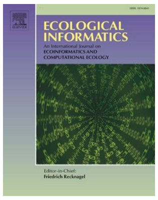
Ecological Informatics 82 (2024) 102761

Contents lists available at ScienceDirect

Ecological Informatics

journal homepage: www.elsevier.com/locate/ecolinf



Exploring the thermal adaptability of silver pompano *Trachinotus blochii*: An initiative to assist climate change adaptation and mitigation to augment aquaculture productivity

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ARTICLE INFO

Keywords:
Climate change
Thermal tolerance
Acclimation temperature
Climate smart marine aquaculture
Food security

ABSTRACT

Temperature is one of the crucial environmental factors affecting the physiology and suitability of fish species for aquaculture, making it vital to predict how the present rate of climate change will impact these species. To assess the heat tolerance of silver pompano *Trachinotus blochii*, the Critical Thermal Maxima (CT_{max}) and Critical Thermal Minima (CT_{min}) were investigated at six different acclimation temperatures (T_{acc}), ranging from 18 to 36 °C. Generalized Additive Model (GAM) was performed on CT_{max} and CT_{min} and tested for data validation. The results revealed that the CT_{max} and CT_{min} for *T. blochii* were 41.1 ± 0.0478 °C and 12.0 ± 0.0748 °C, respectively. The Thermal Tolerance Polygon was calculated to be 357.02 $^{o}C^{2}$ for the specified temperatures. The study revealed that silver pompano acclimated to higher temperatures exhibited greater thermal tolerance. Additionally, it was found that their thermal tolerance could be increased through an acclimation regime, allowing them to adapt better to higher temperatures. The results enlighten the species potential towards securing global food security and sustainable development, as these resilient finfish can be integrated into climate-smart marine aquaculture systems to mitigate the effects of climate change by providing valuable information for future actionable strategies for species diversification.

1. Introduction

Climate change is defined as variations in the statistical distribution of weather over long period of time, often spanning decades to millions of years (Khoshnevis Yazdi and Shakouri, 2010). It is a well-established fact that changing climate has an adverse effect on global fisheries and aquaculture (IPCC, 2007). The unpredictability caused by climate change leads to extreme weather events and alters ocean conditions, affecting marine ecosystems and fisheries, notably water temperature and ocean biogeochemistry. Rising sea temperatures modify marine ecosystems by altering food allocation, disrupting reproduction, and shifting habitat ranges for species (Smale et al., 2019). Due to the

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https://doi.org/10.1016/j.ecoinf.2024.102761
Received 18 October 2023; Received in revised form 5 August 2024; Accepted 6 August 2024

accelerating rate of ocean warming (Cheng et al., 1979), and increasing frequency of in marine heatwaves (Babcock et al., 2019), many species have been compelled to shift their natural distributional ranges to find and maintain suitable environmental conditions to thrive (Pinsky et al., 2020). Recent variations in the distribution and productivity of several fish species may also be attributed to regional climatic variability with high certainty. It is anticipated that these modifications will have an impact on marine fisheries production (Brander, 2007). Studies indicate that potential losses to fisheries due to climate change are greater, as compared to agriculture and these losses are more likely to be felt by communities with lower socioeconomic status (Cinner et al., 2022). As the proportion of aquaculture produced in marine waters continues to increase, it is crucial to proactively anticipate and address the potential opportunities and challenges that may arise in marine production, especially through the influence of climate change (Froehlich et al., 2016). There are still numerous uncertainties regarding the extent and fluctuation of climatic risks across vast ecosystem boundaries, and within entire clades of organisms (Pacifici et al., 2015) affecting the blue economy.

The key to the survival of any organism is its capacity to adapt to a changing environment. According to NCEI.Monitoring.Info@noaa.gov, 2021 Annual Climate Report, the combined land and ocean temperature has increased at an average rate of 0.14 °F (0.08 °C) per decade since 1880; however, the average rate of increase since 1981 has been more than twice as fast: 0.32 °F (0.18 °C) per decade (NCEI.Monitoring.Info@noaa.gov, 2021). Gathering pertinent information on thermal acclimation, the range of tolerable temperatures, and temperature preferences, is crucial for anticipating the responses of fish species to climate change impacts. Furthermore, obtaining such data is necessary for the effective and efficient production of aquaculture (Roessig et al., 2004). Numerous teleosts have evolved their own behavioral and physiological adaptations to deal with temperature variations (Prosser, 1991). Analyzing the underlying processes of the fascinating phenomena of climate tolerance and adaptability might help galvanize action and enhance resilience. The Critical Thermal Methodology (CTM) technique has been widely used to evaluate the thermal tolerance of fishes, as the loss of equilibrium is considered to indicate an animal's ecological death under certain circumstances (Lutterschmidt and Hutchison, 1997). The ability of ectothermic organisms to endure global warming trend, including the heightened frequency, severity, and duration of extreme heatwaves, will be contingent upon their upper thermal threshold capacities (Stillman, 2019). The way these upper thermal limits are impacted by temperature changes may have significant implications for predicting the effects of global warming, as temperatures are expected to increase in the future (Gillooly et al., 2001). The acute warming tolerance of these organisms, assessed through the critical thermal maximum (CT_{max}), displays inter-species variation that corresponds to the thermal characteristics of their specific habitats (Comte and Olden, 2017). Increasing water temperature also affects the sustainable growth of warm-water fish species in lakes (Yaghouti et al., 2023) and several researchers have determined the thermal tolerance limit of freshwater species (Becker and Genoway, 1979; Beitinger et al., 2000; Campos et al., 2021; Currie et al., 1998; Das et al., 2020; Reizenberg et al., 2019).

In the past 50 years, aquaculture has grown rapidly (Bostock et al., 2010), now providing over 50% of the world's seafood (FAO, 2022). This expansion is driven by the demand for fish protein (Godfray et al., 2010). Despite recent growth, aquaculture can expand further into the ocean, as it currently occupies only a small portion of potential growth areas (Duarte et al., 2009; FAO, 2014; Holmer, 2010). One-third of the world's aquaculture comes from marine waters (FAO, 2022). Although, mariculture (marine aquaculture) may have many environmental implications, which can be alleviated via the use of best management techniques and careful site and species selection (Goldburg et al., 2001). Hence, understanding the potential capacity and variety of farmed marine species, as well as the trade-offs associated with their adaptability to various environmental conditions, is essential for improving sustainable marine production.

Evaluating the global potential of mariculture, requires a fundamental reference point, such as an understanding of the physiological demands and constraints of marine animals to grow in specific habitat. Temperature changes influence the rate of biochemical activities, species distribution, and ecosystem-level responses to climatic variability (Perry et al., 2005). However, some species are anticipated to be innately susceptible to climate change due to their exposure and sensitivity to warming, as well as their adaptation capabilities. Further, the capacity of a species to endure adverse conditions has substantial implications for production (Froehlich et al., 2016). Therefore, in the present study, we have utilized different thermal deviations to assess the sensitivity of silver pompano, *Trachinotus blochii* to both increasing and decreasing temperatures and studied them with predicted ocean warming data to forecast the level of thermal tolerance of the species from present-day populations to coming warming scenarios, over the next century. Defining which species currently live near their upper thermal limit can provide a basis for evaluating how marine ecosystems will be changing in the future, especially during extreme weather events, and which species will be most vulnerable to local extinction (Somero, 2005).

According to FAO (2018), sustainable aquaculture is vital for achieving SDGs, especially SDG 2, which seeks to end hunger, achieve food security, improve nutrition and promote sustainable agriculture, and SDG 13, which aims to promote climate action. Apart from this, there is significant global interest in cultivating finfish species in both cold and warm water for the development and expansion of aquaculture (Le François et al., 2010). Aquaculture can potentially enhance resilience through improved resource use efficiencies and increased diversification of farmed species (Troell et al., 2014). Climate-resilient aquaculture adaptations are necessary to sustain production and uphold socio-economics (Abisha et al., 2022). Incorporating high value finfishes is one way to ensure this sustainable production (Jayakumar et al., 2020). The resilience of production systems to climate change is also critical for both environmental sustainability and nutrition (Bogard et al., 2019).

Diversification of aquaculture becomes crucial to meet the rising demand for fish protein and relieve pressure on marine resources caused by capture fisheries (Abisha et al., 2022; Shaffril et al., 2019) and is suggested as one of the best alternatives to cope with climate change effects on the food production sector. In this context, diversification, which involves the introduction of new candidate fish species, is gaining momentum, considering the vast range of agroclimatic conditions that exist in tropical and subtropical countries. The selection of species for cultivation is generally predicted on the quantity of input needed, the pace of development, and the degree of tolerance to diverse environmental conditions (Boyd et al., 2022).

In light of all these aspects discussed, we can take into account, Silver pompano, *T. blochii*, which is an easily domesticated and adaptable pelagic species, well-suited for culture in tropical marine waters. Its sturdiness and adaptability make it a prime candidate for mariculture (Chavez et al., 2011), especially due to its rapid growth, high-quality meat and strong market demand (Ariska and Irawan, 2018). Silver pompano is farmed in open sea cages as well as brackish water cages and ponds across China, India, Indonesia, the Philippines, Taiwan, Malaysia, Florida, Hong Kong, Thailand, and Vietnam (FAO, 2022). The cultivation of Pompano has prompted the development of hatchery and grow-out techniques in Singapore and Taiwan to meet the increasing demand in Asian markets (Surtida et al., 2000). With a significant market demand for Pompano, both domestically and internationally, the potential for the sale of this finfish can reach 20 million pounds per year (McMaster, 2003). Its accessibility due to its widespread geographical distribution over the Indo-Pacific region, including the-Red Sea and East Africa to the Marshall Islands and Samoa, north to southern Japan and south to Australia (Nazar et al., 2017) is a primary factor that contributing to the significance of this study. The optimum growth temperature for silver pompano is recorded to be 29–31 °C (Juniyanto and Akbar, 2008). However, seawater temperatures are likely to exceed this range during summer, moving away from the normal tolerance range of the species (Hoegh-Guldberg et al., 2018). The rising water temperature due to climate change is anticipated to affect the productivity of silver pompano in both wild and aquaculture conditions. Water temperature and growth in fish show a positive correlation (Haag et al., 2019), however, deviations from the thermal optimum can adversely impact metabolic and immune functions, and cause cellular damage (Hochachka and Somero, 2002). Fish populations have this specific thermal optimum, and exceeding these thresholds can have lethal and sublethal impacts, ultimately affecting their long-term performance (Weber et al., 2020). Therefore, it is essential to determine the thermal tolerance limit of *T. blochii* in terms of CT_{max} and CT_{min}.

However, the thermal tolerance limit of commercially significant marine species, such as silver pompano, has not been evaluated yet. The silver pompano proves to be a highly potential tropical marine finfish species for aquaculture practice and can be successfully carried out in coastal earthen ponds, tanks or floating sea cages (Jayakumar et al., 2020; Nazar et al., 2019). Therefore, to bridge the prevalent knowledge gap regarding the thermal tolerance of this candidate species and its physiological response to temperature changes, the present study addresses four main queries here: 1) Being promising candidate mariculture species, what is the potential for silver pompano to combat increasing global temperature as a climate-resilient species? 2) What are the maximum and minimum tolerance thresholds of this species? 3) How does this species contribute to Sustainable Development Goals (SDGs) in new climate change scenarios? 4) How can we use this species to integrate into the species diversification for the future “Ecosystem approach to aquaculture”? Our study’s novelty is underscored by its comprehensive assessment of the thermal tolerance of *T. blochii*, a species for which no global reports on such capabilities currently exist. It addresses the urgent need for resilient species identification and adaptation within the mariculture domain, contributing significantly to the discourse on sustainable ecosystem management in the face of global environmental challenges. Furthermore, this research represents the first comprehensive assessment of the thermal tolerance of *T. blochii* and evaluates both maximum and minimum thermal thresholds under various climate scenarios, offering a comprehensive view of species adaptability. The study also highlights the thermal tolerance capabilities of *T. blochii* for climate-smart mariculture research which is recommended as *"preparedness for future"* for predicting the appropriateness of the candidate species for aquaculture diversification in various subtropical regions across the globe with comparable agro-climate.

2. Material and methods

2.1. Experimental procedures

The non-lethal CTM was used to determine the thermal tolerance of silver pompano, *T. blochii.* This approach allows for the modelling of natural temperature conditions, in addition to the measurement of the temperature range at which physiological indicators of heat stress are observed (Beitinger et al., 2000). The chronic lethal minimum provides insight intothe survival needs of fish in natural environments (Bennett and Beitinger, 1997), although sudden (acute) fluctuations in temperature, such as those encountered in low thermal plunge conditions, are not often observed in nature. (Doudoroff, 1942). The hatchery-raised experimental fish, *T. blochii*, were procured from the Vizhinjam Regional Centre of the Indian Council of Agricultural Research (ICAR) - Central Marine Fisheries Research Institute (CMFRI). Before commencing the experimental procedures, the fish were stocked in the Recirculatory Aquaculture System (RAS) for a period of 15 days at the normal existing temperature. There were 500 individuals measuring 35–45 mm in total length and 1.5–2.0 mg in wet weight. To maintain suitable water quality for the fish, a 40–50%water exchange was performed daily. During the holding time in RAS, the pH, temperature, Dissolver Oxygen (DO), salinity, and photoperiod were maintained at 7.92–7.06, 25-26 °C, 5.6–6.1 mg/L, 34–35 ppt, and 12 L:12D, respectively. The fishes were fed a formulated diet three times a day at 2% of the biomass.

There was a total of fifteen fishes that were randomly assigned to each of the following acclimation temperatures (T_{acc}) in three distinct thermostatic aquariums (each with a 50 l capacity): 18 °C, 22 °C, 26 °C, 30 °C, 34 °C and 36 °C. Fish were acclimated to temperature by reducing or increasing the water’s ambient temperature (25-26 °C) by 1 °C (Currie et al., 2004; Kır et al., 2017; Saravia et al., 2021) per day until they reached the desired T_{acc}. Before the start of the thermal tolerance testing, the fish were kept for a further 15 days at their designated T_{acc}. The fish were not fed for 24 h before being subjected to Critical Thermal Methodology (CTM) tests.

Five randomly chosen fish from each T_{acc} were transferred to thermostatic aquaria (20-L water capacity, sensitivity 0.02 °C), which were maintained at their respective acclimated temperature. Until loss of equilibrium (LOE) was observed, the acclimated fish were treated to a constant rate of ramping up (for CT_{max}) or ramping down (for CT_{min}) of temperature at 0.3 °C min^{-1} (Dalvi et al., 2012; Das et al., 2004; Donelson et al., 2011) from their respective T_{acc} with a control (Becker and Genoway, 1979). The arithmetic mean of the thermal points at which each individual’s locomotive activity becomes disorganised and the organism loses its ability to escape the condition is regarded as the endpoint of the experiment (Beitinger et al., 2000; Cowles and Bogert, 1944). Following the recording of the CT_{max} and CT_{min} readings, the fish were retrieved from the tank using a tiny hand net and transferred to the RAS. Immediately after the completion of the CTM test, the fish were separated from the tank they had been kept in, moved to a new aquarium, and their survival was monitored for the next 24 h.

The thermal tolerance polygon was created from these CT_{max} and CT_{min} data by plotting T_{acc} on the X-axis and tolerance zone on the Y-axis (Azra et al., 2018; Das et al., 2006; Debnath et al., 2006). Following the techniques of Dalvi et al. (2009), Dülger et al. (2012), and Campos et al. (2017), the area of thermal tolerance was derived from the polygon. The upper and lower boundaries were defined by the regression model of CT_{max} or CT_{min} on T_{acc} of fish using the ‘ggplot2’ package in R (Wickham and Wickham, 2016).

2.2. Statistical analysis

The statistical analyses of CT_{max} and CT_{min} were carried out using the Kruskal–Wallis test (ANOVA) and Mann-Whitney test (Wilcoxon rank sum test).

Kruskal-Wallis test (H) given as:

$$H = \left(\frac{12}{N(N+1)}\sum_{j=1}^{k}\frac{R_J^2}{n_j}\right) - 3(N+1) \tag{1}$$

Where k = the number of comparison groups, N = the total sample size, n_j is the sample size in the j^{th} group and R_j is the sum of the ranks in the j^{th} group.

and Mann-Whitney *U* test given as:

$$U_1 = n_1 n_2 + \frac{n_1(n_1+1)}{2} - R_1 \tag{2}$$

$$U_2 = n_1 n_2 + \frac{n_2(n_2+1)}{2} - R_2 \tag{3}$$

Where R_1 and R_2 are the sums of the ranks in groups 1 and 2, respectively.

The normality distribution of CT_{max} and CT_{min} was tested using the Shapiro-Wilk test Normal Quantile plot and Box plots illustrated the distribution of the data (Fig. S1). All the statistical analysis were carried out using R version 4.2.2 software (R Core Team, 2022). Further, Generalized Additive Model (GAM) was used to explore the effects of CT_{max} and CT_{min} on T_{acc}. GAM is able to deal with nonlinear relationships between a dependent variable and multiple predictors in the same model. GAMs are less restrictive in assumptions about the underlying distribution of data (Hastie and Tibshirani, 1990) and multiple predictors are modelled with smooth functions. The GAM models were fitted using the 'mgcv- minimizing generalized cross-validation' package in R (Wood, 2006). The GAM structure can be written as:

$$g(E(Y)) = \alpha + s1(x1) + \ldots + sp(xp) \tag{4}$$

where Y is the dependent variable (i.e., what we are trying to predict), E (Y) denotes the expected value, and g(Y) denotes the *link function* that links the expected value to the predictor variables x_1, ….,x_p. The terms s1(x1), …,sp.(xp) denote smooth, nonparametric functions. Here the model selection for GAM fitting was:

$$Acc_{Temp} = s(CTmax) + s(CTmin) \tag{5}$$

3. Results

3.1. Thermal threshold and acclimatization

In the present study, T_{acc} significantly affected the CT_{max} and CT_{min} of the fishes. The critical thermal maxima and minima of Silver Pompano differed significantly between different T_{acc} ranges. The experimental results showed that T_{acc} had a significant effect on both CT_{max} and CT_{min} ($P < 0.001$). At the 0.3 °C min^{-1} heating rate, the CT_{max} ranged from 35.0 °C to 41.1 °C at six acclimatization temperatures such as 18, 22, 26, 30, 34 and 36 °C (Table 1). Similarly, CT_{min} reduced significantly ($P < 0.05$), with the same T_{acc}. At the 0.3 °C min^{-1} cooling rate, the CT_{min} ranged from 12.0 °C to 18.8 °C for the six acclimatization temperatures. At different acclimation temperatures, CT_{min} values were 12.0, 13.3, 14.2, 16.3, 18.3 and 18.8 °C, respectively. The comparison of CT_{max} of various acclimatization temperatures range of species are listed in Table 1.

According to the study, 26 °C was estimated to be the best T_{acc} for achieving better growth rate in the fishes and ultimately superior quality yield.

Kernal density estimate plot used to represent the data using a continuous probability density curve in one or more dimensions showed the distribution of CT_{max} and CT_{min} given in Fig. 1 a and b. The plot showed that there was major bell-shaped curve representation of data which characterises a normal distribution, which further confirmed that CT_{max} and CT_{min} were normally distributed.

The Kruskal-Wallis test showed that there exists a statistically significant difference in the CT_{max} and CT_{min} of silver pompano, *T. blochii* exposed to different acclimate temperatures (($\chi^2(3) = 86.551$, $p < 0.001$) and ($\chi^2(3) = 86.553$, $p < 0.001$) respectively). Pairwise comparisons using Wilcoxon rank sum test (*p* value adjustment method: Bonferroni) were performed (Tables 2 & 3) as these five distributions were not normally distributed. The *p*-value of $5e^{-05}$ in pairwise comparisons using the Wilcoxon rank sum test with continuity correction for CT_{max} indicated that there is strong evidence to reject the null hypothesis, which states that there is no significant difference in CT_{max} values between each two groups being compared. There was a clear deviation of the minimum and maximum observations from the normal Quantile plot, as depicted in Fig. 2 and Fig. 3. From the graph it was clear that the data was not normally distributed since the points deviated from the reference line. Therefore, we concluded that the temperature spread does not follow a normal distribution.

Table 1
Comparison of CT_{max} and CT_{min} of silver pompano, *T.blochii* exposed to various T_{acc}.

Acclimatization temperature (°c)	Count	CT_{max}		CT_{min}	
		Mean	SD	Mean	SD
18	15	35.0	0.125	12.0	0.075
22	15	36.2	0.097	13.3	0.041
26	15	37.9	0.093	14.2	0.042
30	15	39.4	0.106	16.3	0.142
34	15	40.4	0.074	18.3	0.140
36	15	41.1	0.048	18.8	0.137

3.2. GAM model implementation to thermal regime

The GAM modelling enabled to analyze more precisely the influence of each T_{acc} on CT_{max} and CT_{min} (Fig. 4). The approximate significance of GAM model smooth terms for CT_{max} and CT_{min} is <0.05. Moreover, minimized generalized cross-validation (GCV) in GAM modelling was used for smoothness selection in the mgcv package for R. The smoothing parameters were chosen to minimize prediction error where ϕ will be unknown, and standard CV or GCV was used to estimate prediction error. The estimated value of GCV was 0.0086355. The effective degrees of freedom (edf) of the smooth terms of GAM for CT_{max} was 8.477($p < 0.05$) and for CT_{min} was 8.705($p < 0.05$).

A global mapping has been developed representing the countries where silver pompano were found as a native species, along with their respective environmental temperature regimes prevailing in the region (Fig. 6) (R Core Team, 2022).

4. Discussion

Aquaculture supports millions of people and aids in poverty alleviation through the farming of 424 aquatic species globally (Fao.org, The State of Food and Agriculture, 2019). Considering the high international market value of silver pompano, there is potential to expand its production to new regimes as a climate resilient species. In the present study, we tested one of the potential candidates in marine tropical finfish species, silver pompano, *Trachinotus blochii* through the dynamic method of Critical Thermal Methodology (CTM) to assess its thermal tolerance capacity through acclimation procedures at various temperature regimes possible in the climate change scenario. This maiden investigation into the temperature tolerance of silver pompano can delineate and address the major issues of future climate change over aquaculture by understanding the physiological effect of temperature changes on the species adaptability. Such types of research and development activities are paramount for the mariculture industry to innovate and evolve across the world (Gentry et al., 2023). The study addresses key objectives (3 and 4) by aligning with SDG 2 for zero hunger and adaptability to diverse temperature regimes, supporting its seamless integration into the EAA, ultimately fostering diversification within aquaculture systems. By demonstrating that silver pompano can acclimate to specific temperature ranges mentioned, our research provides a specific adaptation strategy that supports the development of a climate-smart marine aquaculture industry ensuring food security and sustainable development in the region. The farming will be beneficial for coastal communities with limited resources, as the species is omnivorous and possesses thermal tolerance, enabling it to thrive in both cold and hot climates. Additionally, oligotrophic waters can be utilized for farming this particular species, further enhancing its potential for sustainable aquaculture development.

Currently, the IPCC identifies aquaculture as a key sector that requires attention for global food security and adaptation policy (IPCC et al., 2018, 2019). Climate change poses several threats to aquaculture and fisheries across the world. To alleviate its worst impact on the coastal livelihoods which depend on aquaculture and fisheries, scientific and systematic planning is essential at all levels (Allison and Bassett, 2015). Fish species are facing greater risks from global warming than previously anticipated, highlighting the importance of understanding thermal bottlenecks in fish life cycles for predicting and mitigating the

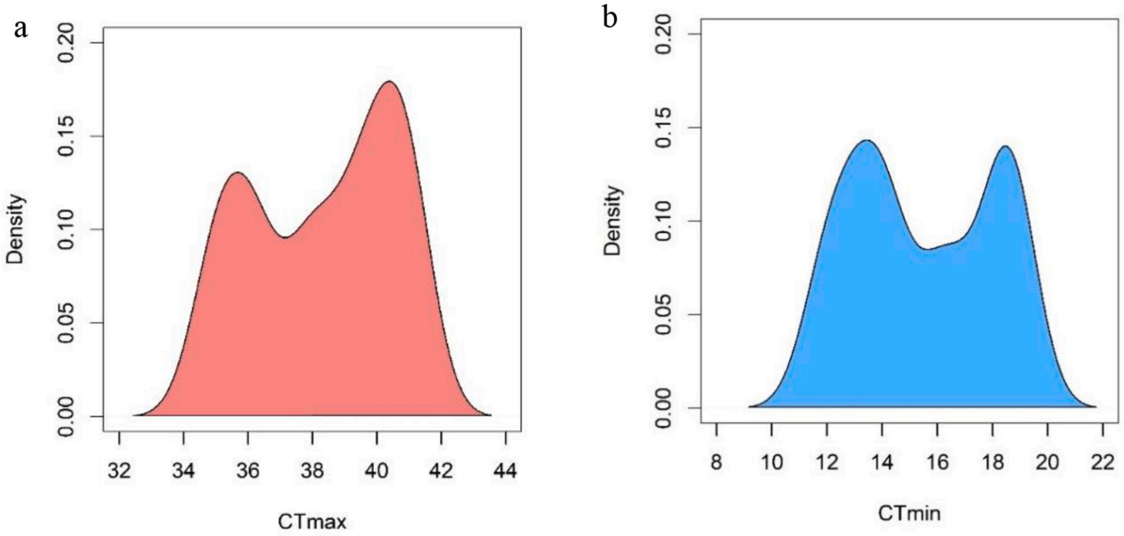

Fig. 1. a and b. Kernel density plot of CT_{max} and CT_{min} for silver pompano, *T. blochii.*

Table 2
Pairwise comparisons using Wilcoxon rank sum test with continuity correction for CT_{max}.

	18	22	26	30	34
22	$5e^{-05}$	–	–	–	–
26	$5e^{-05}$	$5e^{-05}$	–	–	–
30	$5e^{-05}$	$5e^{-05}$	$5e^{-05}$	–	–
34	$5e^{-05}$	$5e^{-05}$	$5e^{-05}$	$5e^{-05}$	–
36	$5e^{-05}$	$5e^{-05}$	$5e^{-05}$	$5e^{-05}$	$5e^{-05}$

P value adjustment method: Bonferroni.

Table 3
Pairwise comparisons using Wilcoxon rank sum test with continuity correction for CT_{min}.

	18	22	26	30	34
22	$4.9e^{-05}$	–	–	–	–
26	$4.9e^{-05}$	$5.0e^{-05}$	–	–	–
30	$4.9e^{-05}$	$5.0e^{-05}$	5.0e-^{05}	–	–
34	$5.0e^{-05}$	$5.0e^{-05}$	$5.0e^{-05}$	$5.0e^{-05}$	–
36	$5.0e^{-05}$	$5.0e^{-05}$	$5.0e^{-05}$	$5.0e^{-05}$	$5.1e^{-05}$

P value adjustment method: Bonferroni.

impacts of climate change on marine ecosystems (Dahlke et al., 2020). It is also crucial to comprehend the physiological mechanisms in aquatic animal communities to elucidate ecosystem changes and project future ecological trends. The direct effects of climatic warming can result in decreased performance in growth, reproduction, foraging, immune competence, behaviors, and competitiveness in organisms (Pörtner and Farrell, 2008). Being a fast-growing sector, aquaculture produces over 50% of global fish (FAO, 2018) to meet increasing food demands (Bene et al., 2016). It is also imperative to ensure the establishment of healthy, well-functioning, and resilient marine ecosystems (as per SDG target 14.2) in the era of climate change (Craig, 2012). However, climate change dwells with its uncertainty and complexity, causing various unfavorable conditions (Galappaththi et al., 2019). Particularly in the tropics, it is anticipated that climate change can lead to severe losses in the productivity of the fisheries sector (Cinner et al., 2022). Tropical species are regarded as more susceptible to climate change due to their proximity to thermal maximum with limited potential for adaptation (Tewksbury et al., 2008). So, understanding the potential of species to acclimatize and adapt to anticipated temperature rise is crucial for predicting the biological consequences of global warming (Mora and Maya, 2006; Munday et al., 2008). Projections of the range expansions of marine species are also critical if we are to anticipate and mitigate the impacts of climate change on marine ecosystems, especially when considering multiple potential scenarios (Wilson et al., 2024). Climate change is recognized as a major threat to biodiversity (McCarthy et al., 2001), affecting not only aquaculture species but also other organisms. For instance, Kwon et al. (2015) observed a decrease in the richness and occurrence probabilities of endemic freshwater species, leading to shifts in their distributions and posing a threat to their future sustainable growth (Yaghouti et al., 2023). Similarly, changes in the potential distribution of seerfish (*Scomberomorus sierra*) under various climate change scenarios indicate significant shifts in their habitat range (Montiel et al., 2019).

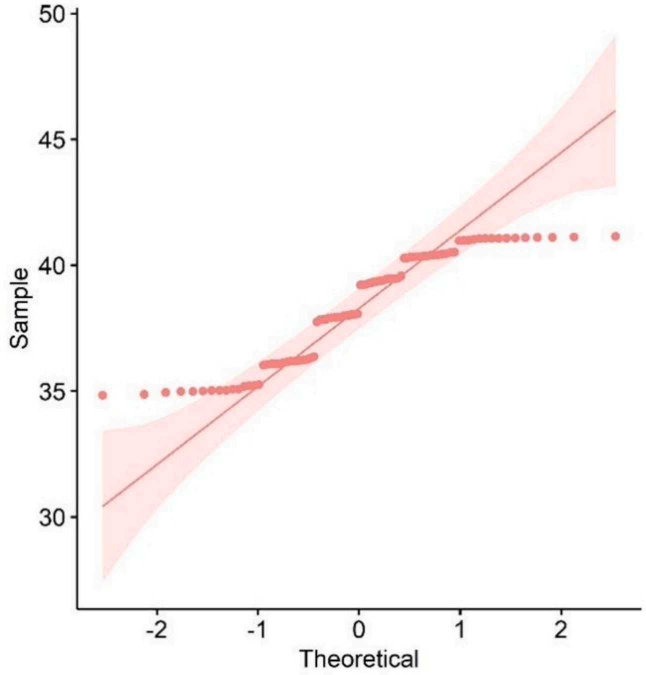

Fig. 2. Normal Quantile plot for CT_{max}.

One of the major implications of climate change on the fisheries and aquaculture environment is rising temperatures, which affect

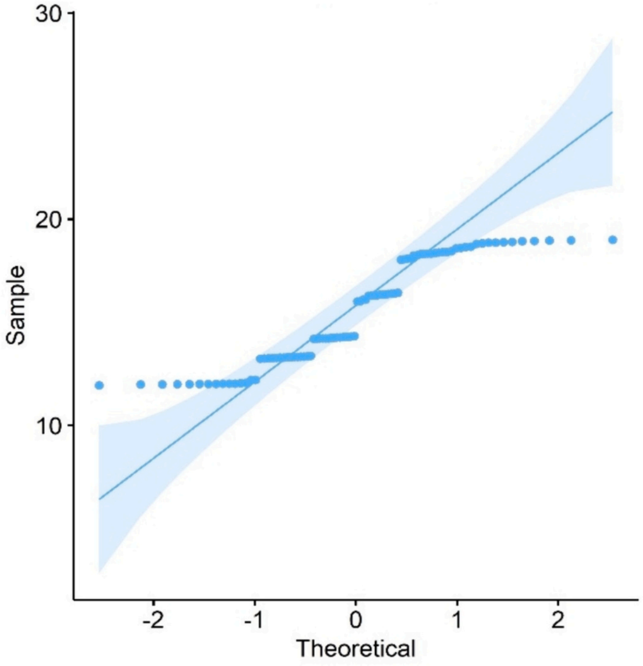

Fig. 3. Normal Quantile plot for CT_{min}.

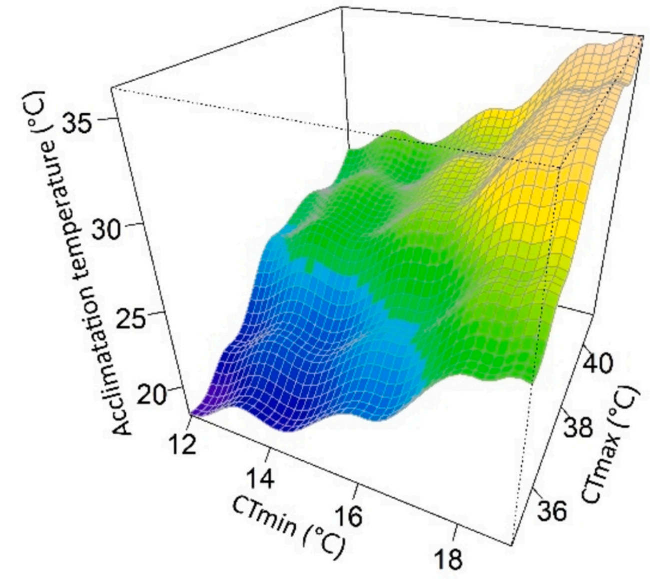

Fig. 4. GAM plot for CT_{max} and CT_{min} of silver pompano, *T. blochii* exposed to various T_{acc}.

individuals at multiple levels. These three stressors impart their effects simultaneously, as they are primarily driven by the increase in atmospheric CO_2 (Capson et al., 2021). Hence, data on the thermal tolerance of the candidate aquaculture species will provide insights to policymakers, scientists, and resource users to understand, adapt to, and project the impacts of climate change on aquaculture production of the species thereby addressing various SDGs on a global scale. This may also allow researchers to match organismal performance with optimal habitats (Saavedra et al., 2020). It is well-proven that anticipatory, data-driven adaptation measures against climate change factors would be much more cost effective than reactive adaptation in any setting (Capson et al., 2021).

Ojea et al. (2020), opined that geographical disparities exist across the globe hindering the implementation of a uniform adaptation planning strategy that fits all scenarios. They also stressed that there will be a species range shift creating situations such that at lower latitudes there will be a decline of those species that cannot adapt to increasing temperatures. Predictions of climate change impacts on populations and ecosystems require the assessment of the physiological capacity of fishes for temperature acclimation and tolerance (Semsar-Kazerouni and Verberk, 2018). In this context, the vital approach to assessing heat tolerance in aquatic species seems to give the most reliable data for comparison purposes with the ambient conditions (Mora and Ospina, 2001). The development and expansion of aquaculture production rely heavily on species selection (Alvarez-Lajonchère and Ibarra-Castro, 2013), especially in the context of changing global climate. Most species selection procedures focus on determining new species for a specific region and one group of organisms (Alvarez-Lajonchère and Ibarra-Castro, 2013; Cao et al., 2007; Quéméner et al., 2002). Silver pompano production is currently being carried out using various farming methods such as offshore sea cages, brackish and backwater cages, coastal ponds, and RAS (FAO, 2016; Nazar et al., 2017). It has a rapid and uniform growth rate compared to other farmed fishes (Gopakumar et al., 2011), superior meat quality with minimal spines, a delightful taste, and has high levels of Omega-3 fatty acids, specifically EPA and DHA (Jayakumar et al., 2019). It can also tolerate a wide range of salinity, between 7 and 58 ppt on acute exposure of individuals acclimated to seawater (35 ppt) (Sampaio et al., 2003). Most selection techniques do not take into account the adaptation potential of aquatic species with respect to climate change and, as a result, the production stability of farming operations remains uncertain.

However, the CTM used in our study yields results in a non-invasive and ethical manner without sacrificing the animal for assessing their thermal tolerance (Beitinger et al., 2000). It serves as an important reference point from both an ecological and physiological perspective, providing an early indication of thermal stress (Stewart and Allen, 2014), which in turn facilitates the estimation of species temperature tolerance. Additionally, understanding fish thermal tolerance is a fundamental step in anticipating population-level responses to warming caused by habitat disturbance and climate change (Schulte et al., 2011). As of now, the CT_{max} and CT_{min} values for silver pompano, *T. blochii*, have not been determined. Climate change is projected to make ocean conditions warmer and more variable (Altieri and Gedan, 2015; Best et al., 2015). This suggests that the aquaculture sector should select species capable of thriving amidst thermal fluctuations to achieve a consistent and sustainable output over time. This is the first study that explored the thermal tolerance limits of silver pompano, measuring their threshold limits while being acclimatized at six specific temperatures which probably arises at. The results of the present study showed that changes in T_{acc} can significantly affect the thermal tolerance of the candidate species by stretching the threshold on both ends of temperature ranges through temperature acclimation. The CTM provides decision makers with the fundamental thermal tolerance ability of the species, allowing them to plan and direct their actions fruitfully towards obtaining the desired SDGs through the species utilization. This will also help minimize the unintended outcomes from the desired targets through informed mitigative measures to attain sustainability.

Several physiological processes in marine organisms are temperature-dependent, making thermal thresholds the primary determinants of how ocean warming will affect their performance (Hochachka and Somero, 2002; Leung et al., 2019). A study by Magel et al. (2020) found that a heatwave caused a 50% decline in the number and variety of fish populations in a coral reef community. Elevated temperatures, have significantly impacted species, as evident in the reduced growth potential of young rainbow trout (Biro et al., 2007) and reproductive effects in a reef fishes such as *Amphiprion melanopus* (Miller et al., 2015). In the southern inshore areas of the coral atoll lagoon, fish mortality has been reported due to the highest seawater temperatures (33–35 °C), leading to a fish kill event at the Cocos (Keeling) Islands in the Indian Ocean (Hobbs and McDonald, 2010). This exemplifies how extreme temperature events can be catastrophic, and highlights the importance of measuring the upper and lower temperature limits that organisms can tolerate. As the temperature exceeds the thermal threshold of an organism, its physiological functioning, energy balance, and, ultimately, fitness start deteriorating (Sokolova et al., 2012). In contrast, favorable impacts of ocean warming can also be found when the raised temperature falls within the ideal temperature range of some species (Leung et al., 2020; Pörtner et al., 2017). Therefore, the thermal threshold can be used to forecast the vulnerability of marine animals to ocean warming (Madeira et al., 2012; Nguyen et al., 2011). In the present study, the highest CT_{max} and lowest CT_{min} values for the tested species were observed between 41.1 °C and 12 °C at acclimation temperatures of 36 °C and 18 °C, respectively. This information can be leveraged to harness the positive effects of climate change by utilizing the adaptability and thermal tolerance of marine finfish such as silver pompano by making use of them for farming in many non-conventional locations and climatic conditions to enhance productivity. This climate resilience of the candidate species may be utilized further in nations for aquaculture production where the silver pompano is a native species. Since the acclimation temperatures were in accordance with the variations of seasonal temperature of various tropical and subtropical countries (Table S1), the candidate species can be employed in these countries for aquaculture production within the observed CT_{max} and CT_{min} values ranging from 35.0 to 41.1 °C and 12.0–18.8 °C respectively. This approach also avoids the inherent risks of farming new or altered species, such as invasive species introduction or genetic pollution of wild populations without compromising production potential and sustainability. Crop diversification is an approved methodology to cope with climate change (Sarial, 2019). This approach can replace traditional species in areas with high summer and low winter temperatures, significantly influencing sustainable aquaculture management through crop rotation. This practice reduces the risks associated with climate change and addresses economic concerns from monoculture. Policy interventions, such as crop rotation or intercropping, can be advised for areas with continuous fish farming, promoting sustainability through an ecosystem-based approach utilizing this species.

For ectotherms, ambient temperature significantly impacts on physiology and fitness since practically all biological rates are temperature-dependent (Brown et al., 2004). However, the ability of marine species to adapt via long-term thermal acclimation to rising water temperatures is often underestimated (Rohr et al., 2018). Long-term thermal acclimation is a crucial process that allows marine organisms to lessen their sensitivity to climate change, with enhanced growth rates (Leung et al., 2021). T_{acc} has been identified as the most crucial factor influencing fish thermal tolerance (Beitinger and Lutterschmidt, 2011). Several studies support the link between CT_{max} and T_{acc} in numerous aquatic species (Akhtar et al., 2012a, 2012b; He et al., 2014; Yanar et al., 2019; Zhang and Kieffer, 2014). In the present study, the highest CT_{max} value observed is 41.1 °C at the T_{acc} of 36 °C (Table 1). The thermal tolerance range showed a considerable increase with an increase in T_{acc}. Therefore, the results of the present study confirm that the fish's prior thermal exposure history or T_{acc} has a significant impact on the thermal tolerance of fish aligning with reports by Das et al. (2004) and Debnath et al. (2006). Consequently, the thermal response of warm-acclimated ectothermic individuals can be utilized to predict their ability to adapt to future ocean warming. Since the preferred T_{acc} overlaps with the climatic conditions of tropical countries with comparable agro-climate characteristics (e.g., Taiwan, China, Indonesia, Sri Lanka, Bangladesh, Madagascar, Colombia, Australia, etc., as given in Table S1), the thermal tolerance ability of the candidate fish species can be utilized in climate-resilient mariculture practices as recommended by FAO through the ecosystem approach to aquaculture (EAA) for achieving sustainability and SDG goals. Aquaculture is considered a strategy for integrating with the natural environment (FAO, 2010), and hence, it is conceivable that the dynamic acclimation method can improve the management of temperature variations for cultured fishes, preventing major losses due to climate extremes for fish farmers globally inhabiting similar geo-climate regions.

Given the growing importance of aquaculture to the world's food basket, it is crucial to understand how climate change might affect "blue growth" and the safety and sustainability of our food supply in the future (Blanchard et al., 2017; Hambrey, 2017). The deviation of the minimum and maximum observations from the normal quantile plot in the study may be explained by the experimental nature, which involves the sustained exposure of fishes in multiple tanks to different temperature conditions. Consequently, it appeared that the acclimatization temperatures to which the fish were subjected had a significant influence on their respective CT_{max} and CT_{min} values. Additionally, the eurythermal characteristics of the species were one of the reasons for conducting this experiment. So, the species is having an inherent capacity to acclimate with varying temperatures and the species is considered as hardy one. Attributes of Thermal Tolerance Polygons have been used to identify temperature-related survival tactics (Bennett and Beitinger, 1997; Conte et al., 2023) and determine optimal culture conditions (Das et al., 2004). The present study recorded the zone of thermal tolerance polygon over the tested probable six acclimation temperatures as 357.02 °C^2 (Fig. 5). The results, indicate that the zone of thermal tolerance of *T. blochii* over the acclimation range (18-36 °C) was higher than that of many tested finfish species such as *Labeo rohita* with 273.5 °C and *Cyprinus carpio* with 311.6 °C (Chatterjee et al., 2004) suggesting the species as an alternative culture option for climate-resilient mariculture operations, especially in tropical region. As a countermeasure to climate change, the candidate species can also be used in aquaculture diversification in regions where, *Trachinotus carolinus,* Florida pompano, shows distribution in various confinements to prevent the entry of this exotic species into natural water bodies (Abisha et al., 2022), such as the Western Atlantic and Americas continent, from Massachusetts, USA, to the Gulf of Mexico and several locations in the West Indies with necessary temperature acclimation for the intended culture period. Conversely, southern and eastern countries in the African continent can directly employ the silver pompano to tackle malnutrition (Ogello and Munguti, 2016), since it is an indigenous species to the region in a commercial manner.

To validate the thermal acclimation response on the thermal tolerance level of the fish species, the Generalized Additive Model (GAM) was used. This model is generally used to explain the influence of environmental parameter variabilities and climatic responses (Ravindra et al., 2019). GAM was chosen for its ability to capture nonlinear relationships, flexibility in incorporating multiple predictors, and model interpretability, supported by previous studies and validated through goodness of fit and cross-validation (Abidi et al., 2022; Coleman et al., 2021; Polgar et al., 2015; Vajedsamiei et al., 2021). Hence, we have performed GAM to evaluate the effects of thermal tolerance with respect to temperature of acclimation. GAM has proven valuable tool for analyzing relationships between environmental variables and fishery resources, as demonstrated in different studies (Khan et al., 2020; Solanki et al., 2017). For analyzing long- and short-term effects, GAM with a penalized spline has been suggested as the best approach to study the environment and climatic linkages. Here we have used GAM for validation of the results obtained from our various analyses. It showed that the thermal treatment had a major effect on fitness components in which various acclimation temperatures were positively influencing thermal tolerance in the silver pompano. The highest collinearity revealed through the GAM results further emphasizes that acclimation temperatures directly influence the thermal tolerance limits of this species.

The ability of marine organisms to tolerate temperature is crucial for determining how climate change and other thermal phenomena may impact their survival rates, as well as the abundance and distribution of species (Mora and Maya, 2006; Schulte et al., 2011). The discovery of thermal tolerance of silver pompano can be leveraged to improve

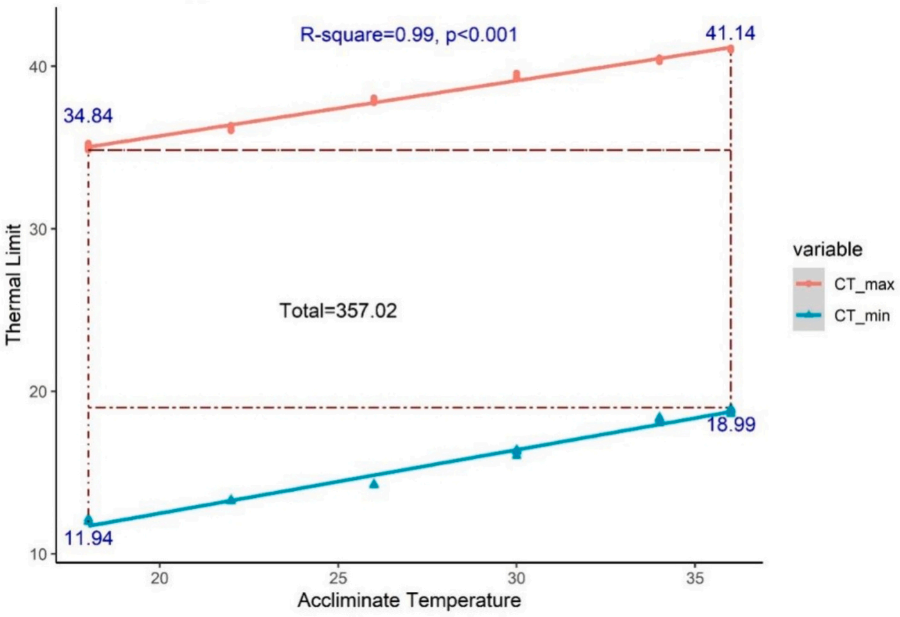

Fig. 5. Thermal tolerance polygon generated from CTM (CT_{max} and CT_{min}) data to indicate thermal tolerance zone of silver pompano, *T. blochii* acclimated to six different temperatures (18 °C, 22 °C, 26 °C, 30 °C, 34 °C and 36 °C).

resource management and prepare for future climate change impacts on aquaculture production. CT_{max} and CT_{min} have proven to be useful for providing information on the ecology and distribution of aquatic animals (Bennett and Beitinger, 1997). Given the ability to account for changes in the rate of global warming and associated climate extremes with respect to different geographical locations, such data would allow for more relevant extrapolations of thermal tolerance of ectothermic species to combat climate change through planning several adaptation and mitigation measures so that the dependent populations and aquaculture productivity will be minimally affected. Moreover, the diversification of aquaculture is gaining impetus as an adaptation measure to combat climate change and meet the rising demand for fish proteins (Abisha et al., 2022; Shaffril et al., 2019). In 2020, global aquaculture production involved 448 species, but only 46 species contributed 90% of the total production (Cai et al., 2023). This concentration indicates a significant lack of species diversity, which poses substantial risks to the industry and global food security, particularly in the context of climate change. Further, thermal tolerance studies on prospective candidate mariculture are very limited, in particular to *T. blochii* which is a high potential species for mariculture adaption across the culture systems. Therefore, identifying and cultivating new resilient species is crucial. Hence, this study is very much relevant for enhancing climate-resilient aquaculture through the diversification of adaptable and tolerant species across global agroclimatic zones. Furthermore, exploring and documenting new resilient species for policy planning aligns with the FAO's frontline research mandate (FAO (Food and Agriculture Organization of the United Nations), 2019, FAO (Food and Agriculture Organization of the United Nations), 2019c). Nevertheless, linking these insights with climate projections, our study not only bridges a critical gap but also provides valuable information for future actionable strategies to develop climate-resilient aquaculture practices. Some potential applications from this study include enabling policymakers to develop regulations and guidelines for sustainable aquaculture practices, to ensure the welfare and productivity of farmed fish, promoting the use of temperature-controlled systems or encouraging the adoption of climate-resilient species. This valuable information can be leveraged to explore new horizons for utilizing this candidate species to mitigate the negative effects of climate change. Species selection for achieving these goals will mostly depend on required farming inputs, growth rate, and tolerance to a broad range of environmental conditions. Therefore, given the higher thermal resilience, the current research suggests that *T. blochii* can be one of the preferred candidate species for holistic mariculture systems across various parts of the globe even in the context of climate change. This crop can be cultivated in multiple locations as a main crop, winter crop, or intercrop, depending on the prevailing temperatures in the respective regions during various intended seasons. Further investigations are warranted to explore the sustainability of silver pompano's thermal tolerance across generations, specifically focusing on transgenerational tolerance.

While general thermal tolerance studies often utilize thermal polygons to evaluate species tolerance limits and acclimatization zones, our approach introduces a novel methodological perspective. Specifically, we have employed GAM to cross-validate thermal acclimatization zones, providing a more nuanced evaluation of the species responsiveness to biological thresholds. The GAM model assesses the responsiveness of thermal thresholds to biological parameters of the candidate species, providing a novel and robust evaluation that has not been previously applied to this species or in line with the context of any other species, as indicated by our extensive literature survey. However, in our study, certain uncertainties associated with the use of GAM arise due to inherent assumptions about data relationships and variable interactions. Although application of GAM is versatile, however rely on assumptions that may not fully capture complex biological and environmental dynamics. We have applied standard scientific protocols in establishing the thermal polygon in the study, nevertheless thermal tolerance can be influenced by variability in environmental factors such as temperature fluctuations, habitat conditions, and other ecological variables, which may introduce uncertainties in accurately determining thermal limits and acclimatization zones. Our findings, specific to *T. blochii* and the study conditions, may not be easily generalized to other species or diverse environmental conditions. Future researchers should aim to validate and refine the approach of application of GAM models in thermal tolerance studies by comparing them with alternative modelling approaches to assess their robustness and accuracy. Incorporating advanced statistical or machine learning techniques could further enhance the precision of thermal tolerance studies. Implementing long-term monitoring programs and field studies that track species performance under variable temperature zones will help in validating

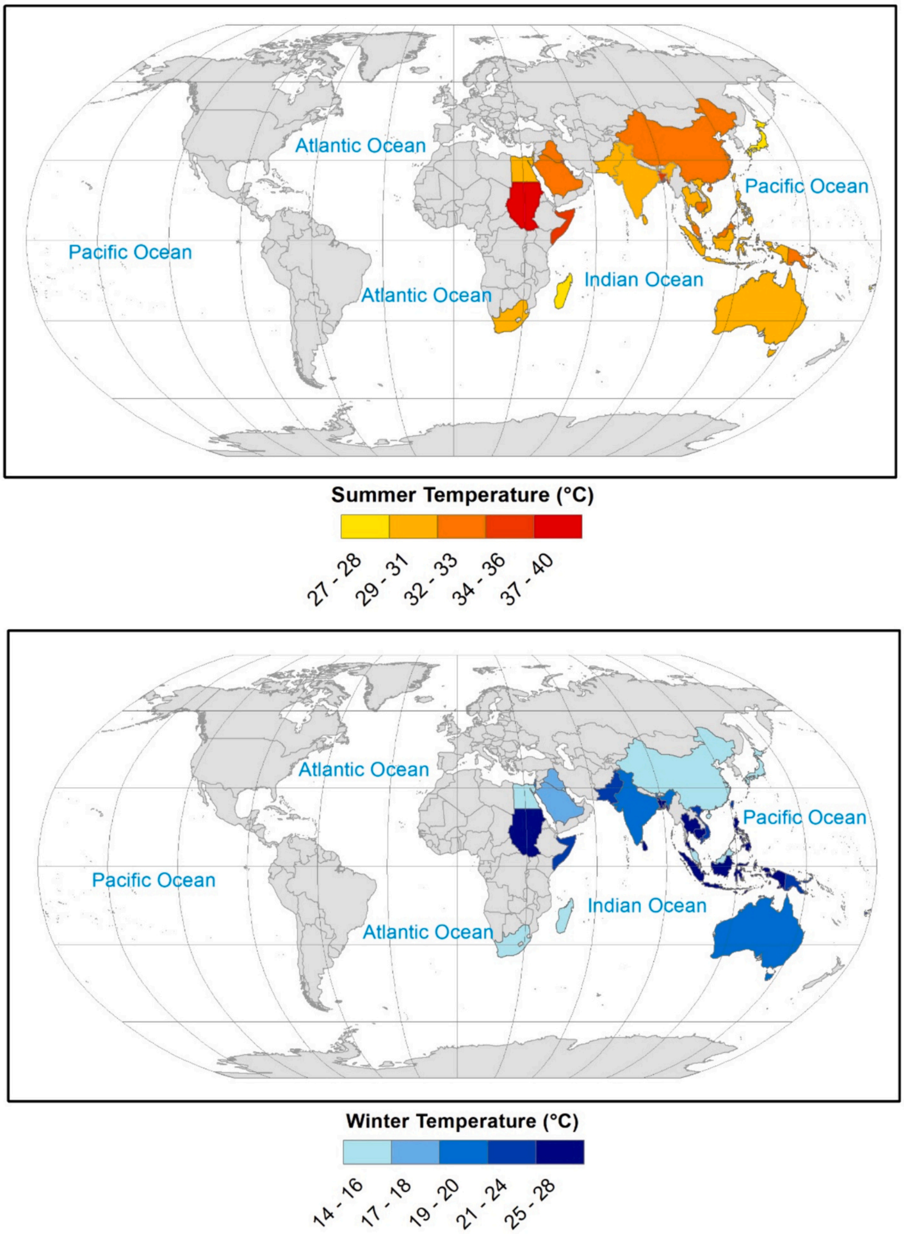

Fig. 6. Countries with silver pompano as a native species and their summer temperature and winter variations. (A global map representing the countries where silver pompano were found as a native species, along with their respective environmtal temperature regimes prevailing in the region (R Core Team, 2022).

laboratory results and thermal acclimatization zones. Addressing these research needs will bridge the existing gaps, deepen the understanding of thermal tolerance mechanisms, and support the sector development through adoption of resilient candidate species for more effective, climate-resilient aquaculture management strategies for the future.

5. Conclusion

The study, through the derived CT_{max} and CT_{min} values conclusively demonstrated that *T. blochii* has a wider thermal tolerance limit, thereby successfully fulfilling the study's objectives. Furthermore, the results reveal that the CT_{max} and CT_{min} values of *T. blochii* can be influenced by various acclimation temperatures (18, 22, 26, 30, 34, and 36 °C), with the fish accustomed to higher temperatures having a higher CT_{max} and the fish accustomed to lower temperatures having a lower CT_{min} It is a known fact that, the aquaculture industry necessitates substantial support in formulating strategies to adapt and mitigate the present and future impacts of climate change. A decline in aquaculture productivity has serious consequences for farmers as well as the rising global population since it is connected to food security (Béné et al., 2015, 2016; FAO, 2016). It becomes essential for climate change adaptation research to continue exploring and enhancing adaptability in aquaculture settings. Therefore, our research focuses on how the identified thermal tolerance of *T. blochii* can be used as an adaptation response to climate change and assist in optimizing global aquaculture production and productivity. This knowledge can help boost highly valuable climate-resilient mariculture methods in various subtropical nations involved in the aquaculture of silver pompano or comparable finfish species in similar temperature ranges. Furthermore, we recommend focusing on underutilized locations to maximize production potential while reducing pressure on already-browbeaten marine resources. The scientific structuring of climate adaptation pathways facilitate new research domains on trade-offs and synergies of adaptation responses along with the possibilities for modelling the works of climate impacts on aquaculture and fisheries (Barange et al., 2014) to identify and analyze the potential conflicts or benefits of different adaptation strategies. This will also assist sustainable ecosystem management in the context of global environmental and climate change. The present results will also have profound influences on policy planning and implementation since they provide structure and building blocks for adaptation planning, as opined by Ojea et al. (2020).

Declaration of generative AI in scientific writing

During the preparation of this work the author(s) used AI-assisted technologies in order to improve readability and language of the manuscript during writing process. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Damodaran Nair Divu: Conceptualization, Funding acquisition, Project administration, Investigation, Supervision, Resources, Methodology, Data curation, Writing – original draft, Writing – review & editing. **Suresh Kumar Mojjada:** Conceptualization, Methodology, Investigation, Formal analysis, Software, Validation, Visualization, Supervision, Project administration, Writing – original draft, Writing – review & editing. **Abdul Azeez Pokkathappada:** Methodology, Investigation, Formal analysis, Software, Validation, Visualization, Software. **Mathavankonathu Kuttan Anil:** Resources, Investigation, Methodology, Writing – review & editing. **Ambarish Purackattu Gopidas:** Resources, Methodology, Writing – review & editing. **Swathi Lekshmi Perumal Sundaram:** Formal analysis, Writing – original draft, Writing – review & editing. **Anbarasu Mahalingam:** Methodology, Writing – review & editing. **Muktha Menon:** Writing – original draft, Writing – review & editing. **Ratheesh Kumar Raveendran:** Resources, Methodology, Writing – review & editing. **Ramesh Kumar Mojjada:** Data curation, Software, Methodology, Formal analysis, Visualization, Validation. **Mayur Shivdas Tade:** Data curation, Methodology, Formal analysis, Writing – review & editing, Resources. **Jai Shree:** Writing – review & editing. **Aarsha Subramanian:** Writing – review & editing. **Suresh Vettath Raghavan:** Resources, Project administration, Writing – review & editing. **Achamveetil Gopalakrishnan:** Funding acquisition, Project administration, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data will be made available upon reasonable request and subjected to the data sharing policy of the Indian Council of Agricultural Research, Government of India.

Acknowledgments

The research is supported by the Indian Council of Agricultural Research (ICAR), New Delhi, Government of India, and we duly acknowledge their funding support. We express our sincere thanks to the Director, ICAR-Central Marine Fisheries Research Institute (ICAR-CMFRI), former and present Head-In-Charge of the Mariculture Division of the Institute. We duly acknowledge the constant support of Coordinator - All India Network Project on Mariculture (AINP-M) and National Innovations in Climate Resilient Agriculture (NICRA) for their facilitation. We duly appreciate and acknowledge the support rendered by the staff of Veraval Regional Station, who have been involved and contributed to this study.

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