PHYTOPLANKTON DIVERSITY, SEASONAL DYNAMICS, AND TROPHIC LINKAGES TO FISH PRODUCTIVITY IN THE CASPIAN SEA: A REVIEW

Tajruba Rzayeva Verdizade[1], Mahmud Humbatov[1], Konul Ahmadova[1*], Shabnam Farzali[2]

[1] Western Caspian University, AZ1001, Baku, Azerbaijan
[2] Department of Aquaculture and Fish Diseases, Fisheries Faculty, Firat University, 23200, Elazig, Türkiye

Abstract: As the world's largest enclosed water body, the Caspian Sea possesses a unique ecosystem and significant economic value. Phytoplankton, as primary producers forming the foundation of the pelagic food web, play a fundamental role in shaping the biological productivity and ecological status of this semi-enclosed sea. This review article synthesizes existing scientific knowledge on the species diversity, seasonal dynamics, interactions with key ecological factors, and impacts on fish stocks of phytoplankton communities in the Caspian Sea. The phytoplankton composition is mainly represented by diatoms (Bacillariophyta), dinoflagellates (Dinophyta), cyanobacteria, and green algae (Chlorophyta). Seasonal variability is clearly expressed: diatoms dominate during spring and autumn blooms, while rising temperatures and nutrient enrichment during summer months lead to the massive development of cyanobacteria and dinoflagellates. Recent climate changes, particularly the increase in sea surface temperature (more than 30°C), changes in salinity, and the influence of photosynthetically active radiation, have intensified eutrophication processes and increased the frequency of harmful algal blooms (e.g., *Pseudo-nitzschia seriata, Nodularia spumigena*). These changes exert cascading effects on zooplankton communities and, consequently, on commercially important fish stocks (kilka, sturgeon, and the Caspian seal). Monitoring phytoplankton dynamics is essential for the sustainable management of the Caspian Sea's biological resources and for ecosystem-based conservation strategies.
Keywords: biodiversity, eutrophication, climate change, fish productivity, harmful algal blooms.

Corresponding author: konul.akhmedova@wcu.edu.az

Received: 13 May 2026 **Accepted: 1 June 2026** **Published: 30 June 2026**

DOI: 10.54414/BUZS7588

Introduction

With an area of approximately 370,000 km^2 and depths exceeding 1,000 meters, the Caspian Sea is the world's largest enclosed water body. Its distinctive hydrological regime – characterized by a negative water balance, persistent sea-level fluctuations, and a salinity gradient ranging from less than 1% in the north to approximately 13%

in the south – has shaped a biota with high endemism and considerable economic significance (Aladin & Plotnikov 2004; Zonn et al. 2005). The sea's fisheries, particularly sturgeon, which supply over 90% of the world's caviar production, as well as kilka and other commercial species, have played a vital role in the economies of the littoral states for centuries (Dumont 2005; Wootton 1998).

Phytoplankton, as the primary producers, constitutes the foundation of the entire pelagic food web in the Caspian Sea (Falkowski & Raven 2007; Reynolds 2006). These microscopic photosynthetic organisms convert solar energy into organic matter, release oxygen, and create a food base for zooplankton, fish larvae, and higher trophic levels (Kirk 2011; Parsons et al. 1984). The composition, abundance, and seasonal succession of phytoplankton are sensitive indicators of environmental change; they respond rapidly to variations in temperature, light, nutrient availability, and salinity (Harris 1986; Wetzel 2001). For this reason, phytoplankton is widely used as reliable bioindicators in assessing water quality, eutrophication levels, and overall ecosystem health (Anderson et al. 2002; Paerl & Otten 2013).

In recent decades, the Caspian Sea ecosystem has undergone significant transformation under the combined influence of climate change and anthropogenic pressures (Kostianoy & Kosarev 2005; Zonn et al. 2010). Rising global temperatures have elevated sea surface temperatures, altered stratification regimes, and affected the timing and intensity of phytoplankton blooms (Behrenfeld et al. 2006; Fendereski 2025). Concurrently, agricultural runoff, industrial effluents, and domestic wastewater, particularly via the Volga River, which supplies approximately 80% of the sea's freshwater inflow, have increased nutrient loads (nitrogen and phosphorus), accelerating eutrophication processes (Heidari et al. 2018; Smith et al. 1999). Furthermore, the introduction of the invasive ctenophore *Mnemiopsis leidyi* in the 1990s drastically altered zooplankton communities, disrupting trophic dynamics (Dumont 2005; Kideys 2002).

This review aims to characterize the species composition and taxonomic diversity of Caspian Sea phytoplankton; analyze seasonal dynamics and the ecological drivers that regulate them; assess the impacts of anthropogenic and climatic influences on phytoplankton communities; and investigate the linkages between phytoplankton productivity and fish stocks. By integrating satellite observations, field studies, and ecological modeling results (Steele & Henderson 1992; Sverdrup 1953), this work presents the current state of phytoplankton in the Caspian Sea and offers recommendations for ecosystem management (Carpenter et al. 1985; Odum & Barrett 2005).

Ecological characteristics and roles of phytoplankton

Phytoplankton are studied in detail in their ecosystems; they are biologically active, photosynthetic microscopic organic matter (Falkowski & Raven 2007; Reynolds 2006). These organisms, which have an autotrophic nutrition type, convert inorganic carbon into organic compounds using solar energy and release oxygen in the process (Kirk 2011; Wetzel 2001). Globally, phytoplankton produces approximately half of the oxygen entering the Earth's atmosphere and plays a vital role as a carbon sink in the carbon cycle (Behrenfeld et al. 2006; Falkowski & Raven 2007).

The primary productivity of phytoplankton in the Caspian Sea determines the energy base of the ecosystem (Odum & Barrett 2005; Parsons et al. 1984). Organic matter produced by photosynthesis is the main food source for zooplankton, mollusks, crustaceans, and fish larvae (Reynolds 2006; Wootton 1998). Changes in the amount and species composition of phytoplankton spread throughout the trophic chain, directly affecting the formation of fish stocks (Carpenter et al. 1985; Lindeman 1942).

Caspian Sea phytoplankton is represented by various taxonomic groups (Reynolds 2006; Tomas 1997). Each of these groups has unique morphological, physiological, and ecological characteristics.

Bacillariophyta (diatoms) is the most widespread and biodiversity-rich group in the Caspian Sea (Bagheri et al. 2011; Heidari et al. 2018). They have a strong cell wall (frustule) made of silica and form mostly single-celled or chain-shaped colonies (Reynolds 2006; Tomas 1997). Diatoms exhibit high abundance in temperate climates and nutrient-rich waters (Sommer et al. 1986; Sverdrup 1953). Among the diatoms that form the basis of spring and autumn blooms, the genera *Cyclotella caspia* (an endemic species), Navicula, Nitzschia, and Coscinodiscus predominate (Bagheri et al. 2011; Heidari et al. 2018). Their high content of protein, lipids, and essential fatty acids make them of high nutritional value for zooplankton and fish larvae (Reynolds 2006; Wootton 1998). In winter, diatoms can constitute 96–99% of total phytoplankton biomass, reaching 4.5-5.0 g/m³ (Vostokov et al. 2023). **Figure 1** depicts a microscopic view of diatoms (Tomas 1997).

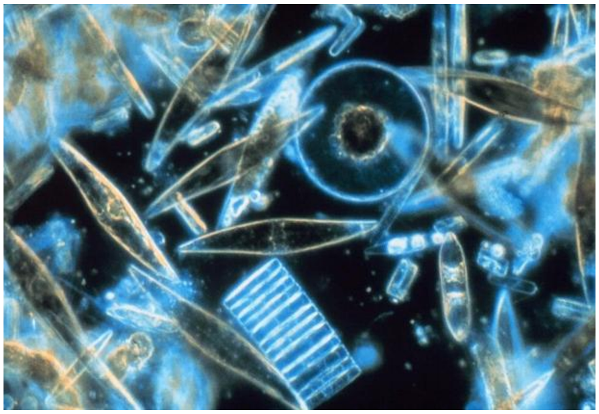

Figure 1. Bacillariophyta (Source: Tomas 1997).

Dinophyta (dinoflagellates) are complex, mostly unicellular, motile organisms (Reynolds 2006; Tomas 1997). They move using specialized flagella, and most species have a covering called theca, which consists of cellulose plates (Hallegraeff 1993; Tomas 1997). Dinoflagellates are mainly distributed in marine and brackish waters, with some species exhibiting mixotrophic nutrition (Reynolds 2006). The genus *Prorocentrum micans* and *Peridinium* are most common in the Caspian Sea (Bagheri et al. 2011; Heidari et al. 2018). Their massive development in the warm season can lead to water "blooming" phenomena (Anderson et al. 2002; Hallegraeff 1993). Some species secrete toxins, creating harmful algal blooms (HABs) (Landsberg 2002; Paerl & Otten 2013). **Figure 2** shows the structure of dinoflagellates (Tomas 1997).

Figure 2. Dinophyta (Source: Tomas 1997).

Chlorophyta (green algae) – although they make up a relatively small portion of phytoplankton, they are mainly distributed near the coast and in areas where rivers flow (Reynolds 2006; Tomas 1997). The presence of chlorophyll "a" and "b" pigments in their cells ensures high photosynthetic activity (Falkowski & Raven 2007; Kirk 2011). Green algae develop more intensively in late summer and autumn (Sommer et al. 1986; Wetzel 2001). Mass reproduction of some species may be an indicator of eutrophication (Smith et al. 1999; Anderson et al. 2002). **Figure 3** depicts a representative of green algae (Leliaert et al. 2012).

Figure 3. Chlorophyta; **A:** Pterosperma (Pyramimonadales), **B:** Nephroselmis (Nephroselmidophyceae), **C:** Palmophyllum (Palmophyllales) **D:** Tetraselmis (Chlorodendrophyceae), **F:** Oocystis (Trebouxiophyceae, Oocystaceae), **G:** Haematococcus (Chlorophyceae, Chlamydomonadales), **H:** Pediastrum (Chlorophyceae, Sphaeropleales), **I:**

Bulbochaete (Chlorophyceae, Oedogoniales), **J:** Chaetophora (Chlorophyceae, Chaetophorales), **K:** Ulothrix (Ulvophyceae, Ulotrichales), **L:** Ulva (Ulvophyceae, Ulvales), **M:** Cladophora (Ulvophyceae, Cladophorales), **N:** Boergesenia (Ulvophyceae, Cladophorales), **O:** Acetabularia (Ulvophyceae, Dasycladales), **P:** Caulerpa (Ulvophyceae, Bryopsidophyceae), **Q:** Klebsormidium (Klebsormidiophyceae), **R:** Spirotaenia, **S:** Nitella (Charophyceae), **T:** Micrasterias (Zygnematophyceae, Desmidiales), **U:** Coleochaete (Coleochaetophyceae). (Source: Leliaert et al. 2012).

Cyanobacteria (cyanobacteria, blue-green algae) are prokaryotic organisms capable of photosynthesis (Paerl & Otten 2013; Reynolds 2006). Their ability to fix atmospheric nitrogen gives them an advantage in conditions where nutrients are limited (Paerl & Otten 2013; Smith et al. 1999). Species such as *Microcystis*, *Oscillatoria*, *Anabaena*, and *Nodularia spumigena* are widespread in the Caspian Sea (Bagheri et al. 2011; Fendereski 2025; Heidari et al. 2018). Their massive growth during high temperatures in the summer months causes water turbidity, oxygen depletion, and the release of toxins (Anderson et al. 2002; Landsberg 2002; Paerl & Otten 2013).

In addition to these four main groups, small amounts of euglenophytes (Euglenophyta) and cryptophytes (Cryptophyta) are also recorded in Caspian waters (Bagheri et al. 2011; Tomas 1997). However, their share in the total phytoplankton biomass is relatively small (Heidari et al. 2018).

Physical and geographical features of the Caspian Sea

The Caspian Sea is located between Europe and Asia, approximately 1,200 km long and 204–466 km wide (Kosarev & Yablonskaya 1994; Zonn et al. 2010). The total length of the coastline is 6,380 km, of which 825 km falls on Azerbaijan (Zonn et al. 2010). The sea covers the coasts of five countries (Azerbaijan, Russia, Kazakhstan, Turkmenistan, Iran) (Kosarev & Yablonskaya 1994). The sea is divided into three main morphometric zones (Kosarev & Yablonskaya 1994; Zonn et al. 2010):

- Northern Caspian: shallow (average depth 5–6 m), characterized by low salinity (under 1%) under the influence of the Volga River.
- Middle Caspian: average depth ~190 m, salinity varies between 8–12%.
- South Caspian: South Caspian: maximum depth is more than 1000 m, salinity reaches 12–13%.

Approximately 130 rivers flow into the Caspian Sea, the largest share being the Volga (~80%), Kura (~6%), and Ural (~5%). Sea level is approximately 28 m below the world ocean level, with long-term variability of 10–20% (Kosarev & Yablonskaya 1994; Zonn et al. 2010).

The climate varies from cold continental in the north to mild subtropical in the south (Kosarev & Yablonskaya 1994; Zonn et al. 2010). In winter, icing is observed in the northern part, while temperatures remain moderate in the south. During the summer months, surface water temperatures can rise above 30°C in the south (Fendereski 2025; Zonn et al. 2005). Water transparency is lower in coastal zones where rivers flow, and higher in the central parts of the sea (Kosarev & Yablonskaya 1994).

The hydrodynamic regime is mainly determined by winds, temperature differences, river currents, and bottom relief (Kosarev & Yablonskaya 1994; Kostianoy & Kosarev 2005). The formation of a thermocline layer during the summer months limits vertical mixing and makes it difficult for nutrients to rise to the surface layers

(Sommer et al. 1986; Sverdrup 1953). These physical characteristics directly affect the spatial distribution and seasonal dynamics of phytoplankton (Kosarev & Yablonskaya 1994; Harris 1986; Reynolds 2006; Zonn et al. 2010).

Phytoplankton species diversity

The species composition of phytoplankton in the Caspian Sea is represented by several algal divisions. According to recent studies (Bagheri et al. 2011; Heidari et al. 2018; Tomas 1997), a total of more than 48 species has been identified. According to observations made in the southwestern Caspian (2020–2021), Bacillariophyta accounts for 80.0%, Cyanophyta for 11.0%, Dinophyta for 4.0%, and Chlorophyta for 3.5%. In the Middle Caspian, *Cyclotella caspia* and *Prorocentrum micans* predominate in spring, and small flagellates and dinoflagellates predominate in summer (Bagheri et al. 2011; Vostokov et al. 2023).

Between 1996 and 2020–2021, the total amount of phytoplankton on the southwestern coast of the Caspian Sea increased 7 times, and the concentration of chlorophyll-a increased 7 times. This increase occurred in parallel with a more than 3-fold increase in nutrients (nitrogen and phosphorus), and the trophic state shifted from oligotrophy to mesotrophy (Bagheri et al. 2011; Heidari et al. 2018; Smith et al. 1999).

New invasive or expanding species have also been recorded in recent years. These include *Pseudo-nitzschia seriata* (a diatom that produces domoic acid), *Cerataulina pelagica*, and *Chaetoceros peruvianus*. The spread of these species is associated with the long-term impact of climate change and warm water conditions (Bagheri et al. 2011; Behrenfeld et al. 2006; Fendereski 2025; Hallegraeff 1993).

The impact of environmental factors on phytoplankton

Temperature is a key factor regulating phytoplankton growth rate, species composition, and bloom phenology (Harris 1986; Reynolds 2006; Sommer et al. 1986). Rising sea surface temperatures lead to a dominance of thermophilic forms (dinoflagellates, cyanobacteria) and a relative decline in diatoms (Paerl & Otten 2013). Satellite data (2003–2021) show that sea surface temperature is the second most important factor influencing chlorophyll-a variability (the first is photosynthetically active radiation) (Behrenfeld et al. 2006; Fendereski 2025).

Light. Photosynthetically active radiation has a dominant effect on chlorophyll-a changes in the Southern Caspian. Reduced water transparency (due to high phytoplankton biomass or suspended particles) limits the transmission of light to deeper layers, concentrating photosynthesis only in the upper layer, which in turn can intensify bloom events (Kirk 2011; Sverdrup 1953; Wetzel 2001).

Food ingredients. Nitrogen and phosphorus compounds are the main limiting factors in the mass development of phytoplankton (Reynolds 2006). Biogenic elements entering the sea through river flows, especially the Volga, have increased significantly over the past 25 years (Heidari et al. 2018; Kosarev & Yablonskaya 1994). This increase has led to eutrophication, elevated chlorophyll-a concentrations, and an increased frequency of harmful blooms (Anderson et al. 2002; Heidari et al. 2018; Paerl & Otten 2013; Smith et al. 1999).

Salinity. The salinity gradient determines the spatial distribution of phytoplankton. Freshwater and brackishwater species predominate in the north, while marine forms predominate towards the south. In recent decades, there has been an increase in salinity, which is due to increased evaporation and a decrease in freshwater inflow (Fendereski 2025; Kosarev & Yablonskaya 1994; Zonn et al. 2010).

Anthropogenic impacts

Eutrophication. Excessive nutrient input from agricultural fertilizers, household and industrial waste has accelerated the eutrophication process. This leads to uncontrolled growth of phytoplankton, decreased water transparency, disruption of the oxygen regime, and the creation of "dead zones" (Landsberg 2002; Smith et al. 1999). Chlorophyll-a levels have increased 7 times in the southwestern Caspian as a result of eutrophication (Anderson et al. 2002; Paerl & Otten 2013; Smith et al. 1999).

Oil and industrial pollution. As the Caspian Sea is one of the ancient centers of the oil and gas industry, oil spills, heavy metals, and organic pollutants have a lasting impact on the aquatic environment (Kostianoy & Kosarev 2005; Neff 2002; Zonn et al. 2005). The oil film reduces the transmission of light to the water, while toxic substances slow down the development of sensitive phytoplankton species and reduce species diversity (Anderson et al. 2002; Neff 2002; Paerl & Otten 2013;).

Invasive species. The introduction of *Mnemiopsis leidyi ctensor* into the Caspian Sea in the 1990s sharply reduced zooplankton populations (Dumont 2005; Kideys 2002). This has weakened grazing pressure on phytoplankton, disrupted the trophic chain, and caused serious damage to stocks of fish species such as kilka (Carpenter et al. 1985; Kideys 2002). At the same time, the introduction of new algae species (e.g. *Pseudo-nitzschia seriata*) is also changing the ecosystem structure (Bagheri et al. 2011; Fendereski 2025; Hallegraeff 1993).

Seasonal dynamics of phytoplankton

Seasonal variability of phytoplankton in the Caspian Sea is clearly expressed and is mainly determined by light, temperature, nutrient availability, and water mixing regime.

The spring season is characterized as "biological spring" or "flowering season". Increased solar radiation, longer daylight hours, and the rise to the surface of nutrient salts (nitrate, phosphate, silicate) accumulated in deep layers in winter create conditions for the rapid development of diatom algae (Harris 1986; Reynolds 2006; Sommer et al. 1986; Wetzel 2001). **Figure 4** shows a schematic representation of spring flowering (Sommer et al. 1986; Sverdrup 1953).

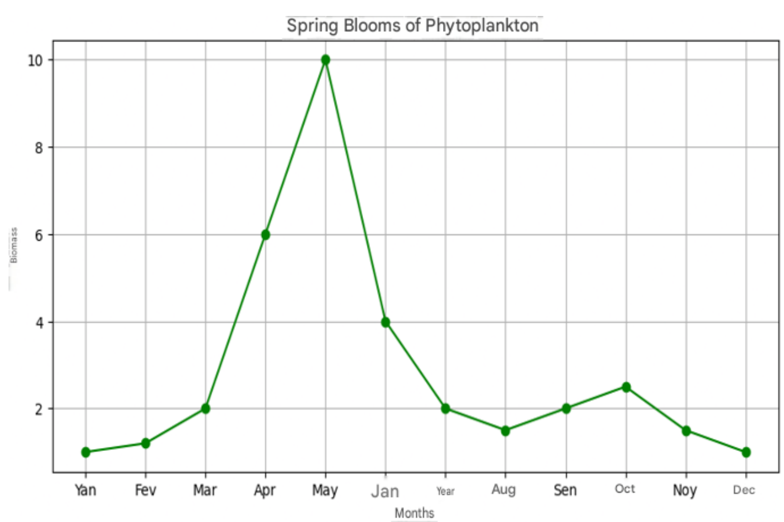

Figure 4. Spring cycle diagram of phytoplankton. (Source: Sommer et al. 1986; Sverdrup 1953)

In summer, due to rising temperatures, the formation of a thermocline layer, and the depletion of nutrients in the surface layers, diatoms decline and are replaced by cyanobacteria and dinoflagellates, which are resistant to heat and low nutrient concentrations (Sommer et al. 1986; Paerl & Otten 2013; Reynolds 2006). **Figure 5** shows the summer cycle diagram (Sommer et al. 1986; Wetzel 2001).

The cyanobacterium *Nodularia spumigena* created a massive bloom in the Anzali region in July 2021, reaching 5,000,000 cells/L (Bagheri et al. 2011; Fendereski 2025). The dominance of these species in eutrophic conditions reduces water clarity, worsens the oxygen regime, and negatively affects fish stocks (Anderson et al. 2002; Landsberg 2002; Paerl & Otten 2013).

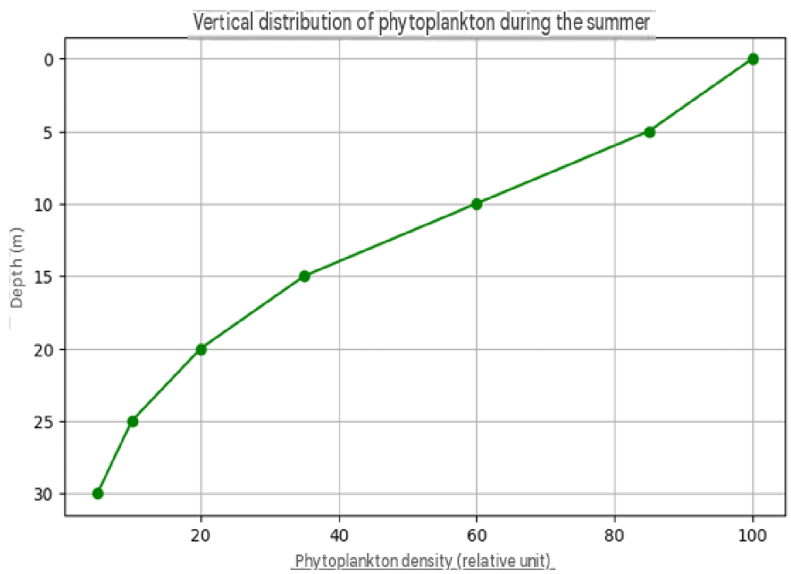

Figure 5. Summer cycle diagram of phytoplankton. (Adapted from Sommer et al. 1986; Wetzel 2001).

In autumn, the gradual decrease in temperature, the strengthening of the wind regime and the intensification of vertical mixing cause the biogenic elements accumulated in the deep layers to rise to the surface (Reynolds 2006; Sommer et al. 1986; Sverdrup 1953). This leads to the second - autumn bloom (Harris 1986; Wetzel 2001). **Figure 6** shows the autumn dynamics (Reynolds 2006; Sommer et al. 1986).

Diatoms again dominate the fall bloom, but this growth is shorter and weaker than the spring bloom (Harris 1986; Sommer et al. 1986). Nevertheless, the fall period plays an important role in the ecosystem's annual productivity and provides an additional resource for zooplankton nutrition (Parsons et al. 1984; Wootton 1998).

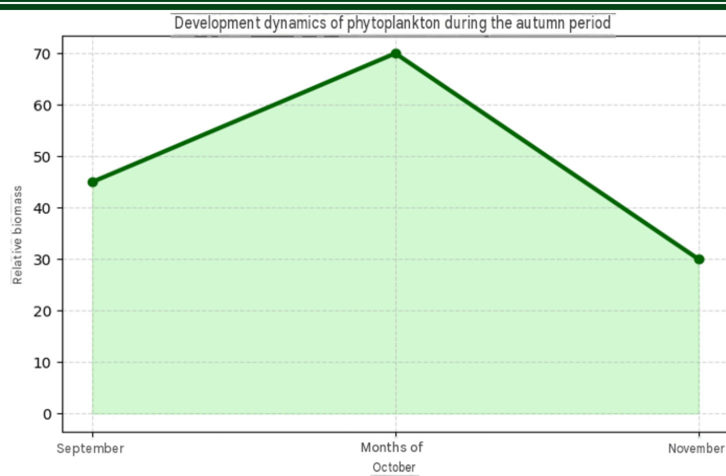

Figure 6. Autumn cycle diagram of phytoplankton (Adapted from Sommer et al. 1986; Reynolds 2006).

In winter, the weakening of solar radiation, the shortening of daylight hours, and the lowering of water surface temperatures minimize photosynthesis processes (Kirk 2011; Reynolds 2006; Sverdrup 1953). **Figure 7** depicts the winter period (Harris 1986; Sverdrup 1953).

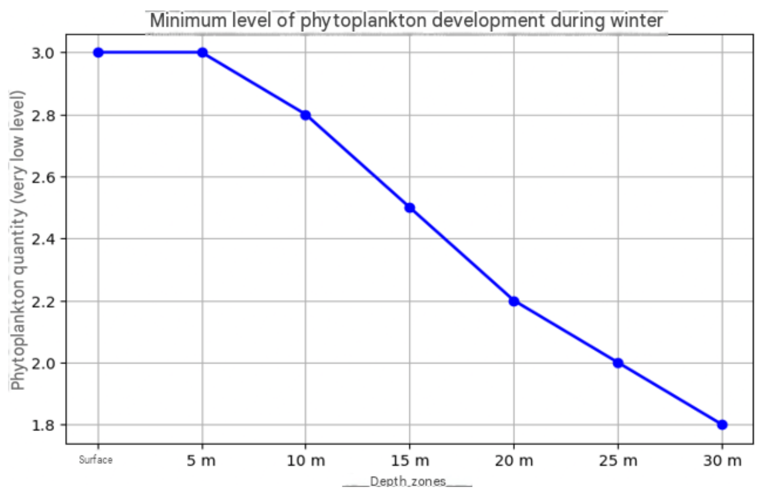

Figure 7. Winter cycle diagram of phytoplankton. (Adapted from Sverdrup 1953; Harris 1986).

In winter, the number and biomass of phytoplankton decrease sharply (Reynolds 2006; Wetzel 2001). However, winter diatom blooms (January-February) are observed in the Middle Caspian, when the biomass reaches 4.5–5.0 g/m³ and diatoms constitute 96–99% of the total phytoplankton (Vostokov et al. 2023). In addition to traditional diatoms, invasive *Pseudo-nitzschia seriata* and *Cerataulina pelagica* contribute to these blooms (Bagheri et al. 2011; Fendereski 2025). The winter period also creates favorable conditions for the accumulation of nutrients in the water column, which is the basis for the spring bloom (Parsons et al. 1984; Sverdrup 1953).

The role of phytoplankton in the trophic chain and its relationship with fish productivity

Phytoplankton, as primary producers

in aquatic ecosystems, constitute the energy base of the entire trophic system (Falkowski & Raven 2007; Lindeman 1942; Odum & Barrett 2005). The energy flow usually occurs in the sequence Phytoplankton → Zooplankton → Small planktonic fish → Predatory fish (Carpenter et al. 1985; Parsons et al. 1984). **Figure 8** schematically depicts the trophic chain of the Caspian Sea (Carpenter et al. 1985; Odum & Barrett 2005).

According to the 10% rule proposed by Lindeman, approximately 10% of the energy is transferred from each trophic level to the next (Lindeman 1942; Odum & Barrett 2005). Therefore, a decrease in phytoplankton biomass causes a cascading decline in fish stocks (Carpenter et al. 1985; Steele & Henderson 1992). Phytoplankton affects fish stocks in several ways (Falkowski & Raven 2007; Parsons et al. 1984; Wootton 1998):

- Direct feeding: Some fish larvae and microphage species feed on large diatoms and dinoflagellates.
- Indirect effect: Energy is mainly transferred through phytoplankton → zooplankton → fish. The abundance of phytoplankton, which is the food base of zooplankton, has a positive effect on the growth of zooplankton, which in turn has a positive effect on the survival of fish larvae.
- Oxygen regime: Oxygen released during photosynthesis is essential for fish respiration. However, massive decomposition after blooming leads to oxygen depletion (hypoxia).
- Spawning areas: Excessive growth of phytoplankton reduces water transparency, limits the development of underwater plants, and destroys natural spawning substrates for fish.

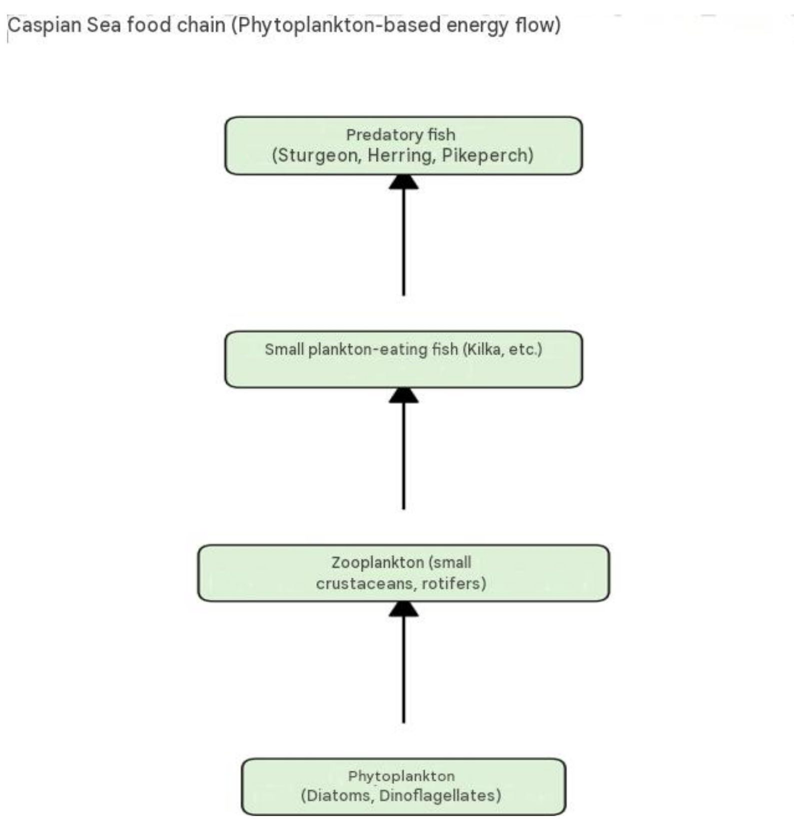

Figure 8. Caspian Sea trophic chain diagram.
(Adapted from Carpenter et al. 1985; Odum & Barrett 2005).

According to the match-mismatch hypothesis (Cushing 1990), the timing of fish larval feeding and phytoplankton blooms determines larval survival (Cushing 1990; Wootton 1998). When climate change alters bloom phenology, this match is disrupted, and fish stocks decline (Behrenfeld et al. 2006; Fendereski 2025).

Figure 9 shows the chain-lag dynamics between phytoplankton (P), zooplankton (Z), and fish (F) biomass (Lindeman 1942; Steele & Henderson 1992). After the phytoplankton peak, zooplankton and fish populations increase a few days later (Carpenter et al. 1985; Steele & Henderson 1992).

In the Caspian Sea, the invasion of *Mnemiopsis leidyi* in the 1990s drastically reduced zooplankton, leading to an overgrowth of phytoplankton, a collapse of kilka stocks, and even the death of sturgeon and Caspian seal (Carpenter et al. 1985; Dumont 2005; Kideys 2002). This event clearly demonstrates the vulnerability of the trophic chain (Carpenter et al. 1985; Kideys 2002).

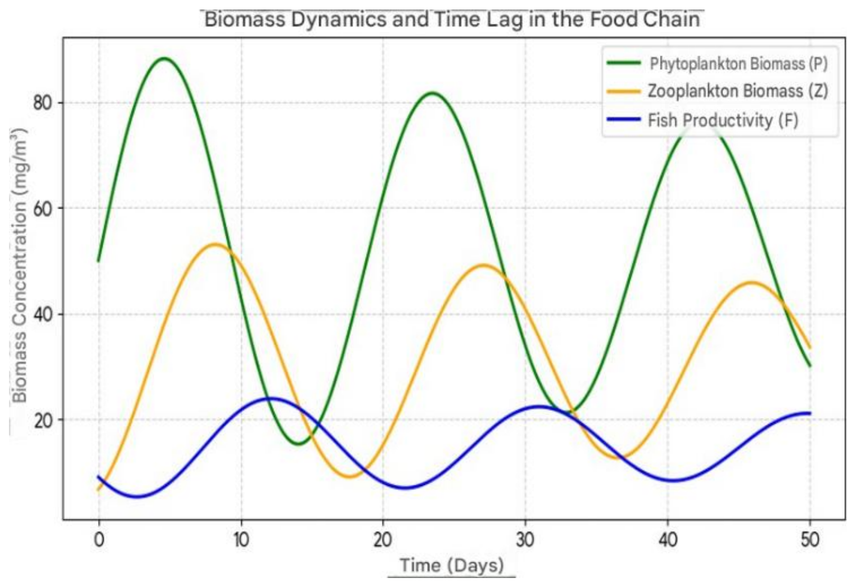

Figure 9. Biomass dynamics and chain lag scheme.
(Adapted from Steele & Henderson 1992; Lindeman 1942).

Negative impacts: Harmful blooms and ecological disturbances

The increase in anthropogenic nutrients causes uncontrolled growth of phytoplankton. After the bloom, bacterial activity increases during the decomposition of biomass, and dissolved oxygen in the water is rapidly depleted (Anderson et al. 2002; Smith et al. 1999). This creates "dead zones" that cause mass fish kills (Andsberg 2002; Paerl & Otten 2013).

Species such as *Nodularia spumigena* (nodularin hepatotoxin) and *Pseudo-nitzschia seriata* (domoic acid – neurotoxin) secrete toxins. These toxins enter the food chain and cause nervous system disorders, gill paralysis, and death in fish. Bioaccumulation of toxins also poses a risk to human health (Anderson et al. 2002; Hallegraeff 1993).

Climate change and pollution are reducing the abundance of high-nutrient diatoms, replacing them with low-nutrient and toxigenic cyanobacteria. This "false productivity" reduces the ecosystem's real fish production potential (Anderson et al. 2002; Carpenter et al. 1985; Smith et al. 1999).

Conclusion and Recommendations

A review of the conducted studies shows that the phytoplankton communities of the Caspian Sea are undergoing rapid transformation under the complex influence of climate change, eutrophication, pollution and biological invasions (Fendereski 2025; Kostianoy & Kosarev 2005; Zonn et al. 2010). The main results are as follows:

1. Species composition: Diatoms, dinoflagellates, cyanobacteria and green algae dominate. The share of invasive and potentially harmful species is increasing (Bagheri et al. 2011; Fendereski 2025).
2. Seasonal dynamics: Spring and autumn diatom blooms are the main productive periods; cyanobacteria and dinoflagellates dominate in summer; biomass is minimized in winter, but diatom blooms are occasionally observed (Reynolds 2006; Vostokov et al. 2023).
3. Ecological factors: Temperature, light, nutrients and salinity are the main regulators of phytoplankton dynamics. Climate change affects each of these factors (Behrenfeld et al. 2006; Fendereski 2025).
4. Anthropogenic impacts: Increased nutrients have led to eutrophication, an increase in the frequency of harmful blooms, and a change in trophic status (Heidari et al. 2018; Smith et al. 1999).
5. Link to fish stocks: The abundance, composition, and phenology of phytoplankton determine the dynamics of zooplankton and fish populations. Harmful blooms pose a direct threat to fish and human health (Landsberg 2002; Paerl & Otten 2013).

Research gaps

- Long-term monitoring: Continuous, coordinated monitoring programs covering all Caspian regions are needed (Fendereski 2025; Kosarev & Yablonskaya 1994; Zonn et al. 2005).
- Mechanism studies: In-depth studies of interspecific competition, regulation of toxin production, and food web dynamics are necessary (Hallegraeff 1993; Reynolds 2006; Sommer et al. 1986).
- Prediction models: Development of ecosystem models integrated with climate change scenarios is essential (Behrenfeld et al. 2006; Fendereski 2025; Steele & Henderson 1992).
- Invasive species management: Strategies to prevent new invasions and mitigate existing impacts should be implemented (Dumont 2005; Kideys 2002).

Management recommendations

- Reducing nutrient inputs (control of agricultural, industrial and domestic waste).
- Monitoring pollution sources and strengthening clean-up measures.
- Sustainable management of fish stocks and implementation of recovery plans.
- Developing climate change adaptation strategies using an ecosystem approach.

Phytoplankton, despite their microscopic size, are a reliable indicator of the health of the Caspian Sea. Monitoring and understanding their dynamics are vital for the conservation of this unique ecosystem and the sustainable use of its biological resources for future generations.

Conflict of Interest

The authors declare that there is no conflict of interest.

References

Aladin N.V., Plotnikov I.S. (2004) Hydrobiology of the Caspian Sea: Environment and biota. In: Nihoul J.C.J., Zavialov P.O., Micklin P.P. (eds) Dying and Dead Seas climatic versus anthropic causes. NATO Science Series: IV: Earth and Environmental Sciences, vol. 36. Springer, Dordrecht. Doi: 10.1007/978-94-007-0967-6_8

Anderson D.M., Glibert P.M., Burkholder J.M. (2002) Harmful algal blooms and eutrophication: Nutrient sources, composition, and consequences. *Estuaries*, 25(4):704–726.

Bagheri S., Mansor M., Makaremi M., Sabkara J., Maznah W.W., Mirzajani A., Khodaparast S. H., Negarestan H., Ghandi A., Khalilpour A. (2011) Fluctuations of phytoplankton community in the coastal waters of Caspian Sea in 2006. *American Journal of Applied Sciences*, 8(12):1328–1336. Doi: 10.3844/ajassp.2011.1328.1336.

Behrenfeld M.J., O'Malley R.T., Siegel D.A., McClain C.R., Sarmiento J.L., Feldman G.C., Milligan A.J., Falkowski P.G., Letelier R.M., Boss E.S. (2006) Climate-driven trends in contemporary ocean productivity. *Nature*, 444(7120):752–755. Doi: 10.1038/nature05317

Carpenter S.R., Kitchell J.F., Hodgson J.R. (1985) Cascading trophic interactions and lake productivity. *BioScience*, 35(10):634–639.

Cushing D.H. (1990) Plankton production and year-class strength in fish populations: An update of the match/mismatch hypothesis. *Advances in Marine Biology*, 26:249–293.

Dumont H.J. (Ed.). (2005) Caspian Sea Biodiversity. Springer.

Falkowski P.G., Raven J.A. (2007) Aquatic Photosynthesis (2nd ed.). Princeton University Press.

Fendereski F. (2025) The spatiotemporal variability of phytoplankton phenology in the Caspian Sea (an ecoregion-based approach). *International Journal of Water Resources Development*, 41(1):102–128. Doi: 10.1080/07900627.2023.2279961

Hallegraeff G.M. (1993) A review of harmful algal blooms and their apparent global increase. *Phycologia*, 32(2):79–99.

Harris G.P. (1986) Phytoplankton ecology: structure, function and fluctuation. Chapman and Hall.

Heidari N., Fatemi S.M.R., Mashinchian A., Musavi N.R. (2018) Seasonal species diversity and abundance of phytoplankton from the southwestern Caspian Sea. *International Aquatic Research*, 10:375–390. Doi: 10.1007/s40071-018-0213-6

Kideys A.E. (2002) Fall and rise of the Black Sea ecosystem. *Science*, 297(5586):1482–1484.

Kirk J.T.O. (2011) Light and photosynthesis in aquatic ecosystems (3rd ed.). Cambridge University Press.

Kosarev A.N., Yablonskaya E.A. (1994) The Caspian Sea. SPB Academic Publishing.

Kostianoy A.G., Kosarev A.N. (Eds.). (2005) The Caspian Sea environment. Springer.

Landsberg J.H. (2002) The effects of harmful algal blooms on aquatic organisms. *Reviews in Fisheries Science*, 10(2):113–390.

Leliaert F., Smith D.R., Moreau H., Herron M.D., Verbruggen H., Delwiche C.F., De Clerck O. (2012) Phylogeny and molecular evolution of the green algae. *Critical Reviews in Plant Sciences*, 31:

1–46. Doi: 10.1080/07352689.2011.615705

Lindeman R.L. (1942) The trophic-dynamic aspect of ecology. *Ecology*, 23(4): 399–417.

Neff J.M. (2002) Bioaccumulation in marine organisms. Elsevier.

Odum E.P., Barrett G.W. (2005) Fundamentals of ecology (5th ed.). Thomson Brooks/Cole.

Paerl H.W., Otten T.G. (2013) Harmful cyanobacterial blooms: Causes, consequences, and controls. *Microbial Ecology*, 65(4):995–1010.

Parsons T.R., Takahashi M., Hargrave B. (1984) Biological oceanographic processes (3rd ed.). Pergamon Press.

Reynolds C.S. (2006) The ecology of phytoplankton. Cambridge University Press.

Smith V.H., Tilman G.D., Nekola J.C. (1999) Eutrophication: impacts of excess nutrient inputs. *Environmental Pollution*, 100(1–3):179–196.

Sommer U., Gliwicz Z.M., Lampert W., Duncan A. (1986) The PEG-model of seasonal succession of planktonic events in fresh waters. *Archiv für Hydrobiologie*, 106(4):433–471. Doi: 10.1127/archiv-hydrobiol/106/1986/433

Steele J.H., Henderson E.W. (1992) The role of predation in plankton models. *Journal of Plankton Research*, 14(1): 157–172.

Sverdrup H.U. (1953) On conditions for the vernal blooming of phytoplankton. *Journal du Conseil*, 18(3):287–295.

Tomas C.R. (Ed.). (1997) Identifying marine phytoplankton. Academic Press.

Vostokov S.V., Pautova L.A., Sahling I.V., Vostokova A.S., Gadzhiev A.A., Petherbridge G., Lobachev E.N., Abtahi B., Shojaei M.G. (2023) Seasonal and long-term phytoplankton dynamics in the middle Caspian according to satellite data and in situ observations in the first decades of the 21st century. *Journal of Marine Science and Engineering*, 11(5):957. Doi: 10.3390/jmse11050957

Wetzel R.G. (2001) Limnology: lake and river ecosystems (3rd ed.). Academic Press.

Wootton R.J. (1998) Ecology of teleost fishes (2nd ed.). Kluwer Academic Publishers.

Zonn I.S., Kostianoy A.G., Kosarev A.N. (Eds.) (2010) The Caspian Sea Encyclopedia. Springer.

Zonn I.S., Kostianoy A.G., Kosarev A.N., Bobrovitskaya N.N. (Eds.). (2005) The Caspian Sea Environment. Springer.