs

(iii) Verification of pollutant discharge permits and enforcement of environmental regulations.

By enabling data democratization, USVs help governments and communities' access up-to-date water quality information, promoting accountability and informed decision-making. Moreover, as Nzengu et al. (2021) argue, the evolution of regulatory frameworks to accommodate autonomous vessels will further integrate USVs into national environmental strategies (Nzengu et al., 2021).

Modern hydrological research increasingly depends on data-driven modeling supported by AI and machine learning (ML). USVs serve as critical data generators feeding these models. Advanced onboard processors allow real-time application of ML algorithms for anomaly detection, adaptive navigation, and environmental prediction. For instance, Yin et al. (2022) used deep learning-based shoreline detection to enhance autonomous navigation and improve environmental mapping accuracy to over 96%. Such methods not only ensure safe operation but also improve the fidelity of environmental datasets used for modeling (Yin et al., 2022). Furthermore, Zhao et al. (2023) demonstrated cooperative path-planning algorithms for multi-USV networks, showing that distributed intelligence allows fleets to optimize sampling routes and improve efficiency in large-scale monitoring operations (Zhao et al., 2023). Through such capabilities, USVs transition from passive data collectors to active agents in adaptive environmental management systems.

The integration of USVs into modern hydrological and environmental research represents a significant scientific and technological leap. They provide:

(i) Enhanced spatiotemporal resolution of hydrological data
(ii) Real-time, adaptive monitoring of dynamic water systems
(iii) Reduced operational risk and cost
(iv) Seamless integration with AI and modeling frameworks
(v) Support for sustainable policy implementation and governance.

By transforming how environmental data are collected, processed, and utilized, USVs are redefining the boundaries of water science. Their relevance is not limited to monitoring but extends to prediction, management, and governance, making them indispensable tools in achieving sustainable water resource management.

Technological Developments in Unmanned Surface Vessels (USVs)

Design and Control Architecture

The technological evolution of USVs is underpinned by advances in mechanical design, control systems, and autonomous decision-making architectures. USVs must operate reliably across complex hydrodynamic conditions, from confined inland waterways to turbulent riverine flows. This necessitates sophisticated designs that balance stability, maneuverability, payload flexibility, and energy efficiency (Peeters et al., 2019). The design of USVs for inland water monitoring requires a multidisciplinary integration of marine engineering, control theory, robotics, and sensor fusion. Unlike ocean-going autonomous vessels, inland USVs must operate in narrow, shallow, obstacle-rich environments with complex boundaries, low GPS visibility, and dynamic human interference. These constraints necessitate distinct innovations in hull design, actuation, and control algorithms.

The hull form of a USV directly affects hydrodynamic performance, energy consumption, and operational stability. For inland monitoring, catamaran and trimaran designs are most common due to their inherent stability and high payload capacity relative to size. Chensky et al. (2021) demonstrated that an ultra-small catamaran-type vessel provided excellent hydrodynamic stability in reservoirs and lakes, enabling consistent sensor readings even under moderate wave disturbance. Conversely, monohull designs are used for smaller, agile USVs operating in confined channels. Peeters et al. (2019) utilized a scaled CEMT-I class barge with 360° steerable thrusters to study dynamic stability and maneuverability, showing that adaptive control could offset instability introduced by asymmetrical loading. Hull materials typically include:

(i) Fiber-reinforced polymers (FRPs) for lightweight strength
(ii) Aluminum for durability and corrosion resistance
(iii) 3D-printed polymer composites, as employed by Temilolorun & Singh (2024), to reduce fabrication costs for small-scale operations (Temilolorun & Singh, 2024).

Modern USVs increasingly adopt modular hull architectures, allowing rapid reconfiguration for diverse missions such as water quality sampling, sonar mapping, or sediment coring. This modularity also supports scalability from micro-USVs (<1 m length) to medium research platforms (>5 m).

The core of any USV's autonomy lies in its control system, which transforms sensor inputs into navigational and operational commands. Control architectures are typically hierarchical, consisting of three levels (Peeters et al., 2020):

(i) *Mission Control Layer*: Handles high-level planning and route optimization.
(ii) *Supervisory Control Layer*: Coordinates navigation, obstacle avoidance, and path tracking.
(iii) *Low-Level Control Layer*: Regulates actuation (rudders, thrusters, propellers) to maintain heading and stability.

Peeters et al. (2019) implemented a "back-seat driver" control paradigm, wherein the low-level control maintained dynamic stability while higher-level autonomy modules, based on the MOOS-IvP (Mission Oriented Operating Suite-Interval Programming) software, executed path-following and decision-making tasks. This approach allowed modular software integration, supporting adaptive autonomy and human supervision when necessary.

Control algorithms range from Proportional–Integral–Derivative (PID) controllers for basic stabilization to Nonlinear Model Predictive Control (NMPC) systems that account for vessel dynamics, currents, and obstacles (Zhao et al., 2023). Recent research trends include:

(i) Adaptive fuzzy control for nonlinear hydrodynamics
(ii) Reinforcement learning for autonomous trajectory optimization
(iii) Sliding-mode control for robust tracking in uncertain conditions.

USVs rely on sensor fusion frameworks to integrate data from multiple onboard sensors such as GPS, IMUs, LiDAR, cameras, radar, and sonar. In confined inland waters where GPS signals are often weak or obstructed by banks and vegetation, inertial navigation systems (INS) and visual odometry provide complementary positioning information. Cheng et al. (2021) introduced the USVInland dataset to train and evaluate algorithms for SLAM in such environments, demonstrating the potential of multi-sensor data for reliable autonomous navigation. The autonomy stack typically includes:

(i) *Perception Layer*: Object detection and environmental awareness (using vision and LiDAR)
(ii) *Decision Layer*: Path planning, obstacle avoidance, and mission re-planning
(iii) *Execution Layer*: Control commands to propulsion and steering actuators.

Yin et al. (2022) enhanced shoreline detection using a deep-learning-based PSPNet with attention mechanisms, achieving 96.9% segmentation accuracy in inland rivers. Such perception improvements are critical for safe autonomous operation in complex waterways.

Even as USVs gain autonomy, human supervision remains important, especially in regulatory contexts. Peeters et al. (2020) developed an Inland Shore Control Centre (I-SCC) capable of remotely supervising and controlling multiple USVs simultaneously. This interface provides:

(i) Real-time situational awareness via sensor telemetry
(ii) Interactive control and mission updates
(iii) Safety monitoring and emergency override capabilities.

Such hybrid autonomy systems combine human cognitive strengths with machine precision, aligning with the “human-on-the-loop” concept that a key transitional step before fully autonomous inland operations.

Design and control architecture advancements underpin the reliability and versatility of USVs. Modular designs, hierarchical control systems, and intelligent sensor fusion now enable safe, adaptive, and precise operation in inland waterways. These innovations collectively form the technological foundation for deploying USVs as dependable tools in environmental monitoring and hydrological research.

Kale's (2023) review of technological developments in USVs situates these vehicles within a continuum of innovations that include autonomous navigation, multi-sensor integration, AI-enhanced obstacle avoidance, and hybrid-electric propulsion. This evolution aligns with earlier research on marine vehicle guidance and control systems, emphasizing dynamic stability and precision navigation (Larson et al., 2006; Pascoal et al., 2006; Breivik, 2010). According to Kale (2023) and Cheng et al. (2021), the miniaturization of sensors, the introduction of modular LiDAR and sonar arrays, and the integration of real-time data communication systems have enabled USVs to function not merely as monitoring tools but as intelligent nodes within digital hydrological networks. These technological milestones reflect broader trends in vehicle autonomy and digital environmental monitoring observed in systems such as SCOUT and AutoCat, which pioneered adaptive guidance and cooperative control (Manley, 1997; Manley et al., 2000; Curcio et al., 2005). This development marks a paradigm shift, from discrete, site-specific data collection to continuous, networked environmental intelligence systems.

Navigation and Communication Systems

Reliable navigation and communication are critical to the safe and efficient operation of USVs, particularly in inland and nearshore environments. Navigation encompasses positioning, path planning, and motion control, while communication ensures data transmission, fleet coordination, and remote supervision. Unlike open-ocean operations, inland waterways present unique challenges: multipath reflections, GPS denial, dynamic obstacles, and variable current patterns (Cheng et al., 2021). Most USVs employ Global Navigation Satellite Systems (GNSS) integrated with Inertial Measurement Units (IMUs) for real-time positioning. However, in GPS-denied conditions, common in urban canals and river gorges, fusion with visual odometry, LiDAR, and radar data is essential. Extended Kalman Filters (EKF) are commonly used to integrate these data streams, providing robust position estimates even under signal loss (Temilolorun & Singh, 2024).

SLAM (simultaneous localization and mapping) is vital for autonomous operations. The USVInland dataset (Cheng et al., 2021) supports benchmarking of SLAM algorithms that use multi-sensor data fusion (LiDAR, stereo vision, radar). Recent studies show that fusing millimeter-wave radar with stereo imagery enhances robustness against light reflections and water surface glare (Cheng et al., 2021).

Path planning involves determining optimal routes under environmental and dynamic constraints. Zhao et al. (2023) introduced a Greedy Partheno Genetic Algorithm (GPGA) to solve extended multi-traveling salesman problems for heterogeneous USV fleets, integrating Nonlinear Model Predictive Control (NMPC) for real-time motion adjustment. This approach demonstrated significant improvements in both computational efficiency and trajectory smoothness for cooperative monitoring tasks. USVs depend on robust communication links for telemetry, command, and data transmission. Common communication architectures include:

(i) Radio frequency (RF) links for short-range control
(ii) Cellular (4G/5G) or satellite communication for long-range data transfer
(iii) Ad hoc mesh networks for fleet coordination in multi-USV missions.

Peeters et al. (2020) emphasized the need for redundant communication systems between USVs and inland shore control centers to prevent mission failures during signal outages. Emerging developments include Software-Defined Radios (SDR) and Edge Computing Nodes onboard USVs, which reduce data bandwidth requirements by performing local processing (e.g., filtering, compression, anomaly detection) before transmission.

In confined inland waterways, environmental awareness is vital for preventing collisions. Sensor arrays typically include stereo cameras, ultrasonic sensors, and LiDAR. Machine vision algorithms, such as those developed by Yin et al. (2022), enable real-time shoreline detection and obstacle segmentation. Integration of vision with radar allows USVs to operate in low-visibility conditions such as fog or heavy rain. Obstacle avoidance strategies employ:

(i) Potential field methods (PFM) for dynamic obstacle repulsion
(ii) Velocity obstacle (VO) approaches for multi-agent navigation

(iii) Deep reinforcement learning (DRL) for adaptive obstacle avoidance.

These algorithms ensure safe and efficient navigation even in unpredictable inland environments.

For large-scale monitoring operations, cooperative navigation among multiple USVs allows for distributed sensing and reduced mission time. Fleet coordination relies on inter-vessel communication, synchronized path planning, and decentralized control. Zhao et al. (2023) demonstrated that coordinated USVs using GPGA-based optimization achieved efficient task division and minimal route overlap, significantly enhancing mission efficiency. Navigation and communication technologies form the operational backbone of USV systems. Through sensor fusion, adaptive control, and resilient communication architectures, modern USVs achieve high autonomy and reliability even in challenging inland environments. These advances are instrumental for long-duration, multi-vessel monitoring missions, ensuring consistent, accurate environmental data collection.

Energy and Propulsion Considerations

Energy efficiency and propulsion design critically determine the endurance, speed, and payload capacity of USVs. Given that inland monitoring missions often last for days or weeks, optimizing power consumption is essential to achieving sustained autonomous operation. USVs use a variety of propulsion configurations depending on mission requirements:

(i) Conventional propellers with rudders (for larger vessels)
(ii) Ducted propellers for compact efficiency
(iii) Waterjets or thrusters for shallow or debris-filled waters
(iv) Azimuth thrusters providing 360° maneuverability.

Peeters et al. (2019) demonstrated that 360° steerable four-channel thrusters provide superior control authority in confined inland vessels, enabling precise motion even at low speeds. Smaller platforms, such as the Temilolorun & Singh (2024) catamaran, use dual T200 electric thrusters controlled via differential drive configurations, allowing for tight turns and station-keeping in aquaculture ponds.

Energy systems for USVs can be grouped into:

(i) *Battery-Powered Systems*: Commonly lithium-ion or lithium-polymer batteries offering high energy density but limited endurance.
(ii) *Hybrid Systems*: Combining internal combustion engines with electric drives for extended missions.
(iii) *Renewable Systems*: Solar-powered USVs, such as the Chensky et al. (2021) platform, which operated continuously for several days using photovoltaic arrays.

The trend toward green, sustainable power systems aligns with international goals to reduce the carbon footprint of monitoring operations.

Intelligent power management systems monitor consumption across propulsion, sensors, and communication modules. Techniques include:

(i) Dynamic power allocation based on mission priorities
(ii) Sleep modes for inactive sensors
(iii) Solar charging optimization based on sun angle prediction.

Integration of Maximum Power Point Tracking (MPPT) in solar systems enhances charging efficiency, while energy-aware path planning ensures mission completion within energy constraints.

Energy optimization is not limited to power systems, hydrodynamic design plays a major role. Reducing hull drag, optimizing propeller design, and balancing weight distribution all contribute to lower power requirements. Computational Fluid Dynamics (CFD) tools are increasingly used to simulate flow patterns and optimize hull geometry before physical prototyping. Recent work by Zhang et al. (2024) introduced a maneuvering model for confined waterways, incorporating shallow-water and bank effects to enhance prediction of vessel motion response. This research provides a crucial foundation for the design of hydrodynamically efficient inland USVs.

Future energy systems for USVs will increasingly leverage:

(i) Hydrogen fuel cells for zero-emission propulsion
(ii) Wave energy harvesting modules for self-sustained operation

(iii) AI-based predictive energy management, which adjusts mission planning dynamically to preserve energy reserves.

Integration of these systems with smart charging docks or autonomous motherships will enable near-continuous operation for environmental monitoring networks.

Advances in propulsion and energy systems are central to realizing the long-term autonomy of USVs. From efficient electric thrusters to solar-hybrid configurations and intelligent power management, these innovations ensure sustainable, extended missions. Together, these technologies enable USVs to operate independently across inland environments, expanding their role as indispensable platforms for continuous hydrological and environmental monitoring.

Applications in Inland Water Monitoring

Water quality assessment is one of the most mature and impactful applications of USVs. With growing concerns over eutrophication, heavy metal contamination, microplastics, and industrial discharges, there is a pressing need for spatiotemporally dense water quality data that traditional sampling methods cannot deliver efficiently. USVs have transformed this field by offering autonomous, mobile, and repeatable monitoring, capable of collecting real-time measurements for a wide range of physical, chemical, and biological parameters. They enable continuous, multi-sensor sampling across large inland waterbodies, rivers, reservoirs, and lakes, without human risk or logistical burden (Chensky et al., 2021).

Modern USVs integrate multi-parameter sondes, fluorometers, and optical sensors that measure key water quality indicators, such as:

(i) *Physical parameters*: temperature, turbidity, conductivity, and total dissolved solids (TDS).
(ii) *Chemical parameters*: dissolved oxygen (DO), pH, oxidation-reduction potential (ORP), nitrate, phosphate, and ammonia.
(iii) *Biological parameters*: chlorophyll-a (for algal biomass) and phycocyanin (for cyanobacteria).
(iv) *Emerging pollutants*: hydrocarbons, pharmaceuticals, and heavy metals via specialized spectroscopic sensors.

Temilolorun & Singh (2024) demonstrated the use of low-cost sensor integration on a 3D-printed twin-hull USV, capable of continuous monitoring of dissolved oxygen, turbidity, and nutrient levels in aquaculture ponds. Their system utilized an Extended Kalman Filter (EKF) for sensor fusion, providing stable, high-frequency measurements even in shallow and dynamic water conditions.

USVs enable real-time monitoring through integrated telemetry systems. Onboard microcontrollers process sensor data and transmit it via 4G/5G or radio links to control stations or cloud servers. This real-time data is essential for early detection of contamination events, such as algal blooms or chemical spills, and for adaptive sampling strategies that allow USVs to focus on zones of concern. Chensky et al. (2021) deployed a solar-powered catamaran USV on the Irkutsk Reservoir, capable of transmitting water quality data and GPS coordinates live to a control center. The system achieved a coordinate accuracy of ±2 m and operated continuously for several days without external recharging. Such autonomous systems are particularly valuable for remote regions or developing countries, where manual sampling is limited by resources or accessibility.

Traditional water sampling, conducted via manual collection or stationary sensors, faces limitations in coverage, temporal frequency, and safety. USVs overcome these by enabling (i) spatial continuity, (ii) temporal consistency, (iii) safety, and (iv) cost efficiency. Spatial continuity is important for mapping gradients across entire water bodies. Temporal consistency is vital for the repeated autonomous missions to detect trends. Safety is crucial remote operation in contaminated or hazardous zones. Cost efficiency is critical for the reduced labor and fuel compared to manned boats. As demonstrated by Temilolorun & Singh (2024), a single low-cost USV can replace multiple manual field campaigns, providing equivalent data quality at a fraction of operational cost.

Water quality data collected by USVs feed directly into hydrodynamic and ecological models. Parameters like dissolved oxygen and nutrient concentrations inform models of eutrophication, while temperature and turbidity data are used for thermal and sediment transport modeling. Integrating USV data with modeling tools (e.g., MIKE ECO Lab, WASP) enhances predictive capacity for managing nutrient loading, pollution dispersion, and ecosystem restoration. The availability of high-frequency spatial data improves calibration and validation accuracy, leading to more reliable policy and management outcomes (Cheng et al., 2021).

USVs have redefined water quality assessment by delivering continuous, autonomous, and high-resolution monitoring across spatially complex and hazardous environments. Their ability to integrate multi-sensor payloads, transmit data in real time, and interface with hydrological models makes them indispensable for modern environmental management. Furthermore, the hydrological and ecological context described by Kale (2023) situates USVs within the urgent need for sustainable freshwater management in regions facing climate-induced hydrological stress (Ejder et al., 2016a, 2016b; Kale et al., 2016a, 2016b, 2018; Sönmez & Kale, 2020). Continuous, autonomous monitoring via USVs provides essential input for watershed modeling, pollution tracing, and climate impact assessments, aligning technological innovation with environmental policy (Anonymous, 2004; Akın & Akın, 2007). Kale (2020b) and Kale (2023) both stress that USVs not only enhance data availability but also democratize monitoring by reducing dependence on large budgets and extensive manpower, making environmental observation more inclusive and scalable. This interdisciplinary relevance underlines the potential of USVs to bridge environmental science, engineering, and sustainability policy.

Bathymetry and Hydrological Mapping

Accurate mapping of bathymetry and hydrodynamics is essential for inland water management, influencing flood modeling, navigation safety, and sediment management. USVs are ideal for this application because they can operate autonomously in shallow, confined, or inaccessible waters, where manned boats or aerial methods are impractical. Recent studies have shown that USVs equipped with sonar, LiDAR, and Ground Penetrating Radar (GPR) achieve bathymetric accuracies comparable to traditional hydrographic methods (Bandini et al., 2021).

Single-beam and multi-beam sonar systems remain the primary tools for bathymetry. Mounted beneath USVs, these systems measure water depth by calculating the time-of-flight of acoustic signals. When combined with GPS and IMU data, USVs can generate detailed 3D bathymetric maps suitable for hydrodynamic modeling and navigation planning. USVs also provide stable platforms for hydroacoustic mapping of sediment layers and submerged structures, as demonstrated by Chensky et al. (2021), whose catamaran vessel successfully conducted bottom profiling over 100 linear kilometers per day.

In a significant innovation, Bandini et al. (2021) demonstrated the use of drone-borne and water-coupled Ground Penetrating Radar (GPR) for inland water bathymetry mapping. Although originally tested on UAVs, similar technology is now being adapted for USVs. The study found that GPR achieved depth measurement accuracies of ±8 cm compared to RTK-GNSS benchmarks, outperforming sonar in vegetated or sediment-rich waters. USVs carrying GPR payloads can thus extend mapping capability to turbid or vegetated environments, where acoustic systems struggle.

In addition to static depth mapping, USVs can measure velocity fields and flow dynamics using Acoustic Doppler Current Profilers (ADCPs). These data are essential for calibrating hydraulic models, assessing sediment transport, and predicting pollutant dispersion. Unlike traditional ADCP deployment, USVs can repeatedly traverse transects without risking personnel safety, providing temporally resolved datasets during flood or drought events.

When integrated with satellite and aerial data, USV-based mapping contributes to multi-scale hydrological analysis. LiDAR data from UAVs or aircraft provide surface elevation, while USVs supply subsurface bathymetry, together forming high-resolution digital elevation models (DEMs). These combined datasets support flood risk modeling, erosion studies, and dam sedimentation assessment.

USV-based bathymetry and hydrological mapping combine the accuracy of in-situ measurements with the automation of robotics, providing rapid, safe, and cost-effective survey capabilities. They play a vital role in building accurate hydrodynamic models and ensuring safe navigation and flood resilience.

Environmental Surveillance and Pollution Tracking

Environmental surveillance requires continuous monitoring of pollution events and ecological changes in inland waters. USVs, with their autonomous mobility and sensor versatility, have emerged as ideal tools for detecting and tracking pollutants such as oil films, heavy metals, microplastics, and organic contaminants.

USVs can be pre-programmed to patrol predefined routes, detecting anomalies using onboard sensors and cameras. Machine vision, spectral sensors, and chemical detectors identify pollution sources and quantify concentrations. Advanced platforms like VIAM-USV2000 use real-time B-spline trajectory planning and set-based guidance to autonomously avoid obstacles while maintaining surveillance coverage (Tran et al., 2021). Optical and infrared cameras, combined with multispectral sensors, allow USVs to detect surface pollutants based on reflectance anomalies. Fluorometers detect hydrocarbons and oil traces in real time, while onboard AI classifies pollutant types and estimates extent. This approach supports early containment measures, reducing ecological damage. USVs equipped with electrochemical or spectrophotometric sensors can measure dissolved heavy metals (e.g., Pb, Cd, Hg) and chemical pollutants directly in the field. Data are transmitted to remote stations for automated mapping and correlation with upstream industrial discharges.

By connecting to Internet of Things (IoT) networks, USVs provide continuous data streams to cloud-based platforms, where anomalies trigger alerts for environmental agencies. This real-time capability transforms reactive pollution management into proactive prevention. Hybrid USV-UAV systems are also emerging, where drones provide aerial surveillance while USVs collect surface samples. USVs redefine environmental surveillance by enabling persistent, autonomous, and intelligent monitoring of pollutants. Their ability to detect, track, and quantify contaminants in real time supports rapid response, regulatory enforcement, and ecosystem protection.

Key Technological Developments and Case Studies

Sensor Integration and Data Fusion

Sensor integration and data fusion are at the heart of USV functionality, enabling the transformation of autonomous surface platforms into intelligent, multi-mission scientific instruments. USVs rely on an array of heterogeneous sensors, acoustic, optical, chemical, and environmental, to observe complex aquatic systems. The fusion of these data sources enhances accuracy, reliability, and interpretability, producing a cohesive environmental picture that supports modeling, management, and decision-making. Unlike traditional platforms, USVs must operate under dynamic environmental constraints (e.g., variable light, currents, or turbulence), requiring adaptive sensor systems capable of self-calibration and real-time correction. Recent developments in machine learning (ML), sensor fusion algorithms, and modular payload systems have elevated USVs from passive collectors of data to active, context-aware monitoring agents (Cheng et al., 2021).

Modern USVs carry multiparameter sondes, fluorometers, and spectrometers for measuring dissolved oxygen, pH, turbidity, chlorophyll-a, nitrates, and heavy metals. Temilolorun & Singh (2024) demonstrated a cost-efficient 3D-printed catamaran equipped with a two-layer control framework and EKF-based sensor fusion, achieving stable localization and environmental data collection in aquaculture ponds.

Visual, LiDAR, radar, and sonar sensors are fundamental for navigation and obstacle detection. The USVInland dataset by Cheng et al. (2021) integrates multisensor recordings, LiDAR, stereo cameras, millimeter-wave radar, and IMUs, across diverse inland water environments, forming a global benchmark for perception research. These systems enable Simultaneous Localization and Mapping (SLAM) and terrain segmentation, vital for safe navigation in GPS-denied waterways.

USVs frequently integrate multi-beam echosounders or side-scan sonar to map underwater terrain, sediment composition, and submerged structures. Chensky et al. (2021) demonstrated that a small catamaran USV equipped with sonar and GPS could autonomously map 15 km^2 of reservoir bathymetry with 2-meter accuracy.

Data fusion integrates heterogeneous sensor outputs to produce coherent, accurate, and reliable environmental representations. Techniques include (i) extended and unscented Kalman filters (EKF, UKF) for real-time state estimation, (ii) particle filters for non-linear data integration, (iii) Bayesian fusion for probabilistic sensor weighting, and (iv) deep learning architectures for multi-modal data alignment. Yin et al. (2022) applied deep learning for shoreline detection, fusing visual and contextual data within an enhanced Pyramid Scene Parsing Network (PSPNet), achieving 98.4% accuracy in complex river scenes. This method exemplifies the fusion of perception and semantic segmentation critical for autonomous water navigation. Despite progress, challenges remain in sensor calibration (especially for pH, DO, and conductivity probes subject to drift and fouling), data synchronization between sensors operating at different frequencies, and environmental interference (reflections, turbidity, and vegetation cause noise in acoustic and optical sensors). To mitigate these, researchers employ redundant sensing and cross-validation, for instance, combining sonar with LiDAR to compensate for optical noise in turbid conditions (Cheng et al., 2021). Integrated multi-sensor payloads and robust fusion algorithms enable USVs to produce comprehensive, high-fidelity environmental datasets. By fusing chemical, acoustic, and visual data streams, USVs achieve unprecedented situational awareness, laying the foundation for autonomous monitoring networks.

Autonomy and Obstacle Avoidance in Confined Environments

Inland waterways differ fundamentally from open-sea environments: they are narrow, shallow, and cluttered with natural and anthropogenic obstacles (banks, bridges, debris). Safe autonomous operation in such domains requires robust perception, real-time decision-making, and advanced control algorithms. Recent developments in AI-based navigation and reinforcement learning have greatly improved USV autonomy in confined and GPS-denied conditions (Yin et al., 2022).

Path planning in confined waterways must consider bank effects, shallow water hydrodynamics, and dynamic obstacles (floating debris, other vessels). Zhao et al. (2023) proposed the Greedy Partheno Genetic Algorithm (GPGA) integrated with Nonlinear Model Predictive Control (NMPC), ensuring smooth trajectories while respecting kinematic constraints. The GPGA enabled multi-USV coordination by balancing exploration (coverage) and exploitation (efficiency), outperforming traditional A* and Dijkstra algorithms.

Deep neural networks now enable USVs to recognize and react to environmental features in real time. Yin et al. (2022) improved PSPNet with Convolutional Block Attention Modules (CBAM), enabling accurate shoreline segmentation even under reflective and foggy conditions that essential for navigation safety. Similarly, Cheng et al. (2021) showed that fusing radar and stereo imagery significantly improved detection of obstacles obscured by water reflections. These innovations provide the semantic understanding required for advanced autonomy, moving beyond reactive control to context-aware navigation.

The next frontier is multi-USV cooperation, where fleets perform distributed monitoring. Zhao et al. (2023) and Peeters et al. (2020) explored cooperative path planning and fleet supervision through shore-based control centers. In such systems, autonomy is distributed, each USV independently navigates while sharing positional and sensory data for collective optimization. This approach improves spatial coverage and resilience to single-vessel failures.

The VIAM-USV2000, developed by Tran et al. (2021), represents a landmark in autonomous navigation within confined rivers. It incorporates (i) B-spline trajectory generation for smooth path planning, (ii) set-based guidance for dynamic obstacle avoidance, (iii) integrated IMU and GPS fusion for robust localization. Field experiments in Vietnamese rivers demonstrated real-time adaptive navigation, validating the feasibility of full autonomy in constrained inland environments.

Autonomous navigation and obstacle avoidance have matured from reactive rule-based systems to AI-driven adaptive architectures. Through sensor fusion, deep learning, and cooperative control, modern USVs navigate safely in highly dynamic inland conditions, laying the groundwork for fully autonomous hydrological monitoring fleets.

Notable Prototypes and Experimental Systems

Numerous research groups and commercial entities have developed experimental USVs to test design hypotheses, control systems, and mission capabilities. These prototypes demonstrate the evolution from remote-controlled vessels to intelligent autonomous systems optimized for inland monitoring.

Peeters et al. (2020) developed the Hull-to-Hull experimental platform, part of the European Watertruck+ initiative, to explore automation in inland cargo vessels. The prototype featured 360° steerable thrusters and hierarchical control integrating MOOS-IvP software. Experimental trials confirmed reliable autonomy in riverine conditions, marking an important step toward unmanned inland transportation.

Chensky et al. (2021) introduced an ultra-small solar-powered USV for autonomous mapping and water quality assessment in Siberia's Irkutsk Reservoir. It achieved continuous operation for several days using photovoltaic panels and Li-ion batteries, performing hydroacoustic mapping and environmental sampling autonomously. This vessel represents a sustainable approach to long-duration monitoring in remote regions.

The USVInland platform (Cheng et al., 2021) provides the world's first multisensor dataset for inland navigation research. Covering over 26 km of riverine environments, it incorporates LiDAR, radar, stereo cameras, GPS, and IMUs. This dataset underpins numerous research efforts in SLAM, water segmentation, and perception, effectively setting the benchmark for inland USV research. As discussed, the VIAM-USV2000 prototype demonstrated advanced maneuverability and obstacle avoidance in confined rivers using AI-assisted navigation. Its modular design, compact frame, and advanced autonomy stack position it as a leading experimental system for tropical inland waters (Tran et al., 2021).

Temilolorun & Singh (2024) designed a 3D-printed twin-hull USV using off-the-shelf electronics, demonstrating that effective water quality monitoring can be achieved for under USD 1000. Their open-source framework (built on ROS) allows local customization, making autonomous water monitoring accessible in developing regions which is an essential step toward equitable water governance.

Karetnikov et al. (2022) developed a standardized test water zone for evaluating unmanned and self-piloted vessels. The site features independent bow and stern tracking systems and enhanced safety protocols. This infrastructure provides a blueprint for future certification and benchmarking of USVs under controlled conditions.

The broader scientific discourse reinforces this trend. Early projects such as ROAZ (Portugal), Springer (UK), Charlie (Italy), and Measuring Dolphin (Germany) established the foundation for modern USV design and environmental application (Caccia et al., 2005, 2008; Naeem et al., 2006; Martins et al., 2007). These systems integrated modular sensors for bathymetry, current profiling, and pollutant detection, capabilities that today are enhanced through artificial intelligence, allowing for adaptive sampling strategies and autonomous mission planning (Curcio et al., 2005; Caccia et al., 2009). Kale (2020b) also noted that these international developments inspired local Turkish efforts such as GLOBİDA and LEVENT, pioneering national-level autonomous marine platforms (Gözcelioğlu, 2010; ASELSAN, 2013). Such initiatives exemplify how global advances in USV design have catalyzed regional innovation, aligning with Turkey's strategic efforts to enhance technological independence in environmental observation.

From experimental prototypes to sustainable, deployable systems, the last decade has seen extraordinary progress in USV technology. Advances in control systems, autonomy, and energy efficiency have transformed USVs into reliable research platforms capable of operating independently in inland waterways. The cumulative outcome is a new generation of smart, modular, and scalable robotic systems central to the future of environmental monitoring.

Challenges and Limitations

Technical Challenges: GPS Denial, Reflections, and Shallow Water Navigation

Despite remarkable technological advances, USVs face persistent technical constraints that complicate their deployment in inland water monitoring. While oceanic environments are largely open and homogeneous, inland waterways are often narrow, dynamic, and cluttered, featuring banks, bridges, vegetation, submerged debris, and high levels of electromagnetic and acoustic interference. These complexities impose significant challenges for navigation, positioning, and sensing (Cheng et al., 2021).

Accurate localization is a prerequisite for autonomous navigation and data georeferencing. However, inland waterways often present "GPS-denied" environments, especially in urban canals, mountain valleys, and areas with dense vegetation or overhead bridges. GPS signals may be obstructed or distorted by multipath interference, where signals reflect off water or nearby structures, causing erroneous position estimates. In small rivers with high banks or dense foliage, position errors exceeding ±10 meters are common (Cheng et al., 2021). To mitigate this, USVs use sensor fusion techniques, integrating inertial measurement units (IMUs), Doppler velocity logs (DVLs), and visual odometry systems. The USVInland dataset (Cheng et al., 2021) was developed precisely to support the training and validation of algorithms that compensate for GPS loss through Simultaneous Localization and Mapping (SLAM) approaches. Nevertheless, drift accumulation in IMU-based dead reckoning remains a major limitation, particularly in missions exceeding several hours without satellite correction. Emerging research focuses on visual-inertial SLAM, LiDAR odometry, and acoustic beacon networks to improve reliability, yet no universally robust solution exists for all environmental conditions.

Optical and acoustic sensors suffer significant degradation due to reflections, turbidity, and wave disturbance. LiDAR systems, for example, may misinterpret specular reflections from the water surface as false obstacles, while sonar readings can be distorted by acoustic reverberation and air bubbles (Yin et al., 2022). Yin et al. (2022) addressed this by training a deep-learning shoreline segmentation network (PSPNet-CBAM) to distinguish between real shoreline features and reflection artifacts, improving detection accuracy to 96.9%. However, such AI-driven perception models require large, well-annotated datasets, which remain scarce for inland environments. For sonar-based systems, shallow waters present additional challenges due to multi-path echoes and bottom reverberation, which reduce the accuracy of bathymetric and obstacle detection. Filtering techniques, such as adaptive beamforming and wavelet denoising, have been proposed, but their computational cost can limit real-time applicability on small USVs with constrained onboard processors.

Operating in shallow waters introduces nonlinear hydrodynamic effects, including increased viscous drag, squat phenomena, and unsteady flow separation around the hull. These factors not only affect propulsion efficiency but also disturb sensor readings (e.g., turbidity sensors affected by propeller-induced resuspension). Zhang et al. (2024) developed a maneuvering model for shallow, confined waterways that accounts for bank effects, bottom proximity, and low Reynolds-number flow conditions. Their model revealed that lateral stability and turning performance decrease by up to 40% in water depths less than twice the vessel's draft, a critical consideration for small, heavily instrumented USVs. Additionally, biofouling and debris entanglement can hinder sensors and propulsion, particularly in vegetated or polluted canals. Regular maintenance and self-cleaning systems are required but add complexity and cost.

In urban areas, USVs face interference from radio, cellular, and industrial electromagnetic fields, which can disrupt communication and onboard electronics. Acoustic sensors are also affected by anthropogenic noise from shipping, dredging, or hydropower operations. These interferences reduce signal-to-noise ratios, complicating navigation and environmental data acquisition. Future systems may adopt spread-spectrum communication protocols, frequency hopping, or acoustic shielding to mitigate these problems, but practical implementation remains limited.

Technical limitations, ranging from signal degradation and hydrodynamic instability to environmental interference, remain major barriers to fully autonomous inland water operations. Addressing these challenges will require advances in sensor fusion, adaptive control, and resilient communication to ensure robust performance under complex field conditions.

Safety, Regulatory, and Operational Issues

Beyond technical constraints, safety and regulation represent significant barriers to the widespread deployment of USVs in inland waters. Although maritime automation has matured in ocean shipping, inland waterways remain legally and institutionally unprepared for crewless operations. The coexistence of autonomous and manned vessels in congested river systems introduces ethical, legal, and operational complexities that current frameworks only partially address (Nzengu et al., 2021).

In most jurisdictions, navigation laws assume human presence onboard vessels. This presents challenges for certification, collision liability, and insurance for USVs. Nzengu et al. (2021) highlighted that European Union inland navigation codes lack clear definitions for unmanned operation, making regulatory approval ambiguous or impossible. Moreover, communication protocols and data integrity requirements are not standardized across national agencies, leading to inconsistencies in data reporting and system interoperability. Without harmonized rules, cross-border research and environmental monitoring remain bureaucratically constrained.

Safety risks in USV operation can arise from:

(i) Loss of control due to communication failure
(ii) Collision with manned vessels or infrastructure
(iii) Environmental hazards such as floating debris or weather extremes.

Peeters et al. (2020) addressed these concerns by developing a shore-based control architecture capable of monitoring and overriding autonomous operations. Their Inland Shore Control Centre (I-SCC) ensured human oversight for safety-critical missions, representing a transitional framework toward fully autonomous yet accountable systems.

Zhang et al. (2019) used fuzzy Bayesian networks to model safety risk in unmanned inland ships. Their analysis revealed that human–machine interaction, software reliability, and environmental perception accuracy were the most influential risk factors. The study recommended multi-layer redundancy in sensors and communication systems to achieve safety equivalence with manned operations.

Autonomous decision-making introduces questions of liability and accountability. If an unmanned vessel causes environmental harm or collision, determining responsibility, whether human, institutional, or algorithmic, remains legally ambiguous. Additionally, the use of AI-based decision systems raises ethical issues regarding transparency, bias, and explainability. As regulatory frameworks evolve, they must address (i) certification of autonomy algorithms, (ii) ethical data governance and privacy, and (iii) human oversight and intervention rights. International bodies such as the International Maritime Organization (IMO) and Central Commission for the Navigation of the Rhine (CCNR) are beginning to discuss amendments to inland navigation codes to account for autonomous operation.

Operational challenges include maintenance, deployment, and retrieval. Unlike large oceanic vessels, small USVs have limited payload and battery capacity, requiring frequent recovery and servicing. In field deployments, biofouling, sensor clogging, and battery degradation are recurrent issues. Logistical support infrastructure, docks, charging stations, and remote control hubs, remains underdeveloped, especially in developing regions. Hybrid solutions, such as mobile docking buoys or autonomous recharging stations, are being explored to extend mission endurance but are not yet commercially viable. Regulatory and operational barriers currently limit the full integration of USVs into inland water monitoring systems. Establishing standardized frameworks for safety, liability, and operation will be critical to scaling autonomous monitoring technologies globally.

Data Reliability and Integration into Existing Monitoring Frameworks

Data generated by USVs must be accurate, reliable, and compatible with existing hydrological information systems (HIS) and environmental monitoring networks. However, variability in sensor calibration, communication protocols, and metadata standards poses major challenges for data integration and long-term usability (Peeters et al., 2020).

Water quality sensors are prone to drift, fouling, and temperature dependency. Regular calibration is essential but challenging during autonomous operations. Some systems employ in-situ calibration routines using onboard reference standards, while others rely on machine learning models trained to detect anomalies in sensor behavior. Chensky et al. (2021) highlighted those long-term deployments in natural waters often lead to progressive biofilm formation, requiring either anti-fouling coatings or periodic mechanical cleaning.

Different USV manufacturers and research groups employ heterogeneous data formats, making interoperability a persistent problem. The lack of standardization complicates integration into national databases such as HydroMet or EU WISE systems. Adopting open data formats (e.g., CSV, HDF5) and interoperable metadata standards (ISO 19115, INSPIRE) is therefore essential. Emerging frameworks based on the Sensor Observation Service (SOS) and Internet of Things (IoT) protocols are being used to standardize real-time data sharing among autonomous platforms.

As USVs increasingly rely on wireless communication, data integrity and cybersecurity become critical concerns. Potential risks include signal jamming, spoofing, or data tampering, which could compromise mission safety and scientific reliability. Encryption protocols and secure transmission channels (TLS, VPNs) must therefore be standard components of USV communication architectures. Additionally, packet loss and latency in cellular or satellite links can lead to data gaps. Redundant local storage and store-and-forward mechanisms mitigate this issue but add hardware complexity.

Integrating USV data into hydrological models and decision support systems enhances predictive analytics for flood forecasting, pollution management, and resource planning. However, this requires consistent temporal and spatial referencing, as well as data harmonization across sensors and models. Efforts such as the USVInland and AUTOSHIP projects have pioneered integration frameworks, linking autonomous observations to digital twins of inland waterways. These digital replicas use real-time USV inputs to simulate hydrodynamic and ecological processes, improving management decisions and policy development (Cheng et al., 2021). Reliable data collection and integration remain essential but underdeveloped aspects of USV operations. Achieving consistent calibration, standardization, and interoperability across systems will be key to leveraging autonomous technologies for large-scale, data-driven water governance.

Future Directions

Artificial Intelligence and Machine Learning for Autonomous Decision-Making

Artificial Intelligence (AI) and Machine Learning (ML) are redefining the operational paradigm of USVs, transitioning them from reactive robotic systems to predictive, adaptive, and context-aware agents. Traditional control architectures relied on deterministic models and rule-based navigation; however, these approaches are limited in complex inland environments characterized by dynamic currents, obstacles, and uncertain sensory data. Recent research demonstrates that AI can enhance every layer of USV autonomy, including perception, navigation, mission planning, and environmental interpretation (Yin et al., 2022).

The first critical domain for AI in USVs is environmental perception, particularly in visually and acoustically complex inland waterways. Deep learning (DL) architectures such as Convolutional Neural Networks (CNNs), U-Nets, and Transformers are increasingly used for shoreline detection, obstacle recognition, and semantic segmentation of water scenes. Yin et al. (2022) enhanced the PSPNet framework by integrating Convolutional Block Attention Modules (CBAM), enabling improved shoreline extraction accuracy even in poor weather and high-reflectance conditions (96.9% accuracy). This capability allows USVs to discern between water surface, vegetation, and artificial structures which is an essential requirement for autonomous path planning. Moreover, LiDAR-camera fusion networks trained on datasets like USVInland (Cheng et al., 2021) provide enhanced perception in GPS-denied areas, enabling real-time obstacle classification and hydrological feature identification.

Reinforcement Learning (RL) represents one of the most transformative approaches for autonomous control. By enabling USVs to learn optimal navigation policies through trial and error, RL bypasses the need for explicit environmental modeling. Recent applications include:

(i) Deep Q-Learning (DQL) for adaptive obstacle avoidance
(ii) Policy Gradient methods for dynamic trajectory optimization
(iii) Multi-agent reinforcement learning (MARL) for cooperative fleet coordination.

Zhao et al. (2023) developed a hybrid GPGA-NMPC approach that blends RL-based adaptation with traditional control theory, achieving smoother and more energy-efficient navigation trajectories. Future work may involve transfer learning, allowing USVs trained in simulation to operate efficiently in real-world conditions.

AI also enables predictive maintenance and anomaly detection in USV operations. Machine learning models trained on telemetry data can forecast component failures, battery degradation, and sensor drift, allowing proactive maintenance scheduling. In environmental monitoring, ML algorithms can automatically identify deviations in water quality parameters, including detecting emerging pollution events or ecological anomalies before they become critical. Integration of such systems into Internet of Things (IoT) frameworks facilitates real-time alerts and adaptive mission planning (Temilolorun & Singh, 2024).

As AI-driven autonomy becomes central to decision-making, transparency and explainability emerge as critical concerns. Explainable AI (XAI) frameworks aim to make algorithmic decisions interpretable, ensuring accountability in safety-critical scenarios (e.g., collision avoidance, pollutant identification). For environmental governance, explainable decision logic is essential for regulatory compliance and public trust. Ethical frameworks must also address issues of data privacy, bias, and algorithmic fairness, particularly when USVs are deployed in sensitive ecological or industrial regions. Recent advances highlight AI-based autonomy, swarm coordination, and energy sustainability as future research frontiers. Kale (2023) notes that swarm-enabled cooperative USVs can simultaneously map vast water bodies while dynamically sharing information, improving both spatial coverage and system robustness. These directions build upon early efforts in cooperative multi-robot systems (Pascoal et al., 2006) and adaptive control (Breivik, 2010), extending them to multi-USV coordination under uncertain inland environments. Combined with renewable energy systems (e.g., solar or hybrid electric propulsion), these features contribute to reduced operational carbon footprints and support global sustainability goals. Importantly, the inclusion of machine learning in sensor calibration and anomaly detection allows USVs to autonomously detect pollution events or hydrological changes, representing a new generation of intelligent, adaptive monitoring platforms (Demetillo & Taboada, 2019; Kale, 2023). Such advances, echoing the early frameworks by Pascoal et al. (2006) and Caccia et al. (2008), demonstrate that autonomous surface platforms are evolving into resilient, networked agents of environmental intelligence.

Cooperative Multi-USV Systems for Large-Scale Monitoring

While single USVs provide valuable localized data, cooperative multi-USV systems (also known as USV swarms or fleets) offer scalable solutions for large-scale, high-resolution monitoring. By distributing sensing tasks among multiple coordinated vessels, researchers can drastically reduce mission time while increasing spatial coverage and redundancy (Zhao et al., 2023). This concept aligns with broader trends in networked robotics and distributed artificial intelligence, enabling autonomous collaboration among multiple USVs for mapping, water quality assessment, and pollution tracking.

Multi-USV systems rely on multi-agent coordination algorithms that govern task allocation, formation control, and collision avoidance. Communication is typically achieved through ad hoc mesh networks, allowing peer-to-peer data exchange even without central control. Zhao et al. (2023) proposed a Greedy Partheno Genetic Algorithm (GPGA) that optimizes mission allocation in heterogeneous USV fleets. By combining global optimization with local autonomy, fleets can collectively survey large rivers or reservoirs while maintaining efficient coverage and minimal redundancy. Such distributed autonomy frameworks are critical for adaptive missions, for instance, when one USV detects a pollution plume, it can alert neighboring vessels to converge for detailed sampling.

As the number of autonomous vessels increases, human oversight transitions from direct control to fleet-level supervision. Peeters et al. (2020) introduced the Inland Shore Control Centre (I-SCC) concept, where operators monitor multiple USVs via a unified interface, intervening only in exceptional circumstances. This "human-on-the-loop" model ensures safety while allowing scalability, where one operator can oversee 5-10 USVs simultaneously.

Cooperation is not limited to USVs alone; integrated USV-UAV (drone) systems are emerging as hybrid solutions. UAVs provide aerial imagery and situational awareness, while USVs perform in-situ sampling. Data fusion between aerial and surface perspectives enhances accuracy and efficiency, creating comprehensive spatiotemporal datasets for water management and pollution surveillance.

Cooperative multi-USV systems represent the future of scalable, resilient, and intelligent monitoring. By leveraging swarm intelligence, distributed AI, and hybrid control architectures, these fleets can transform inland water monitoring from isolated observations into dynamic, networked environmental intelligence systems.

Regulatory Evolution and Sustainable Implementation

Technological innovation alone cannot ensure the sustainable adoption of USVs. Equally important are regulatory adaptation, ethical oversight, and socio-environmental sustainability. As USVs become integral to environmental monitoring, their operation must align with international standards, legal frameworks, and sustainability goals (Nzengu et al., 2021).

Different nations maintain varying maritime regulations, many of which were drafted before the advent of autonomous vessels. To facilitate cross-border research and data sharing, regulatory harmonization is necessary. The European Union's AUTOSHIP Project and IMO's MASS

(Maritime Autonomous Surface Ships) initiative are pioneering frameworks for certifying autonomy levels and communication protocols. Nzengu et al. (2021) emphasized that establishing performance-based standards, rather than prescriptive rules, can accelerate innovation while ensuring safety. These frameworks should include certification for AI algorithms, redundancy requirements, and clear definitions of remote supervision responsibilities.

Sustainability involves minimizing the ecological footprint of USV operations. Solar-powered and hybrid USVs, such as the one developed by Chensky et al. (2021), exemplify low-emission monitoring. Incorporating renewable energy and recyclable materials aligns with UN SDG 13 (Climate Action) and SDG 14 (Life Below Water). Furthermore, open-source, low-cost USV designs like Temilolorun & Singh (2024) promote technological democratization, enabling developing regions to participate in autonomous water monitoring without high capital investment. This inclusivity strengthens global environmental governance and capacity-building.

As USVs collect vast amounts of environmental and potentially sensitive industrial data, ethical data management is crucial. Policies must ensure transparency, protect local communities' rights, and prevent misuse of collected data. Establishing open-data repositories with standardized metadata and quality assurance protocols promotes scientific reproducibility and global collaboration. Additionally, as AI-driven systems make autonomous decisions, regulations must address algorithmic accountability, ensuring that decisions are auditable, explainable, and aligned with ethical standards.

For USVs to become mainstream, they must integrate into existing hydrological and environmental monitoring frameworks. This requires institutional coordination among research institutes, regulatory agencies, and local authorities. Infrastructure such as docking stations, remote control hubs, and maintenance facilities must also evolve to support continuous USV operation. Governments and NGOs can facilitate adoption through pilot programs, shared data initiatives, and incentive structures promoting automation in water resource management.

The future of inland water monitoring lies in autonomous, sustainable, and cooperative systems that blend technological sophistication with ethical governance. USVs will function as integral nodes within digital twin ecosystems, continuously updating hydrological models and environmental databases. This will enable real-time environmental intelligence, transforming how societies monitor, manage, and protect freshwater resources.

The convergence of technological innovation, regulatory reform, and sustainability principles will define the next decade of USV development. By embedding AI ethics, renewable energy, and cooperative frameworks into their design and governance, USVs can become pivotal tools for sustainable and equitable water management. The technical, regulatory, and data-related challenges outlined above collectively constrain the scalability of USVs in inland water monitoring. Addressing these requires not only technological innovation but also institutional adaptation, cross-disciplinary collaboration, and international standardization.

Over the past two decades, USVs have emerged as one of the most transformative technologies in hydrological and environmental monitoring. This chapter has explored the conceptual foundations, technological evolution, and multidisciplinary applications of USVs in inland water systems which are environments characterized by spatial heterogeneity, dynamic hydrodynamics, and pressing environmental stressors. The evidence synthesized from engineering, environmental science, and policy literature demonstrates that USVs are transitioning from experimental prototypes to operationally mature monitoring platforms, bridging critical gaps in data availability, spatial resolution, and sustainability (Chensky et al., 2021).

Technological advances in design and control architecture have provided USVs with the capacity to operate safely and autonomously in complex inland environments. From early radio-controlled boats to AI-enhanced autonomous systems, progress has been marked by:

(i) Modular hull designs (catamaran, trimaran, and monohull) optimized for stability and energy efficiency (Peeters et al., 2019)
(ii) Hierarchical control architectures integrating mission planning, supervisory coordination, and low-level actuation (Peeters et al., 2020)

(iii) Advanced perception systems using LiDAR, radar, and deep-learning-enhanced vision (Yin et al., 2022)
(iv) Renewable and hybrid propulsion systems ensuring sustainable, long-endurance missions (Chensky et al., 2021).

Together, these developments have established the engineering foundation for robust, modular, and scalable USVs capable of fulfilling both scientific and operational missions.

USVs support a diverse range of environmental and hydrological applications:

(i) *Water Quality Assessment*: Autonomous platforms collect high-frequency, multi-parameter water quality data, such as dissolved oxygen, nutrients, and chlorophyll-a, allowing for real-time mapping of pollution gradients and algal blooms (Temilolorun & Singh, 2024).
(ii) *Bathymetry and Hydrodynamics*: Equipped with sonar and LiDAR, USVs generate precise bathymetric maps and velocity profiles, facilitating flood risk assessment, sediment transport modeling, and infrastructure inspection (Bandini et al., 2021).
(iii) *Environmental Surveillance*: Through sensor fusion and AI analytics, USVs autonomously detect and track pollutants, from oil slicks to heavy metals, integrating seamlessly into early warning systems (Tran et al., 2021).

These applications collectively redefine inland monitoring from static observation to dynamic, real-time environmental intelligence.

Recent technological breakthroughs have strengthened USV capabilities in three major domains:

(i) *Sensor Integration and Data Fusion*: Advanced fusion algorithms (EKF, Bayesian, deep-learning-based) combine multi-modal sensor data, acoustic, optical, and chemical, into coherent environmental representations (Cheng et al., 2021).
(ii) *Autonomy and Obstacle Avoidance*: Deep reinforcement learning and predictive control allow real-time adaptation to

complex hydrodynamic conditions and moving obstacles (Zhao et al., 2023).

(iii) *Sustainable Power Systems*: Solar and hybrid-electric propulsion, combined with intelligent energy management, extend mission endurance and reduce environmental footprint (Chensky et al., 2021).

These developments position USVs as cornerstones of autonomous environmental sensing networks, capable of continuous operation and scalable deployment.

Despite their promise, USVs face limitations that must be addressed for widespread adoption:

(i) *Technical Constraints*: GPS denial, sensor interference, and hydrodynamic instability in shallow waters remain major barriers (Cheng et al., 2021).

(ii) *Regulatory and Safety Gaps*: Most national and international frameworks lack provisions for autonomous vessel operation, particularly regarding liability, certification, and communication protocols (Nzengu et al., 2021).

(iii) *Data Integration Issues*: Inconsistent metadata standards, calibration challenges, and cybersecurity risks limit interoperability with existing hydrological databases (Peeters et al., 2020).

Addressing these issues will require cross-disciplinary collaboration, regulatory reform, and technological innovation.

The future of inland water management lies in digitally integrated hydrological systems powered by autonomous sensing. USVs are envisioned as mobile nodes within real-time environmental data networks, complementing satellite and UAV observations. Such integration supports digital twins of river basins and reservoirs that continuously assimilate sensor data to predict floods, pollution events, and ecological changes (Cheng et al., 2021).

AI-driven data fusion will underpin the next generation of USV-based monitoring systems. By combining data from multiple autonomous platforms, surface, aerial, and subsurface, AI will enable multi-scale, multi-modal environmental modeling. Adaptive algorithms will dynamically adjust sampling density, prioritize hotspots, and optimize routes based on real-time environmental feedback. In this context, AI ceases to be merely a control mechanism and becomes a collaborative partner in scientific discovery, which is interpreting, predicting, and even hypothesizing environmental phenomena.

Future inland monitoring will increasingly rely on cooperative multi-USV systems operating in decentralized networks. Using blockchain-inspired consensus mechanisms and edge computing, USV fleets will share environmental data securely and autonomously coordinate missions. This distributed model will enhance resilience, reduce latency, and eliminate dependency on central command centers (Zhao et al., 2023). In large river basins such as the Amazon, Mekong, or Nile, cooperative fleets could enable basin-scale continuous monitoring that previously impossible with manned operations.

Technological development must progress in parallel with policy and governance innovation. Regulatory frameworks must balance innovation with accountability, ensuring that autonomy does not compromise safety, transparency, or public trust. Ethical governance should include:

(i) Algorithmic transparency and auditability
(ii) Data sovereignty and access equity
(iii) Sustainability principles embedded in design and operation.

The policy discourse should frame USVs not merely as tools but as instruments of environmental stewardship, contributing to global commitments such as the UN Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation) and SDG 13 (Climate Action).

Climate change amplifies the need for adaptive and resilient water monitoring systems.

Extreme hydrological events, floods, droughts, pollution spills, demand continuous, autonomous observation capacity. Solar- and hydrogen-powered USVs, operating as part of multi-platform sensor networks, can provide real-time resilience intelligence for policymakers, helping communities anticipate and mitigate environmental disasters (Chensky et al., 2021). Moreover, by reducing the carbon footprint of monitoring operations, renewable USV fleets align with the broader goals of sustainable infrastructure and decarbonized science.

One of the most promising trends is the democratization of USV technology. Low-cost, open-source designs, like those developed by Temilolorun & Singh (2024), allow communities, universities, and small research institutions to participate in autonomous monitoring without major financial barriers. Such inclusivity fosters data equity and participatory environmental management, ensuring that autonomous monitoring contributes to global justice rather than technological disparity.

The full potential of USVs can only be realized through collaboration across disciplines (i) engineers to improve design and autonomy, (ii) hydrologists and ecologists to define relevant environmental parameters, (iii) computer scientists to advance data analytics, and (iv) policy experts to craft adaptive governance frameworks. This convergence mirrors the broader transition toward systems thinking in environmental management, where technology, data, and policy are integrated into a unified vision of planetary stewardship.

Inland water systems are lifelines for human civilization and biodiversity. Their health, however, is increasingly threatened by pollution, climate change, and unsustainable resource use. USVs represent a new frontier in environmental science and technology that autonomous partners capable of tirelessly monitoring, learning, and responding to environmental dynamics. The convergence of robotics, AI, and sustainability will give rise to a global network of intelligent aquatic observers which is forming the backbone of a planetary environmental observatory. This vision is not merely technological; it is ecological, ethical, and profoundly human, reflecting our collective responsibility to preserve the Earth's most vital resource: water.

In conclusion,

(i) Technological innovation has rendered USVs reliable, modular, and sustainable tools for inland monitoring.

(ii) Artificial intelligence and data fusion are unlocking autonomous decision-making and real-time environmental prediction.
(iii) Regulatory and ethical evolution are needed to ensure safe, transparent, and equitable deployment.
(iv) Sustainability and cooperation will define the long-term success of USV-based monitoring networks.

As we look to the future, USVs will not merely measure water; they will empower humanity to understand, protect, and manage it responsibly.

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