The Çukurova Sequential Aquaculture Model (CUSAM): A Climate-Adapted Strategy for Reservoir Aquaculture

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Abstract

Climate change is increasingly affecting freshwater aquaculture through rising water temperatures, altered hydrological patterns, and greater environmental variability. These challenges highlight the need for adaptive production strategies that improve resource utilization and enhance the resilience of aquaculture systems. This study presents the Çukurova Sequential Aquaculture Model (CUSAM), a climate-adaptive production approach developed and experimentally evaluated in Seyhan Dam Lake, Türkiye. The model integrates rainbow trout (*Oncorhynchus mykiss*) production during the cold-water period (10–19 °C) with blue tilapia (*Oreochromis aureus*) production during the warm-water period (25–30 °C), using the same floating cage infrastructure to enable sequential production of two commercially important species within a single year. Experimental results demonstrated the feasibility of sequential production under the seasonal thermal conditions of the reservoir and showed more continuous utilization of cage infrastructure across the annual production cycle. By matching species to seasonally suitable temperature conditions, CUSAM converts seasonal thermal variability from a production constraint into an opportunity for strategic species succession. The model can potentially reduce infrastructure idle periods, increase production flexibility, and improve the annual utilization of reservoir resources. Although developed under the environmental conditions of the Çukurova region, CUSAM may be applicable to Mediterranean and subtropical reservoir ecosystems experiencing comparable seasonal temperature patterns and climate-related production constraints. The model provides a practical framework for enhancing the resilience and sustainability of freshwater cage aquaculture under changing climatic conditions.

Keywords: Climate adaptation; Reservoir aquaculture; Sequential production; Cage aquaculture; Climate resilience; *Sustainable aquaculture*; *Oncorhynchus mykiss*; Oreochromis aureus.

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Introduction

Global warming and climate change are increasingly reshaping the environmental conditions that support inland aquaculture. Rising water temperatures, changes in dissolved oxygen availability, altered evaporation and hydrological regimes, and more frequent climate-related extremes can influence the suitability of aquatic environments for fish production. These changes affect not only the conditions under which fish are cultured but also how production systems need to be planned and managed. As seasonal environmental conditions become less predictable, greater flexibility may therefore be required in production timing, species selection, and farm management to maintain the resilience of inland aquaculture systems (FAO, 2022; IPCC, 2023). According to the Paris Agreement signed in 2015, there is a need for effective and progressive responses to the upcoming threat of climate change, taking into account the particular vulnerabilities of food production systems, through mitigation and adaptation measures (Barange *et al*., 2018).

In this context, the prolongation of the production season or the realization of the second production cycles within the year in regions dominated by high temperatures are gaining more and more importance in terms of sustainable production strategies. Located in southern Turkey, the Çukurova Region stands out climatically with its long summer season, high temperature values, and rich water resources. The dam lakes in the region offer high production potential despite variable climatic conditions throughout the year. However, increasing average temperature values and irregularities in the water regime in recent years make it necessary to re-evaluate the classical production models. This situation has brought to the agenda the applicability of the secondary crop aquaculture approach in particular. Because monoculture cultivation of a single species does not allow the production season to be completed cyclically. Neither tilapia monoculture nor rainbow trout monoculture has the capability for year-round production. In this case, neither tilapia nor trout production can yield the required profit. A decrease in water temperature in winter restricts tilapia production, while a similar decrease in water temperature increases in summer, making trout production impossible this time. Under these conditions, the economic value derived from a cage system cannot sustain the economic management of the enterprise. However, it has been observed that production can be made sustainable through the implementation of CUSAM. The trout+tilapia model preferred in this model was later diversified by the production of striped Asian catfish (*Pangasianoodon hypophthalmus*) in the same reservoir (Mumoğulları and Dikel, 2020; Dikel, 2021).

Cage aquaculture in dam lakes is a commonly used method for generating economic income in many parts of the world (Costa-Pierce, 2002). These water reservoirs, especially those created later for energy production or irrigation purposes, are now drawing attention as significant fish production areas (Hogeboom *et al*., 2018). The inclusion of aquaculture in lake management plans is significant because it represents a major source of income. These production sites, which were not previously used for this purpose, can host highly successful applications through proper planning and the selection of the right techniques. In addition to the many known advantages of fish production in cage systems, the fact that it is open to all climatic movements within the natural ecosystem is one of the most important handicaps that must be taken into account during production (Beveridge 2008; Boyd *et al*., 2020). Beyond all the problems encountered in cage fish farming, ensuring the economic projection necessary to sustain the system stands out as perhaps the most vital issue, especially in developing economies. In particular, in small-scale businesses, employing personnel for only one season due to seasonal production is a serious problem. Finding qualified workers is already a major issue in non-continuous production models. Furthermore, in ecosystems where only one production season allows for the production of a single species, and given the small production volume of the business type, single-season production models are not economically viable.

Against this background, the present study aims to reconsider seasonal temperature variability not merely as a constraint on reservoir aquaculture, but as a potential production opportunity that can be strategically managed through species succession. Building on historical experimental evidence obtained from the sequential cage culture of rainbow trout (*Oncorhynchus mykiss*) and tilapia (*Oreochromis aureus*) in Seyhan Dam Lake, southern Türkiye, this study introduces the Çukurova Sequential Aquaculture Model (CUSAM) as a climate-change-adaptive conceptual framework for reservoir aquaculture. Rather than replicating the original short-term production trials, CUSAM extends their underlying biological principle by matching cool and warm water species with broader seasonal thermal windows, thereby promoting more continuous use of existing cage infrastructure throughout the year. The framework further considers how climate-driven shifts in water temperature, locally appropriate species selection, adaptive production scheduling, and emerging digital decision-support technologies could be integrated into future reservoir aquaculture strategies. By linking past experimental experience with present climate challenges and future production needs, this study seeks to demonstrate how seasonal thermal dynamics can be incorporated into proactive aquaculture planning rather than being regarded solely as an environmental limitation. Finally, the potential geographical transferability of the CUSAM principle is explored across selected reservoir regions with comparable seasonal characteristics, providing a basis for future site-specific validation and adaptation. In this context, CUSAM is proposed not as a fixed trout–tilapia production protocol, but as a flexible framework in which species succession and production periods can be adjusted to local environmental conditions, climate trajectories, biological requirements, and socioeconomic constraints.

Methodology and conceptual framework development

Study design and conceptual approach

This study was designed as a conceptual synthesis combining historical experimental evidence with contemporary scientific literature on climate change, freshwater aquaculture, seasonal species selection, and reservoir-based fish production. Rather than conducting a conventional systematic review, the study aimed to reinterpret previously generated field data within the context of current and anticipated climate-related challenges in aquaculture and to develop a transferable seasonal production framework.

The conceptual basis of the study originated from an earlier cage-culture experiment conducted in Seyhan Dam Lake, located in the Çukurova region of southern Türkiye. The original study investigated the feasibility of sequentially producing rainbow trout (*Oncorhynchus mykiss*) and tilapia (*Oreochromis aureus*) under naturally changing seasonal water temperatures. The experimental findings were previously reported by Alev and Dikel (2003). In the present study, these historical observations were reconsidered from a climate-change-adaptation perspective and integrated with current knowledge to formulate the Çukurova Sequential Aquaculture Model (CUSAM).

Historical experimental data used for model development

The empirical basis of CUSAM was derived from the seasonal cage-culture trial conducted in Seyhan Dam Lake. Rainbow trout were produced during the cool-water period, when water temperatures ranged approximately between 9 and 18°C, whereas tilapia production followed during the warm-water period at approximately 25–30°C. This study investigated the production of two different species under lake conditions; it was determined that rainbow trout (*O. mykiss*) could be reared during the relatively cool period, and tilapia (*O. aureus*) during the summer period. In the study, trout reached a final weight of 277.54±18.5 g from an average initial weight of 56.45±6.10 g in 75 days, with a daily live weight gain of 2.95 g and a feed conversion ratio of 1:1.15. Tilapia reared during the summer period reached a final weight of 131.58±7.12 g from an initial weight of 0.95±0.27 g in 90 days, with a daily weight gain of 1.45 g and a feed conversion ratio of 1:1.21. These data were not considered as the results of a new experiment, but rather as historical empirical evidence supporting the biological feasibility of sequential production under the seasonal conditions of the Çukurova region.

Literature-based conceptual synthesis

Scientific literature was examined to place the historical observations within the contemporary context of climate change and aquaculture adaptation. The literature assessment focused primarily on five interconnected themes: (i) climate-change-induced alterations in freshwater temperature regimes; (ii) thermal requirements and tolerances of cold- and warm-water aquaculture species; (iii) climate adaptation strategies in freshwater aquaculture; (iv) reservoir and cage aquaculture; and (v) seasonal, sequential, and multi-species production approaches.

Relevant peer-reviewed literature, international reports, and authoritative assessments concerning climate change and aquaculture were considered, with particular emphasis on studies addressing Mediterranean, subtropical, and seasonally variable environments. The literature synthesis was used to identify environmental and production characteristics potentially supporting the transferability of the CUSAM approach beyond the original study area.

Development of the Çukurova Sequential Aquaculture Model (CUSAM)

The CUSAM framework was constructed by matching seasonal thermal conditions with the biological requirements of candidate aquaculture species. The model follows a sequential production principle in which a cool-water species occupies the production system during the cooler part of the year and is replaced by a warm-water species as water temperatures increase. For the Çukurova case, the annual production cycle was structured around rainbow trout production from late autumn to spring, followed by tilapia production from early summer to autumn. A transition period between the two production phases allows harvesting, cage cleaning, net replacement, maintenance, and preparation for the subsequent species. The conceptual model therefore integrates four principal components: seasonal temperature dynamics, species-specific thermal requirements, sequential use of production infrastructure, and climate-adaptive production planning.

Assessment of potential geographic transferability

To evaluate the broader applicability of CUSAM, regions displaying climatic characteristics broadly comparable to the Çukurova region were conceptually examined. Particular attention was given to Mediterranean and subtropical environments characterized by relatively mild winters, warm summers, pronounced seasonal thermal variation, and the presence of reservoirs or inland water bodies potentially suitable for cage aquaculture. Geographical latitude was used as an initial comparative indicator rather than as a direct predictor of aquaculture suitability. Regions located approximately within the 36–38°N latitude band were considered alongside their climatic characteristics, seasonal thermal patterns, reservoir availability, and potential compatibility with cool-season and warm-season aquaculture species. The identified locations were therefore regarded as potential analogue regions, rather than confirmed sites for direct implementation of CUSAM. Site-specific application would require further assessment of water temperature profiles, dissolved oxygen, water quality, reservoir hydrodynamics, carrying capacity, biosecurity, infrastructure, market conditions, and national regulations.

Future-oriented components of the model

The model was additionally evaluated in relation to emerging climate-smart aquaculture technologies. Artificial intelligence-assisted decision-support systems, Internet of Things (IoT)-based environmental monitoring, predictive modelling, automated feeding, and real-time water-quality surveillance were considered potential supporting components rather than elements of the original experimental system. Their inclusion in the conceptual framework reflects the future development pathway of CUSAM, particularly for dynamically determining stocking, feeding, harvesting, and species-transition periods under increasingly variable climatic conditions.

Results and conceptual development of CUSAM

Historical experimental basis of the model

The empirical foundation of CUSAM originates from the sequential cage-culture trial conducted in Seyhan Dam Lake, in which rainbow trout (*Oncorhynchus mykiss*) and tilapia (*Oreochromis aureus*) were evaluated during different seasonal thermal conditions. The original experiment demonstrated that the same cage-production infrastructure could support two species with contrasting thermal requirements at different periods of the year. Rainbow trout were evaluated during a 75-day cool-season production period, whereas tilapia were cultured for 90 days under warmer conditions. The growth performance, feed utilization, biomass production, and survival obtained during these historical trials are summarized in Table 1. These results constitute the empirical basis of the present conceptual framework but should not be interpreted as performance predictions for the extended production windows proposed under CUSAM.

From historical experimental evidence to the CUSAM framework

The development of CUSAM represents a conceptual extension of the biological principle demonstrated in the original sequential lattice culture trials; it is not a direct extrapolation of the experimental results. A historical study conducted at Seyhan Dam Lake has shown that two fish species with significantly different thermal requirements can be grown consecutively in the same cage production system by taking advantage of naturally occurring seasonal changes in water temperature. During the original trials, rainbow trout were evaluated in cool season conditions for 75 days, while blue tilapia were evaluated in warmer period for 90 days. The growth and production performance obtained during these trials (Table 1) provided empirical evidence that seasonal species succession is biologically possible under the environmental conditions of the reservoir.

Table 1: Growth performance of rainbow trout (*Oncorhynchus mykiss*) and tilapia (*Oreochromis aureus*) during the original sequential cage-culture trial in Seyhan Dam Lake.

Performance parameter	Rainbow trout	Tilapia
Initial stocking		
Mean body weight (g)	56.45 ± 6.10	0.95 ± 0.27
Initial biomass (kg m^{-3})	2.822	0.297
Harvest		
Mean body weight (g)	277.54 ± 18.50	131.58 ± 7.12
Final biomass (kg m^{-3})	13.46	6.513
Growth		
Net biomass gain (kg m^{-3})	10.638	6.216
Individual weight gain (g)	221.09	130.63
Daily weight gain (g day^{-1})	2.948	1.451
Feed conversion ratio (FCR)	1.112	1.25
Survival rate (%)	97	99

Source: Adapted from Alev and Dikel (2003). The original experimental periods were 75 days for rainbow trout and 90 days for tilapia.

Historical water temperature observations recorded during these production periods further support the thermal basis of this approach. During the trout production period, water temperatures remained in a significantly colder December than those recorded during the tilapia period, indicating the pronounced seasonal thermal transition characteristic of Seyhan Dam Lake. This seasonal contrast was the environmental mechanism that allowed the same lattice infrastructure to accommodate first the cold-water type, and then the warm water type. Therefore, the original experiment demonstrated not only the production performance of the two species, but more importantly, the possibility of matching species-specific thermal requirements with temporally separated environmental windows within a single reservoir system.

The current CUSAM framework extends this historical observation to a broader seasonal production strategy. In contrast to the relatively short experimental periods used in the original study, CUSAM takes into account the potentially usable production window available under the current seasonal conditions of the Cukurova region. November April May provide a cold season production window of about four to five months for rainbow trout, the water temperatures in Seyhan Dam Lake usually extend from November/December to April/May, and the suitable temperatures are around 9-18°C. The temperature of the rainbow trout in the Seyhan Dam lake is about the same as in the Seyhan dam lake, the rainbow trout production window is about the same as in the Seyhan dam lake, the rainbow trout production window is about Under the conceptual CUSAM scenario, this extended production period can ensure that appropriately sized trout hatchlings reach the target harvest weight of about 300-450 g, depending on the stocking size, temperature dynamics, feeding strategy, fish performance and other region-specific production conditions.

After the trout harvest and a short transition period for cage cleaning, net replacement, maintenance and preparation, the same infrastructure can then be allocated to hot water production. June October Tilapia can then take advantage of the warmer seasonal window, which extends from June to October, when water temperatures can reach about 25-30 °C. December. This period of about four to five months can support production towards the conceptual Sunday size target of about 200-250 g. These recommended harvest weight ranges should not be interpreted as experimentally validated results of historical trials. Instead, they represent conceptual production targets for the extended seasonal windows proposed under the CUSAM and need to be verified by up-to-date field trials.

This distinction between historical empirical evidence and the proposed CUSAM production framework is fundamental for interpreting the model. While the 75-day trout and 90-day tilapia trials provide conceptual proof for seasonal species succession, CUSAM extends this principle by aiming to use a larger portion of the naturally available annual thermal cycle. As a result, CUSAM does not just repeat the original experiment; it transforms the empirical observation into an adaptive annual production strategy in which stocking, growing, harvesting and species transition are synchronized with reservoir temperature dynamics.

From this perspective, the main innovation of CUSAM lies not in the specific trout-tilapia combination, but in the seasonally synchronized succession of species with opposite thermal requirements. Rainbow trout and tilapia represent the reference combination derived from the experience of Çukurova; however, the basic principle allows the inclusion of other locally suitable cold and warm water species, where ecological conditions, biological safety considerations, regulations and Sunday requirements allow. The annual production cycle proposed within the CUSAM framework and its deviation from the original experimental periods is summarized in Figure 1. Based on the historical production data and the seasonal thermal characteristics of Seyhan Dam Lake, an annual sequential production cycle was constructed by matching the thermal requirements of rainbow trout and tilapia with naturally occurring seasonal temperature windows (Fig. 1).

Climate-change adaptation potential of CUSAM

Climate change is progressively altering the environmental conditions under which inland aquaculture systems operate. Increasing air and water temperatures, changes in the timing and duration of seasonal thermal periods, more frequent heat extremes, fluctuations in dissolved oxygen, and changes in reservoir hydrology may progressively reduce the reliability of production calendars based on historically stable seasonal patterns. These changes are particularly important for cage aquaculture, where farmers have limited control over the surrounding aquatic environment and production performance is therefore closely linked to natural temperature dynamics. Under such conditions, maintaining a fixed production calendar or relying on a single species throughout the year may increasingly expose producers to thermal stress, reduced growth performance, deteriorating feed efficiency, and greater production risk.

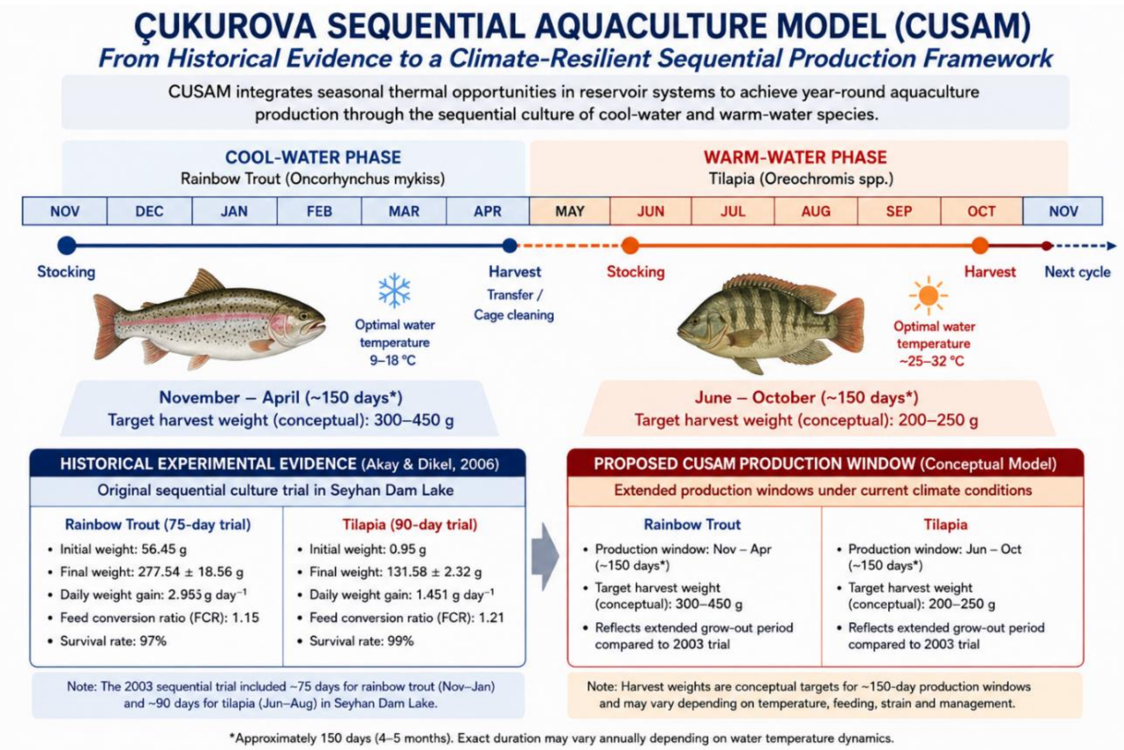


Figure 1: Annual production cycle of the Çukurova Sequential Aquaculture Model (CUSAM). The model synchronizes cool-season rainbow trout production with warm-season tilapia production within the same reservoir cage infrastructure, enabling two sequential production cycles through seasonal species succession.

CUSAM approaches this challenge through adaptive synchronization between environmental conditions and biological production requirements. Rather than attempting to maintain a constant production environment, as would be possible to some extent in highly controlled aquaculture systems, the model uses naturally occurring seasonal thermal windows to determine when a particular species can be most appropriately stocked, grown, and harvested. In its reference configuration for the Çukurova region, rainbow trout represents the cool-water production phase, whereas tilapia represents the subsequent warm-water phase. The transition between these phases is therefore governed primarily by environmental suitability rather than by a rigid calendar date.

This distinction becomes increasingly important under climate change. The November–April/May and June–October production periods proposed in the current CUSAM framework should consequently be regarded as adaptive production windows rather than fixed annual schedules**.** In a warmer year, for example, the period suitable for rainbow trout may begin later and terminate earlier, whereas conditions favourable for warm-water production may occur earlier and persist for longer. Conversely, interannual climatic variability may delay these transitions or temporarily reduce the suitability of either production phase. Thus, the operational principle of CUSAM is not that the same stocking and harvesting dates should be repeated every year, but that production decisions should follow the actual thermal conditions of the reservoir.

This approach also provides an important distinction between climate adaptation and climate benefit**.** CUSAM does not assume that increasing water temperatures are advantageous for aquaculture. Continued warming may ultimately narrow or even eliminate suitable production windows for temperature-sensitive species such as rainbow trout in some reservoirs, while extreme summer temperatures may also exceed the optimal ranges of warm-water species. Moreover, warming-related reductions in dissolved oxygen, altered stratification patterns, harmful algal blooms, disease risks, and changes in reservoir water availability may impose additional constraints. The adaptive value of CUSAM therefore lies in increasing production flexibility within environmentally acceptable limits rather than in attempting to compensate indefinitely for deteriorating environmental conditions.

From a production perspective, this flexibility can contribute to greater climate resilience in several ways. Sequential production reduces dependence on a single species and a single seasonal production opportunity. It can improve the annual utilization rate of cages and associated infrastructure that would otherwise remain inactive during thermally unsuitable periods. It may also allow farmers to adjust stocking size, production duration, harvest timing, and species selection according to expected environmental conditions. In regions close to major consumer markets, such as the Çukurova metropolitan area, seasonal production may additionally provide opportunities to coordinate harvest periods with market demand while reducing the logistical disadvantages associated with transporting fish from distant high-altitude production areas.

Importantly, the adaptive principle underlying CUSAM is not restricted to the rainbow trout–tilapia combination. These species represent the historical and biological reference on which the framework was developed; however, future implementation should prioritize locally appropriate species succession. A cool-water species could potentially be followed by a warm-water species selected according to local thermal regimes, ecological compatibility, biosecurity, legislation, market demand, and production economics. In this sense, the transferable component of CUSAM is the principle of seasonally synchronized species succession**,** rather than a predetermined species pair.

Climate change also introduces a temporal dimension to the model. The thermal windows suitable for particular species today may not remain unchanged over coming decades. Consequently, CUSAM should be viewed as a dynamic rather than static production framework**.** Long-term water-temperature records and climate projections could be used to periodically reassess the duration and timing of production windows, identify emerging thermal risks, and evaluate whether alternative species or production schedules may become necessary. This perspective transforms seasonal temperature from a background environmental variable into an explicit component of aquaculture planning.

Accordingly, the climate-adaptation potential of CUSAM can be summarized as a transition from calendar-based production toward environment-responsive production**.** Historical experience provides evidence that seasonal species succession is feasible in Seyhan Dam Lake, while the contemporary CUSAM framework extends this principle by proposing that stocking, harvest, species transition, and infrastructure use should increasingly respond to observed and anticipated environmental conditions. Such an approach may become particularly relevant for reservoir aquaculture systems located in transitional climatic regions, where relatively small shifts in seasonal temperature can substantially alter the duration of suitable production periods.

Digital and predictive support for future CUSAM

The future implementation of CUSAM will increasingly depend on the ability to detect, interpret, and anticipate environmental change at the farm level. Because the model is based on the dynamic matching of species-specific thermal requirements with seasonal production windows, reliable environmental monitoring becomes a central component of operational decision-making. In this context, digital technologies can provide the data infrastructure required to transform CUSAM from a seasonally planned production concept into an environment-responsive and predictive aquaculture framework**.**

Continuous monitoring of water temperature, dissolved oxygen, pH, conductivity, turbidity, and other relevant water-quality parameters can provide real-time information on the suitability of the reservoir environment for each production phase. Internet of Things (IoT)-based sensor networks may allow these variables to be monitored continuously rather than through periodic manual measurements, thereby improving the temporal resolution of environmental information. For cage-based systems, where producers have limited ability to directly control surrounding water conditions, such monitoring is particularly valuable for identifying rapid changes that may affect feeding, growth, stress, or survival.

Artificial intelligence and predictive modelling can further extend the value of these data by supporting short- and medium-term forecasting. Historical environmental records combined with real-time sensor data may be used to estimate the likely duration of suitable thermal windows, anticipate temperature thresholds, and support decisions regarding stocking, harvest, and species transition. Rather than relying exclusively on fixed calendar dates, future CUSAM applications could therefore use predictive information to determine when a cool-water production phase should begin or end and when conditions become suitable for the subsequent warm-water phase.

Feeding management represents another area in which digital support could substantially improve the efficiency of CUSAM. Feed intake, growth rate, and feed conversion are strongly influenced by water temperature and fish metabolic activity. AI-assisted feeding systems could integrate environmental conditions, biomass estimates, historical growth data, and behavioural observations to adjust feeding rates dynamically throughout each production phase. Such an approach may reduce feed waste, improve feed conversion efficiency, and minimize unnecessary nutrient loading into reservoir ecosystems.

Predictive tools may also contribute to growth and harvest planning. Growth models updated with real-time environmental and production data could provide estimates of expected harvest size and production timing under changing thermal conditions. This is especially relevant for CUSAM because the duration of each production window may vary among years. A warmer spring, for example, may require an earlier trout harvest, whereas a prolonged warm autumn may extend the tilapia production period. Digital decision-support systems could help producers evaluate these trade-offs before environmental conditions become limiting.

In addition to production optimization, digital monitoring can strengthen risk management. Increasing water temperature may be associated with declining dissolved oxygen, changes in stratification, increased disease pressure, and other environmental risks. Automated threshold alerts and predictive early-warning systems could provide producers with sufficient time to reduce feeding, lower stocking pressure, accelerate harvest, or prepare for species transition. In this way, digital technologies can improve the adaptive capacity of CUSAM by shortening the time between environmental change and management response.

More advanced implementations may incorporate digital twins or integrated decision-support platforms capable of combining environmental data, fish growth models, production costs, and climate forecasts within a single management environment. Such systems could simulate alternative production scenarios before decisions are implemented in the field. For example, producers could compare the expected consequences of extending the trout phase, harvesting earlier, delaying tilapia stocking, or selecting an alternative warm-water species under a predicted temperature scenario.

Importantly, these technologies should be regarded as supporting tools rather than prerequisites for CUSAM implementation**.** The fundamental principle of the model remains the synchronization of species succession with seasonal environmental conditions. Small-scale producers may apply this principle using relatively simple temperature and water-quality monitoring, whereas larger operations may progressively incorporate automated sensing, predictive analytics, and AI-assisted decision support. This scalability is important for maintaining the practical relevance of CUSAM across regions with different technological and economic capacities.

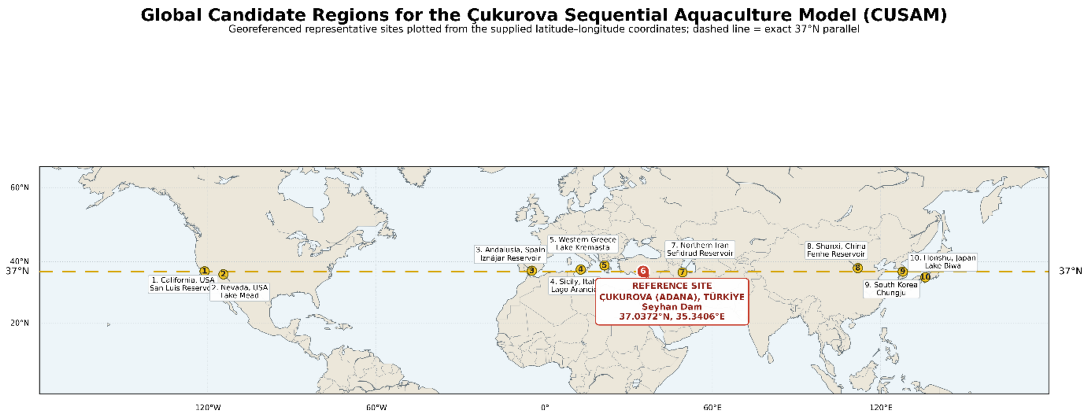
Ultimately, the digital development pathway of CUSAM can be conceptualized as a progression from monitoring to prediction and from prediction to adaptive action**.** Sensors provide information on current environmental conditions, predictive models estimate how these conditions are likely to change, and decision-support systems translate this information into operational choices concerning stocking, feeding, harvest, and species transition. Through this integration, CUSAM may evolve from a seasonal production schedule into a data-informed and climate-responsive management framework capable of adjusting to increasing environmental variability

Global transferability and potential application of CUSAM

Although CUSAM was originally developed under the ecological and seasonal conditions of the Çukurova region, its underlying principle is not necessarily restricted to a single geographical location. The model is primarily based on matching species-specific thermal requirements with naturally occurring seasonal temperature windows, thereby allowing sequential use of the same aquaculture infrastructure throughout the year. Consequently, regions characterized by pronounced seasonal transitions between cool- and warm-water conditions may provide opportunities for adapting the CUSAM principle to local reservoir aquaculture systems.

The geographical distribution illustrated in Figure 2 provides an initial perspective on regions where the underlying principles of CUSAM may potentially be explored. However, geographical proximity to the 37°N latitude alone is insufficient to determine the suitability of a reservoir system for sequential aquaculture. The practical transferability of CUSAM depends primarily on the interaction between seasonal thermal conditions, species-specific temperature requirements, the availability of suitable inland water bodies, existing aquaculture practices, and the duration of potential production windows.

To provide a broader comparative perspective, selected regions representing Mediterranean, subtropical, arid-subtropical, and humid-subtropical conditions were evaluated conceptually in relation to the ecological requirements of sequential aquaculture (Table 2).



Candidate site	Coordinates	Candidate site	Coordinates
1. California, USA — San Luis Reservoir	37.0579°N, 121.1213°W	6. Çukurova, Türkiye — Seyhan Dam	37.0372°N, 35.3406°E
2. Nevada, USA — Lake Mead	36.1461°N, 114.4132°W	7. Northern Iran — Sefidrud Reservoir	36.7587°N, 49.3878°E
3. Andalusia, Spain — Iznájar Reservoir	37.2584°N, 4.3283°W	8. Shanxi, China — Fenhe Reservoir	38.0667°N, 111.9167°E
4. Sicily, Italy — Lago Arancio	37.6360°N, 13.0694°E	9. South Korea — Chungju	36.9813°N, 127.9359°E
5. Western Greece — Lake Kremasta	38.9000°N, 21.5333°E	10. Honshu, Japan — Lake Biwa	35.2165°N, 135.9993°E

Note: latitude is a geographic reference only; CUSAM feasibility requires site-specific thermal, water-quality, biological, regulatory and economic assessment.

Figure 2: Global candidate regions for the potential transferability of the Çukurova Sequential Aquaculture Model (CUSAM) around the 37°N latitude.

Table 2: Potential regions with ecological and climatic conditions for the adaptation of the Çukurova Sequential Aquaculture Model (CUSAM).

No.	Region / Country	Climatic characteristics	Approx. cool-season water temperature (°C)	Approx. warm-season water temperature (°C)	Representative reservoir / water body	Potential sequential production strategy	CUSAM adaptation potential
1	California, USA	Mediterranean / warm-temperate	10–16	24–30	San Luis Reservoir	Cool-water species → warm-water species	High
2	Nevada, USA	Arid / warm-temperate	8–15	24–30+	Lake Mead region	Seasonal trout → warm-water species	Moderate
3	Andalusia, Spain	Mediterranean	11–17	24–30	Iznájar Reservoir	Trout/cool-water species → warm-water species	High
4	Sicily, Italy	Mediterranean	10–16	25–31	Lago Arancio	Cool-water species → warm-water species	High
5	Western Greece	Mediterranean / transitional	9–16	24–30	Lake Kremasta	Trout → warm-water species	High
6	Çukurova, Türkiye	Mediterranean	9–18	25–30	Seyhan Dam Lake	Rainbow trout → tilapia	High Reference model
7	Northern Iran	Continental / Mediterranean-influenced transition	8–16	24–30	Sefidrud Reservoir	Cool-water species → warm-water species	High
8	North/Central China	Temperate–continental / monsoonal transition	5–15	23–29	Fenhe and comparable reservoirs	Cool-water species → warm-water species	High
9	South Korea	Temperate monsoonal	5–14	23–28	Chungju Reservoir	Cool-water species → warm-water species	High
10	Honshu, Japan	Temperate monsoonal	6–15	23–28	Lake Biwa region	Cool-water species → warm-water species	High

Particular attention was given to seasonal water-temperature ranges and the possibility of matching cool-season and warm-season production phases with appropriate aquaculture species. The comparison also considers representative reservoirs or inland water bodies and existing aquaculture activities as indicators of the potential operational context for adapting the CUSAM principle.

Importantly, the production sequences presented in Table 2 should be interpreted as potential adaptation scenarios rather than validated production protocols**.** While the rainbow trout–tilapia sequence represents the original biological basis of CUSAM in the Çukurova region, direct replication of this species combination may not be environmentally, biologically, economically, or legally appropriate in every region. Accordingly, CUSAM should be regarded as a flexible production framework in which locally suitable cool-water and warm-water species can be selected according to regional environmental conditions, aquaculture regulations, biosecurity requirements, market demand, and climate projections.

The Çukurova region, located close to the 37°N latitude, provides a useful reference environment for exploring the geographical transferability of this approach. Several regions across the Mediterranean basin, western Asia, East Asia, and North America occur within or near a comparable latitudinal corridor and contain reservoir systems exposed to marked seasonal temperature fluctuations. Selected candidate regions and representative reservoir systems are illustrated in Figure 2**.**

The map presents selected reservoir systems and geographical regions with seasonal climatic characteristics that may provide opportunities for adapting the sequential production principle underlying CUSAM. Seyhan Dam Lake in the Çukurova region of Türkiye is highlighted as the reference site where the original sequential rainbow trout–tilapia production approach was experimentally evaluated. Candidate locations are plotted according to their geographical coordinates, while the dashed line represents the exact 37°N parallel. The 37°N latitude is used as a geographical reference for identifying broadly comparable regions and should not be interpreted as a direct indicator of suitability for CUSAM implementation. Successful transfer of the model to other reservoir systems would require site-specific assessment of seasonal water-temperature dynamics, dissolved oxygen, water quality, hydrological conditions, carrying capacity, candidate species, biosecurity, production infrastructure, market conditions, and national regulations.

Discussion

From seasonal constraint to adaptive production opportunity

Climate change is generally discussed in aquaculture primarily in terms of increasing environmental risk, and this perspective is well justified. Rising water temperatures, altered hydrological regimes, reduced oxygen availability, and increasing frequency of extreme climatic events can directly affect fish physiology, growth, survival, disease susceptibility, and the overall suitability of production environments (Ficke *et al.*, 2007). These effects may be particularly important in inland cage aquaculture, where producers have limited capacity to control the surrounding water body and are therefore strongly dependent on natural environmental conditions. Cold-water species are especially vulnerable when warming causes water temperatures to approach or exceed their physiological optimum, while prolonged warming may progressively shorten the period during which their culture remains technically feasible. These concerns are consistent with broader assessments identifying warming, changes in oxygen availability, hydrological alteration, and extreme events as major climate-related challenges for inland fisheries and aquaculture.

Due to the nature of aquaculture, those engaged in aquaculture are vulnerable not only to the direct effects of climate change but also to a wide range of indirect consequences stemming from environmental degradation (Yadav *et al*., 2024). Direct effects include physical and environmental changes associated with climate events that can disrupt aquatic ecosystems, alter production conditions, and damage farm infrastructure. Indirect effects can manifest through decreased productivity, increased input and operating costs, economic losses, market instability, disruption of supply chains, and increased disease risks (Shaffril *et al*., 2017). These effects are closely linked to the fact that environmental degradation can reduce biological performance, while decreased productivity and increased production costs can simultaneously weaken the economic resilience of farm operations. Consequently, climate adaptation in aquaculture should not be addressed solely through biological or technological interventions, but integrated adaptation strategies that consider environmental, production, economic, and social dimensions are increasingly necessary to strengthen the long-term resilience of aquaculture systems and the communities' dependent on them (Hossain *et al*., 2025).

However, adaptation requires more than identifying environmental threats. It also requires production systems to respond to changing environmental conditions by modifying management practices, production schedules, species selection, and the use of available resources. Recent climate-adaptation frameworks for aquaculture similarly emphasize that adaptation should be context-specific, based on vulnerability and risk assessment, and continuously revised as environmental conditions change. The FAO Aqua-Adapt framework, for example, treats adaptation as an iterative process involving climate projections, vulnerability assessment, implementation of adaptation measures, and subsequent monitoring and evaluation. This perspective is particularly relevant to reservoir aquaculture because the suitability of a production environment cannot be assumed to remain constant throughout the year or across successive years.

Within this context, CUSAM proposes a shift in perspective from viewing seasonal thermal variability exclusively as a production constraint toward managing it as an environmental signal for adaptive production planning. This does not imply that global warming itself represents an opportunity for aquaculture. On the contrary, continued warming may eventually make some existing production systems biologically or economically unsustainable. Rather, the opportunity lies in recognizing that, while environmental conditions remain within biologically acceptable ranges, different portions of the annual thermal cycle may support species with contrasting temperature requirements. Production can therefore be synchronized with these thermal windows instead of attempting to maintain a single species under increasingly unsuitable conditions.

The historical experience from Seyhan Dam Lake provides a useful empirical basis for this interpretation. The successful cultivation of rainbow trout during the cool period and tilapia during the subsequent warm period demonstrated that seasonal thermal transitions could permit biologically distinct production phases within the same reservoir and cage infrastructure. In the original trials, these phases were evaluated over relatively short experimental periods; therefore, the historical results should not be interpreted as direct validation of the extended production windows proposed by CUSAM. Their greater significance lies in demonstrating the biological feasibility of species succession according to seasonal environmental suitability. CUSAM builds upon this observation by extending the principle from an experimental sequence into an adaptive annual production framework.

This distinction becomes increasingly important under contemporary climate conditions. Conventional production calendars generally assume a reasonably predictable relationship between season and water temperature. Climate change and increasing interannual variability weaken this assumption. A nominal calendar date may no longer reliably indicate whether environmental conditions are suitable for stocking or harvesting a particular species. Under CUSAM, therefore, November, May, June, or October should not be interpreted as immutable operational boundaries. They represent approximate seasonal reference periods derived from the Çukurova production environment. The actual transition between cool- and warm-water production should ultimately be determined by observed environmental conditions and biological thresholds.

Such an approach introduces the concept of environment-responsive production into reservoir aquaculture. In a relatively cool year, the suitable production window for rainbow trout might persist longer, whereas an unusually warm spring could require earlier harvest or transition. Similarly, the warm-water phase may begin earlier, extend later, or become temporarily unsuitable during extreme summer conditions. This flexibility is important because climate change does not simply shift mean temperatures upward; it can also increase variability and alter the timing, duration, and intensity of environmentally suitable periods. FAO assessments have likewise emphasized that climate change can modify the suitability of geographical areas for aquaculture and that adaptation strategies must account for both long-term warming and shorter-term environmental variability.

From this perspective, the central adaptive mechanism of CUSAM is not the replacement of one species by another as a direct response to warming, but the dynamic matching of biological requirements with available environmental opportunities. This is an important distinction. If environmental conditions exceed acceptable physiological or ecological limits, changing species cannot be considered an unlimited solution to climate change. Reservoir carrying capacity, dissolved oxygen, water availability, disease risk, ecosystem integrity, and regulatory restrictions remain fundamental constraints. CUSAM therefore operates within environmental limits rather than attempting to overcome them.

The framework also reflects a broader transition occurring in climate-resilient aquaculture thinking. Adaptation increasingly requires flexibility at the level of species, farming systems, management practices, technology, and governance rather than reliance on a single technological intervention. Current FAO guidance similarly promotes aquaculture systems that are more productive, efficient, resilient, climate-smart, and environmentally responsible. CUSAM contributes to this perspective by introducing temporal flexibility as an additional dimension of adaptation: the same physical production infrastructure can potentially serve different biological production functions at different times of the year.

Consequently, the relevance of CUSAM extends beyond the original trout–tilapia sequence. Its broader contribution is the proposition that seasonal environmental heterogeneity can be incorporated explicitly into aquaculture planning. The question for future reservoir aquaculture may therefore shift from *"Which species can be produced here?"* toward *"Which species is most appropriate under these environmental conditions, during which part of the year, and when should the system transition to the next production phase?"* This change in perspective transforms seasonal temperature from a passive environmental constraint into an active decision variable while maintaining the fundamental requirement that production remains within ecological and biological limits.

Sequential species succession as the core principle of CUSAM

Species diversification has increasingly been recognized as a potential strategy for improving the resilience and adaptive capacity of aquaculture under climate change. Diversification can reduce dependence on a single species and provide producers with alternative production opportunities when environmental, biological, or market conditions become unfavourable. However, diversification is commonly considered in terms of increasing the number of cultured species, introducing alternative species, or redistributing production geographically (Dikel, 2009; Chai *et al*., 2023; Falconer *et al*., 2024). The CUSAM framework introduces an additional temporal dimension to this concept by proposing that species with contrasting thermal requirements can be cultured sequentially rather than simultaneously**,** with each species occupying the portion of the annual thermal cycle most compatible with its biological requirements. This approach is consistent with the growing recognition that species diversification should incorporate both future climate conditions and site-specific thermal suitability.

The distinction between sequential and conventional diversification is important. Under CUSAM, the objective is not simply to increase the number of species produced within a farm. Instead, the production year is divided into biologically meaningful thermal windows, and each window is allocated to a species capable of utilizing those conditions efficiently. In the reference case of Seyhan Dam Lake, rainbow trout represents the cool-season component and tilapia the warm-season component. The historical trials demonstrated the biological feasibility of this sequence, while the present framework extends the underlying principle toward longer and environmentally responsive production windows. Consequently, the trout–tilapia combination should be understood as the reference configuration of CUSAM rather than its universal prescription**.** This interpretation considerably increases the potential transferability of the model.

The central requirement is the existence of sufficiently distinct seasonal environmental windows that can support species with different thermal preferences. Therefore, implementation in another reservoir would not necessarily require either rainbow trout or tilapia. Alternative cool-, temperate-, or warm-water species could be considered according to local environmental conditions, available juveniles, growth characteristics, ecological compatibility, biosecurity requirements, legislation, consumer preferences, and market value. Such flexibility is consistent with climate-adaptation approaches that recommend shifting toward less vulnerable or more resilient species where environmental conditions change (Maulu *et al*., 2021)

Nevertheless, species succession should not be interpreted as unrestricted species substitution. Introducing non-native or potentially invasive species solely because their thermal requirements appear compatible with future temperatures could create substantial ecological and regulatory risks. Candidate species must therefore be selected within the ecological and legal context of each reservoir. Native or already established cultured species may be preferable where appropriate, and any proposed succession should be evaluated for escape risk, disease transmission, interactions with wild populations, and ecosystem carrying capacity. In this respect, the geographical regions identified in Figure 2 and Table 2 represent candidate environments for testing the CUSAM principle rather than recommendations for introducing the Çukurova trout–tilapia combination into those locations**.**

A further advantage of sequential production is its potential to increase the temporal utilization of existing aquaculture infrastructure. Seasonal cage aquaculture based on a single temperature-sensitive species can result in prolonged periods during which cages, mooring systems, service equipment, and associated labour capacity remain underutilized. A second production phase may potentially convert part of this inactive period into productive use without requiring an entirely separate farming platform. This characteristic differentiates CUSAM from diversification strategies that depend primarily on expanding farming area or establishing additional production systems. However, the extent to which increased infrastructure utilization translates into economic benefit remains to be experimentally and economically demonstrated.

Sequential production also provides an opportunity for a deliberate transition period between species. The interval following harvest can be used for net cleaning or replacement, cage maintenance, inspection of mooring systems, biosecurity procedures, and preparation for the subsequent production cycle. Such transition periods should be considered an integral component of CUSAM rather than unproductive interruptions. Their duration may vary according to farm conditions, species, environmental conditions, and operational requirements, and they may contribute to reducing biological and technical risks associated with continuous production.

Importantly, diversification alone cannot guarantee climate resilience. Recent work emphasizes that species diversification should form part of a broader system-level strategy incorporating water and environmental management, feed efficiency, biosecurity, value chains, governance, and other adaptive interventions (Dinh, 2026). CUSAM should therefore not be regarded as a stand-alone solution to climate change. Its contribution lies in providing a temporal production architecture within which species selection can be combined with environmental monitoring, farm management, biosecurity, market planning, and eventually predictive decision-support systems.

The core principle of CUSAM can thus be expressed as seasonally synchronized species **succession**: matching successive species to environmentally suitable production windows while using the same basic production infrastructure across the annual cycle. This principle distinguishes the conceptual model from the historical experiment from which it originated. The historical trout–tilapia trials demonstrated that sequential production was biologically possible under Çukurova conditions; CUSAM generalizes this observation into a flexible framework in which the species, timing, and duration of each production phase can be adapted to local and changing environmental conditions.

Importantly, the need for such temporal and locally adapted production strategies is also supported by recent producer-level evidence. Maulu *et al*. (2024) emphasized that aquaculture vulnerability to climate change is determined not only by direct environmental exposure but also by producers' geographical location, socioeconomic conditions, access to information, and adaptive capacity. Their nationwide assessment of aquaculture producers in Zambia identified limited species diversity, insufficient financial resources, lack of insurance, and inadequate knowledge of alternative production options among the factors increasing climate vulnerability. Notably, adjustments in fish cultivation periods, livelihood diversification, and modification of production infrastructure were among the adaptation strategies already being adopted by producers. These observations support the underlying rationale of CUSAM: climate adaptation in aquaculture should be locally configured and sufficiently flexible to allow production practices and culture periods to respond to changing environmental conditions rather than remaining fixed over time (Maulu *et al*., 2024). This producer-level perspective also indicates that biological adaptation alone is unlikely to be sufficient. Climate-related disturbances can propagate beyond the farm environment through production costs, market conditions, supply chains, and household livelihoods, thereby increasing the vulnerability of producers and aquaculture-dependent communities (De Silva and Soto, 2009; Barange *et al*., 2018; Maulu *et al*., 2021a, 2024). Such vulnerability may be particularly pronounced among small-scale producers with limited financial and technological capacity to respond to environmental change. Consequently, localized adaptation strategies should consider not only thermal suitability and species selection, but also access to climate information, financial capacity, market conditions, infrastructure, and institutional support (Brugère and De Young, 2015; Maulu *et al*., 2024).

In this sense, CUSAM adds a temporal question to conventional species diversification: not only "which species should be cultured?", but also "which species should be cultured at which time of the year?" As climate change increasingly modifies the suitability and duration of aquaculture production periods, incorporating this temporal dimension into species-selection strategies may become an important component of climate-responsive reservoir aquaculture.

Production, economic and sustainability implications

Beyond its biological and climate-adaptation rationale, the potential value of CUSAM should also be considered from production, economic, and sustainability perspectives. Seasonal cage aquaculture based on a single temperature-sensitive species may leave production infrastructure partially or completely unused during environmentally unsuitable periods. Cages, mooring systems, service equipment, and associated operational capacity nevertheless represent investments whose costs continue beyond the active grow-out period. By allocating different portions of the annual thermal cycle to species with contrasting environmental requirements, sequential production may increase the annual utilization efficiency of existing aquaculture infrastructure without necessarily requiring a proportional expansion of the farming area.

This aspect is particularly relevant to the historical conditions that motivated the development of the model in Çukurova. Rainbow trout production in low-altitude Mediterranean environments is constrained by increasing water temperatures as the warm season approaches. Consequently, production facilities established for cool-season trout culture may remain inactive after trout harvest even though the reservoir itself continues to provide conditions potentially suitable for warm-water aquaculture. The original Seyhan Dam Lake experience demonstrated that this seasonal discontinuity could, in principle, be converted into a second production opportunity by subsequently using the same cage system for tilapia. CUSAM extends this observation by treating annual infrastructure utilization, rather than the performance of either species alone, as an important component of production-system efficiency.

Sequential production may also contribute to the diversification of production and income opportunities. Dependence on a single species can expose farms to species-specific risks associated with environmental stress, disease, feed costs, juvenile availability, price fluctuations, and changing consumer demand. Producing different species during separate periods of the year may distribute some of these risks across the production cycle and provide more than one harvest and marketing opportunity. This potential benefit is particularly relevant under climate change, where biological and economic uncertainties can occur simultaneously. Climate-related disturbances may reduce productivity while increasing operational costs and generating broader economic consequences throughout aquaculture value chains (De Silva and Soto, 2009; Barange *et al*., 2018).

However, production diversification should not automatically be equated with greater profitability. Sequential culture introduces additional operational requirements, including the procurement of different juveniles and feeds, changes in feeding and husbandry practices, net cleaning or replacement, biosecurity procedures, harvesting and restocking logistics, and potentially different marketing channels. The profitability of CUSAM will therefore depend on whether the additional revenue generated during the second production window exceeds these transition and operating costs. Market-size requirements and harvest timing will also be important because achieving biological growth potential does not necessarily guarantee economic optimization. For this reason, future evaluation of CUSAM should incorporate partial-budget analysis, cost–benefit assessment, break-even analysis, and sensitivity analysis alongside conventional growth and feed-utilization measurements.

Market proximity may represent another relevant component of the model, particularly in regions such as Çukurova where large urban consumer markets are located relatively close to suitable reservoir production areas. Seasonal trout production closer to consumption centres may potentially reduce some of the logistical constraints associated with transporting fish from distant high-altitude production regions. Similarly, a subsequent warm-water harvest could provide an additional seasonal product to local markets. Nevertheless, these potential advantages will depend on consumer acceptance, market prices, processing and cold-chain infrastructure, and competition with established products. Market feasibility should therefore be evaluated locally rather than assumed as an inherent advantage of sequential production.

From a sustainability perspective, more intensive temporal use of existing infrastructure could potentially improve the amount of production obtained from already established farming assets. This differs conceptually from strategies based primarily on increasing cage numbers or expanding the spatial footprint of aquaculture. In reservoirs where further physical expansion is environmentally or socially constrained, improving the productive use of existing infrastructure may represent an alternative pathway for increasing annual output. However, greater infrastructure utilization must not be interpreted as justification for exceeding ecological carrying capacity. Two successive production cycles may increase annual feed inputs, nutrient release, organic loading, and cumulative environmental pressure even if cage numbers remain unchanged. Environmental sustainability must therefore be evaluated on an annual system basis rather than separately for each production phase.

This consideration is particularly important for reservoir ecosystems, where aquaculture interacts with multiple ecosystem services and water uses. The environmental feasibility of CUSAM should consequently consider seasonal and cumulative feed inputs, nutrient budgets, sedimentation, water exchange, dissolved oxygen dynamics, reservoir trophic status, and interactions with wild aquatic communities. The transition between production phases may also provide an opportunity for cage cleaning, maintenance, biosecurity procedures, and, where necessary, a short fallowing period. Such intervals should be incorporated into production planning rather than eliminated solely in pursuit of maximum infrastructure utilization.

The practical sustainability of sequential production will also depend on whether farms possess sufficient technical and financial capacity to manage two biologically distinct production phases. Transitioning between species may require additional working capital, access to suitable juveniles and feeds, technical knowledge, labour organization, and reliable marketing channels. These requirements may be particularly important for small- and medium-scale enterprises, for which the additional complexity of sequential production could offset some of the benefits obtained from increased infrastructure utilization. Therefore, the feasibility of CUSAM should be evaluated not only in terms of biological performance but through the interaction between environmental suitability, operational capacity, economic feasibility, and market opportunity**.**

At a broader level, these considerations suggest that the potential sustainability contribution of CUSAM derives from temporal optimization rather than simple production intensification**.** The objective is not to maximize biomass continuously throughout the year, but to use environmentally suitable periods more strategically while avoiding production when biological or ecological conditions become unfavourable. This distinction is fundamental to the climate-adaptive character of the model. An economically and environmentally successful CUSAM system would therefore not necessarily be the system with the greatest annual biomass production, but the one that achieves an appropriate balance among biological performance, infrastructure utilization, economic return, environmental carrying capacity, and climate resilience.

Accordingly, the economic and sustainability performance of CUSAM should ultimately be assessed through an integrated set of indicators rather than through fish growth alone. Future validation studies should combine biological variables such as survival, growth, feed conversion ratio, and harvest biomass with economic indicators including production cost, gross margin, infrastructure utilization, and market value, as well as environmental indicators such as feed-derived nutrient inputs, water-quality responses, and carrying-capacity constraints. Such an integrated assessment would determine whether sequential seasonal production can translate its biological feasibility into a genuinely economically viable and environmentally responsible climate-adaptation strategy for reservoir aquaculture.

CUSAM in the context of climate-smart and digital aquaculture

The conceptual development of CUSAM coincides with a broader transformation in aquaculture toward production systems that are increasingly climate-responsive, data-informed, and adaptive. Contemporary approaches to sustainable aquaculture no longer consider productivity as an isolated objective but increasingly emphasize the simultaneous improvement of production efficiency, environmental responsibility, resilience, and adaptive capacity (Boyd *et al*., 2020). The FAO

Guidelines for Sustainable Aquaculture explicitly promote the development of aquaculture systems that are more productive, efficient, resilient, climate-smart, and socially and environmentally responsible (FAO, 2025a). Within this broader perspective, CUSAM can be interpreted as a climate-adaptation framework in which temporal production planning and species selection constitute the primary adaptive mechanisms, while digital technologies provide an increasingly important layer of environmental observation and decision support.

This interpretation is also consistent with the recently developed FAO Aquaculture Adaptation Framework for Climate Change (Aqua-Adapt), which emphasizes that adaptation should be based on climate projections, risk and vulnerability assessment, implementation of appropriate adaptation measures, and continuous monitoring and evaluation (Soto and Sampaio, 2025). Importantly, this approach treats adaptation as an iterative process rather than a one-time management intervention. Such a perspective is directly relevant to CUSAM because the seasonal production windows proposed by the model cannot be assumed to remain temporally fixed under continuing climate change. Their duration and timing may vary among years and may shift progressively over longer climatic periods. Consequently, periodic reassessment of thermal suitability becomes an integral component of the model rather than an optional management activity.

The transition from fixed production schedules toward environment-responsive production creates an important role for digital aquaculture (Sevin and Dikel, 2025). Continuous sensor-based monitoring can increase the temporal resolution with which farmers observe water temperature, dissolved oxygen, and other environmental variables, while integration of Internet of Things (IoT) technologies can facilitate the collection and transmission of such information (Huang, 2025; Öz *et al.*, 2025). Recent developments combining artificial intelligence with IoT systems (AIoT) demonstrate increasing potential for real-time environmental monitoring, data-driven decision-making, and automation in aquaculture (Ahmed *et al.*, 2022). These capabilities are particularly relevant to reservoir cage farming because environmental conditions cannot be controlled to the same extent as in closed or highly engineered production systems.

However, the principal contribution of digitalization to CUSAM would not be the accumulation of environmental data itself. Its greater value would lie in converting observations into management-relevant information. Artificial intelligence and machine-learning approaches are increasingly being investigated in aquaculture for applications including environmental monitoring, feeding, biomass estimation (Dikel and Erarslan, 2025), health assessment (Öz *et al.*, 2025), forecasting, and operational decision-making (Føre *et al*., 2018; Ringo *et al*., 2025). Recent reviews nevertheless emphasize that practical adoption remains constrained by data availability and quality, model transferability, infrastructure requirements, technical expertise, and the difficulty of deploying models reliably under variable commercial farm conditions. Thus, digitalization should not be interpreted as automatically generating adaptive capacity; its contribution depends on whether data and predictions can be translated into timely and biologically meaningful farm decisions.

This distinction is particularly important for CUSAM. The relevant question is not simply whether future water temperature can be predicted, but whether such prediction improves decisions regarding when to stock, when to harvest, when to modify feeding, and when to transition from one species to another**.** In this sense, the digital pathway of CUSAM can be represented as a progression from monitoring to prediction and from prediction to adaptive action**.** Monitoring characterizes the current production environment; predictive models estimate its probable trajectory; and decision-support tools translate this information into operational alternatives. Such a decision-oriented structure would allow the seasonal boundaries of CUSAM to become dynamic rather than calendar-defined.

The increasing replacement of traditional aquaculture approaches with data-driven and intelligent systems enables more precise, traceable, and sustainable management of production processes (Sevin and Dikel, 2025). One of the most notable components of this transformation is digital twin (DT) technology, which has become widespread in various industries in recent years (Fuller *et al*., 2020). Digital twin technology represents a further potential development along this path. In aquaculture, DTs aim to integrate continuously updated sensor observations with mathematical or computational representations of the production system, enabling the monitoring, simulation, prediction, and evaluation of alternative management scenarios (Duarte *et al*., 2024; Føre *et al*., 2024; Jeremiah *et al*., 2024). For CUSAM, a future digital representation of a reservoir cage farm could potentially combine environmental conditions, fish growth, biomass, feeding, thermal forecasts, and production economics to compare alternative seasonal strategies before they are implemented. Rather than automatically controlling production, such a system could allow farmers to explore questions such as whether trout should be harvested earlier under a predicted warm spring, whether stocking of the subsequent warm-water species should be delayed, or how an altered production window might influence expected harvest biomass and economic performance.

Nevertheless, the technological maturity of such systems should not be overstated. A recent systematic review of 80 studies on Decision Support

Systems and Digital Twins in aquaculture found rapid research growth but also a substantial gap between prototype development and sustained on-farm implementation. Major limitations included data standardization and quality, model generalization across farms and seasons, continuous calibration and validation, and insufficient evidence regarding cost-effectiveness and adoption pathways. Digital Twin applications in aquaculture therefore remain predominantly at research and developmental stages rather than representing established commercial practice (Shubairi *et al*., 2026). These limitations are particularly relevant to CUSAM because reliable prediction across seasons and years would require long-term, site-specific environmental and production datasets. For this reason, technological complexity should not become a prerequisite for implementation of the basic CUSAM principle. A small or medium-scale producer equipped with reliable temperature and dissolved-oxygen measurements could potentially apply environment-responsive species scheduling without sophisticated AI infrastructure. More technologically advanced farms could progressively incorporate automated sensors, forecasting algorithms, decision-support systems, and eventually digital twins. Such a tiered digitalization pathway would allow the model to remain accessible while providing opportunities for increasing predictive capability as data availability, technical capacity, and economic resources improve.

This scalability is particularly important from a climate-smart aquaculture perspective. Digital transformation can contribute to climate adaptation only when technological solutions are appropriate to farm scale, economically accessible, understandable to users, and capable of supporting actual management decisions. The objective should therefore not be maximum automation, but appropriate digitalization: using the level of technology necessary to reduce uncertainty and improve the timing and quality of decisions without creating technological or economic barriers that outweigh the expected benefits.

Ultimately, CUSAM can be positioned within climate-smart and digital aquaculture as a biologically grounded production framework whose adaptive capacity may be progressively strengthened through environmental monitoring, forecasting, and decision support. Its fundamental mechanism remains the synchronization of species-specific biological requirements with changing seasonal conditions; digital technologies do not replace this ecological principle but can improve the capacity to implement it dynamically. In this sense, the future development of CUSAM may represent a transition from historically observed seasonal production, to environmentally responsive management, and ultimately to predictive climate-adaptive aquaculture.

Limitations and future research needs

Although the Çukurova Sequential Aquaculture Model (CUSAM) is grounded in historical experimental evidence and contemporary knowledge on climate adaptation, several limitations should be acknowledged. First, the empirical basis of the model originates from earlier sequential cage-culture trials conducted in Seyhan Dam Lake, whereas the extended production windows proposed under CUSAM have not yet been validated through contemporary long-duration field experiments. Accordingly, the conceptual harvest targets and seasonal production windows presented in the framework should be regarded as testable production scenarios rather than established performance outcomes.

Second, the model is based primarily on thermal suitability, while the feasibility of sequential production in reservoir systems is also influenced by dissolved oxygen, stratification, water-level fluctuations, water quality, carrying capacity, disease pressure, feed availability, reservoir hydrodynamics, and extreme climatic events. Future studies should therefore evaluate the interaction between seasonal temperature dynamics and these additional environmental variables under real farming conditions.

Third, the rainbow trout–tilapia sequence represents the historical reference combination from which CUSAM was developed, but it should not be interpreted as a universally applicable species pair. Regional adaptation will require the selection of locally appropriate cool-water and warm-water species according to ecological compatibility, biosecurity, legal restrictions, market demand, and production economics. Multi-location trials across Mediterranean, subtropical, and warm-temperate reservoir systems would be particularly valuable for testing the broader transferability of the model.

Another important limitation concerns interannual and long-term climatic variability. Production windows that are suitable under current conditions may shift, shorten, or expand under future warming scenarios. Long-term monitoring of reservoir temperatures, dissolved oxygen, and hydrological conditions is therefore necessary to determine how stable the proposed production windows remain over time. Climate projections should also be incorporated into future evaluations to assess whether some reservoirs may gradually lose suitability for cool-water species or require alternative warm-water production strategies.

Economic validation is equally important. Although sequential production may improve annual cage utilization and reduce periods of inactivity, its actual profitability will depend on juvenile supply, feed costs, labour, market prices, harvest timing, infrastructure requirements, and transition costs between species. Future studies should therefore combine biological performance with farm-level economic analysis, including cost–benefit assessment, sensitivity analysis, and risk evaluation.

Finally, the digital and predictive components proposed within CUSAM remain conceptual. Future research should examine how IoT-based monitoring, machine-learning models, early-warning systems, and digital decision-support tools can be integrated into operational reservoir farms. Validation of these technologies should focus not only on prediction accuracy but also on usability, cost, scalability, and their practical value for small- and medium-scale producers.

Future research should therefore move CUSAM from a conceptual framework toward an experimentally validated adaptive production system through long-term, multi-site, multi-species, and economically integrated studies. Such work would allow the model to be refined, regionalized, and potentially incorporated into climate-smart reservoir aquaculture planning.

Conclusions and recommendations

The Çukurova Sequential Aquaculture Model (CUSAM) represents a climate-change-adaptive production framework developed by reinterpreting historical sequential cage-culture experience within the context of current and future environmental change. The model is based on a simple but transferable principle: the sequential use of seasonally suitable cool-water and warm-water species within the same reservoir-based production infrastructure.

Historical evidence from Seyhan Dam Lake demonstrated that rainbow trout and tilapia could be produced successfully under distinct seasonal thermal conditions using the same cage system. CUSAM extends this empirical observation by proposing broader adaptive production windows that respond to seasonal temperature dynamics rather than fixed calendar dates. In this sense, the principal innovation of the model is not the trout–tilapia combination itself, but the concept of seasonally synchronized species succession.

The model also reframes climate variability as a management variable. Rising temperatures should not be interpreted as inherently beneficial to aquaculture; however, production systems can become more resilient when species selection, stocking, harvest, and transition periods are aligned with actual environmental conditions. This shift from calendar-based production toward environment-responsive production may become increasingly important in reservoir systems exposed to changing thermal regimes.

CUSAM may offer several potential benefits, including more continuous use of cage infrastructure, improved annual production capacity, reduced idle periods, diversified farm income, and greater flexibility under climate uncertainty. Its broader application, however, requires regional adaptation. Local water quality, hydrology, species availability, carrying capacity, biosecurity, legal regulations, market access, and socioeconomic conditions must determine the final configuration of the model.

For future implementation, producers and researchers should prioritize continuous environmental monitoring, locally appropriate species selection, adaptive production scheduling, and periodic reassessment of seasonal thermal windows. Where economically feasible, digital technologies such as IoT sensors, predictive modelling, AI-assisted decision support, and early-warning systems may further strengthen the adaptive capacity of the model by supporting timely decisions on feeding, stocking, harvest, and species transition.

The geographical comparison presented in this study suggests that the underlying CUSAM principle may be adaptable to other Mediterranean, subtropical, and warm-temperate reservoir regions, but such transfer should be treated as a hypothesis requiring site-specific validation. Therefore, the next stage in the development of CUSAM should focus on multi-year field trials, economic feasibility studies, and regional validation under different climatic and production conditions.

Ultimately, CUSAM provides a practical conceptual bridge between past aquaculture experience, present climate-related challenges, and future adaptive production planning. By integrating seasonal ecology, species biology, production management, and emerging digital technologies, the framework may contribute to the development of more flexible, resource-efficient, and climate-responsive reservoir aquaculture systems.

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