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Research Article

Thermal physiology of juvenile white snook (*Centropomus viridis*): Implications for its culture

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ABSTRACT. Aquaculture in Latin America has grown; however, it continues to rely on a limited number of species, which limits its potential for diversification and innovation. The white snook (*Centropomus viridis*), a high-value species native to the eastern tropical Pacific, with strong demand in local and international markets, remains underutilized due to gaps in our understanding of its physiology. The present study provides the first detailed thermal profile of *C. viridis*, identifying temperature conditions that could enhance survival, growth, and aquaculture performance. After 30 days of thermal acclimation at 20, 23, 26, 29, and 32°C, 230 juveniles (46 per temperature; 15 ± 3.4 g at acclimation start; two replicate tanks of 23 fish each) were assessed for their upper and lower critical thermal limits (CT_{max} and CT_{min}), thermal window area, preferred temperature, and thermal metabolic scope (TMS). Tolerance to higher temperatures increased with acclimation temperature, reaching CT_{max} values of 36.9 to 41.9°C. CT_{min} increased from 9.9 to 16.4°C across the acclimation gradient. These results show a narrow thermal window area (228°C^2). The overall preferred temperature was 27.3°C. The maximum TMS was observed at 29°C, indicating that this temperature may represent a thermally favorable condition for maximizing aerobic performance. These findings establish a crucial physiological foundation for optimizing *C. viridis* aquaculture and will contribute to the diversification and resilience of native species for future marine farming in Mexico.

Keywords: *Centropomus viridis*; aquaculture; climate change; optimal temperature; physiology; thermal tolerance

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INTRODUCTION

Marine fisheries have been fundamental to global human food production, as they support coastal communities and contribute to economic development through job creation and the commercialization of resources (Teh & Sumaila 2013, FAO 2022). However, over the past few decades, global marine fisheries productivity has declined, largely due to anthropogenic pressures, including overfishing and habitat degradation (FAO 2022). Additionally, climate change has emerged as a principal factor, modifying oceanographic conditions and directly influencing fish populations. Global analyses indicate that more than 80% of key fish stocks have experienced population declines, with many exhibiting negative trends since the 1990s (Brander 2010, Chust et al. 2025, Liu et al. 2025a, Xu et al. 2025).

Climate change impacts multiple environmental parameters that can directly influence the physiological performance and survival of marine fish populations (Sumaila et al. 2011, Bahri et al. 2018, IPCC 2022). For example, it increases the frequency and intensity of marine heatwaves and promotes ocean deoxygenation (via reduced oxygen solubility and enhanced stratification); together with ocean acidification, these stressors impose multi-stressor constraints on fish. Because these drivers often co-occur and interact in nature, their combined effects can shift performance thresholds-for instance, higher temperatures raise metabolic demand while hypoxia reduces oxygen supply-so physiological limits may be reached at lower temperatures under low-oxygen conditions (Pörtner 2008, Pörtner & Peck 2010, Somero 2012). Given that temperature is a primary environmental factor influencing thermal biology, metabolic rates, growth, survival, reproductive cycles, and the geographic distributions of marine fishes, cascading effects include shifts in species distributions and phenology, altered predator-prey interactions and recruitment, degradation of key habitats (e.g. coral reefs, seagrasses, mangroves), changes in catch composition and yields, and socioeconomic impacts on fisheries-dependent communities (Schulte 2011, Lluch-Cota et al. 2023, Agarwal et al. 2024). It is therefore particularly informative to evaluate how thermal changes may affect fishes of ecological, economic, and commercial importance.

Under this context, aquaculture emerges as a strategic alternative to meet the global demand for aquatic protein, offering controlled environments that support the predictable and accelerated growth of cultured species (FAO 2022). However, achieving sustainable and efficient production of marine fish in tropical environments requires more than infrastructure and formulated feed; it demands a precise understanding of species-specific physiological limits. Optimizing tropical marine aquaculture depends on identifying environmental conditions that align with the biological performance of the species, particularly in terms of thermal tolerance, metabolic efficiency, and developmental timing (Khan & Herbert 2012, Khan et al. 2014, 2024, Dagoudo et al. 2025). In Latin America, aquaculture is primarily concentrated on a few species, including shrimp, bivalves, tilapia, and salmonids (FAO 2020). Reliance on a few species can lead to market saturation and reduced profitability, emphasizing the need to explore native or traditional species. There is a need to expand the range of cultivated species with high commercial potential (Baldini et al. 2022) to increase diversification, resilience, and innovation in the sector. Promoting new species is a key step toward more robust and regionally adapted production systems.

The white snook (*Centropomus viridis* Lockington, 1877) is a high-value fish widely recognized throughout the American tropics. It is a strong candidate for diversification in tropical marine aquaculture due to its broad market acceptance and favorable culture traits (Ulloa-Ramírez et al. 2008, Labastida-Che et al. 2013, Ibarra-Castro et al. 2017). The species occurs across tropical and subtropical coastal waters of the eastern-central Pacific-from Baja California to Peru, including the Galapagos Islands (Fischer et al. 1995, Castro-Aguirre et al. 1999). In Mexico, the leading country for *C. viridis* fisheries, wild populations face intense fishing pressure, raising concerns about overexploitation and potential population collapse (Arreguín-Sánchez & Arcos-Huitrón 2011, CONAPESCA 2017).

To date, *C. viridis* has demonstrated high-quality fillets, rapid growth, adaptability to captive conditions, and acceptance of formulated diets (Álvarez-Lajonchère & Tsuzuki 2008, Abdo-de la Parra et al. 2020). Despite advances in hatchery technology (Ibarra-Castro et al. 2017), there remains limited knowledge about the thermal thresholds that define optimal growth performance in juvenile *C. viridis*, representing a critical gap, because temperature acts as a master regulator of survival, growth, organ development, and overall performance from egg to juvenile (Pörtner & Farrell 2008). However, in the hatchery protocols, temperature is treated as a fixed input (i.e. maintaining a constant temperature set-point rather than adjusting it to life-stage-specific physiological metrics), rather than as a biological variable with measurable consequences for specific growth rate, feed conversion, early survival, and developmental timing (Ibarra-Castro et al. 2017).

The overarching goal of this study was to generate a stage-specific thermal physiology baseline for juvenile *C. viridis* under controlled conditions, providing operational benchmarks for aquaculture and a mechanistic context for potential sensitivity to warming. We integrated experimental metrics across acclimation temperatures-critical thermal limits (CT_{max}, CT_{min}), thermal window, preferred temperature (T_{pref}), and the temperature associated with maximal thermal metabolic scope (TMS)-to derive benchmarks relevant to husbandry set points, acclimation protocols, and seasonal planning for juveniles. Our specific objectives were: 1) to quantify CT_{max}, CT_{min}, and the thermal window of juveniles across acclimation treatments, 2) to determine T_{pref} and identify the juvenile performance optimum under our conditions via the TMS peak and 3) to compare these metrics to delineate safe operating ranges and to interpret mechanistically how warming could increase exposure above T_{pref}/optimal ranges and closer to CT_{max}. We hypothesized that (i) both CT_{max} and CT_{min} would shift upward with acclimation, with limited additional heat tolerance at the warmest treatments; (ii) TMS would exhibit a unimodal response with a peak near T_{pref}; and (iii) aerobic capacity would decline when rearing temperatures exceed the TMS peak, implying narrower management margins during warm episodes.

MATERIALS AND METHODS

Organisms, maintenance, and thermal acclimation

A total of 230 juvenile Pacific white snook (*C. viridis*) with an average weight of 2 ± 0.3 g (mean ± standard deviation, SD) and a total length ranging from 6 to 8 cm were provided by the Marine Finfish Hatchery at CIAD-Mazatlán. The fish were transported to the Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE), located in Baja California, Mexico, and acclimated in the Wet Laboratory of the Marine Biotechnology Department.

Upon arrival, all individuals were maintained for two months in a 2,000 L tank equipped with continuous aeration and operated as an open, flow-through seawater system. Fresh seawater was supplied continuously from the facility header line, and outflow occurred through a vertical standpipe (level-control tube) that set the water depth and discharged the effluent to drain; no recirculation was used. The environmental parameters in the holding tank were as follows: temperature, 26 ± 1°C (mean ± SD); salinity of 35; dissolved oxygen, 7.0 ± 0.6 mg L^{-1}; and pH, 8.1 ± 0.1. Fish were fed twice daily (09:00 and 17:00 h) to apparent satiation using a commercial diet (45% protein, 17% lipid; Nova Op Inc., Skretting, Utah, USA). Uneaten feed and feces were siphoned 20 min post-feeding.

For the thermal acclimation experiment, fish (15 ± 3.4 g) were randomly assigned to 10 200-L tanks (n = 23 fish per tank) with continuous aeration and 10% daily seawater renewal. The initial water temperature in all tanks was 26°C. The temperature was then ramped at a rate of ±1°C per day to the target acclimation temperatures of 20, 23, 26, 29, and 32°C (two tanks per temperature), where the fish remained for a 30-day thermal acclimation period. Temperature control was achieved using 1,000-W submersible heaters regulated by external digital controllers (H2Pro, MX-1035, USA) and a seawater chiller (RESUN, CL-600, China) to lower the temperature when required. The wet-lab ambient temperature was 19 ± 1°C. Throughout the 30-day acclimation period, all tanks were maintained within ±1°C of their set point (i.e. 20 ± 1, 23 ± 1, 26 ± 1, 29 ± 1, and 32 ± 1°C). Fish also received the same commercial diet and feeding schedule described above; the regimen was identical across temperature treatments. During the 30-day acclimation period and all subsequent trials, seawater quality remained within the same ranges reported above: salinity of 35, dissolved oxygen levels of ≥7.0 mg L^{-1} under continuous aeration, and a pH of 8.1 ± 0.1.

Thermal tolerance limits

After completing the 30-day thermal acclimation period, the thermal tolerance limits of *C. viridis* juveniles were assessed using the dynamic method described by Fry (1947) and adapted by Beitinger & Bennett (2000). This approach involved exposing individual fish to gradual temperature changes, beginning at each fish's acclimation temperature (20, 23, 26, 29, and 32°C), to determine their upper and lower critical thermal limits (CT_{max} and CT_{min}).

To evaluate CT_{max}, 50 juveniles were tested (5 fish per tank × 2 replicates × 5 temperatures). Each fish was individually placed in a 40 L aquarium equipped with a 1,000-W immersion heater controlled by an external digital controller (H2Pro, MX-1035, USA), placed next to a recirculation pump (to promote bulk mixing) and an air stone (to avoid stratification). Starting at the fish's acclimation temperature, water temperature was increased at 0.3°C min^{-1} via stepwise set-point increments, preventing overshoot, until the fish exhibited the behavioral sequence (e.g. increased swimming activity, loss of orientation) culminating in loss of equilibrium (Desforges et al. 2023, Ern et al. 2023, Chasse et al. 2025, De Bonville et al. 2025, Raby et al. 2025). This final response was used to determine the CT_{max} endpoint. Temperature was monitored every minute with an electronic thermometer (Hanna Instruments, Checktemp HI 98509, USA; resolution, 0.1°C; accuracy, ±0.2°C).

A separate group of 50 juveniles, under the same temperature and replication scheme, was tested for CT_{min} using a horizontal thermal gradient with a recirculating chiller (NESLAB HX 150, USA) to lower the temperature. Starting at the acclimation temperature, fish (inside perforated plastic boxes) were allowed to rest for 30 min and then moved along the gradient to achieve a cooling rate of 0.3°C min^{-1} until loss of equilibrium, as in CT_{max}. The water temperature inside the box was recorded every minute with the same thermometer model used for CT_{max} (HI 98509).

Upon loss of equilibrium, fish were immediately returned to their respective acclimation tanks. All individuals recovered fully over the subsequent 96 h in every treatment, with 100% survival (n = 10 per temperature for CT_{max} and CT_{min}). Using the CT_{max} and CT_{min} values, the thermal window area (expressed as $°C^2$) was calculated as an indicator of thermal breadth, following Beitinger & Bennett (2000).

Preferred temperature and thermal metabolic scope

A horizontal thermal gradient system was used to determine the T_{pref} of the juveniles. The system consisted of a 400 cm-long PVC pipe fitted with a chiller (NESLAB HX 150, USA) and a 1,000 W heater, positioned at opposite ends. The resulting gradient ranged from 8 to 36°C and was confirmed to be linear ($y = 6.20 + 1.60x$; $R^2 = 0.98$). A porous aeration line ran the length of the pipe to ensure homogeneous mixing and prevent stratification. Seawater exchange in the horizontal thermal gradient system was maintained at a flow rate of 180-200 mL min^{-1}.

For each acclimation treatment, five individually tagged fish were placed simultaneously in the gradient (Σn *C. viridis* juveniles: 5 temperatures × 2 replicates × 5 fish = 50 fish). Acute temperature preference was determined following Reynolds & Casterlin (1979) by recording the location of each fish along the gradient every 10 min for 120 min. The water temperature of each segment occupied was recorded using a digital thermometer (HI 98509, Hanna Instruments, USA). Final T_{pref} were plotted against acclimation temperatures to generate a preference profile, and this final temperature was identified as the intersection point with the 45° equality line.

The TMS-an alternative methodology to the aerobic scope of Fry (1947)-was estimated following the temperature-induced metabolic rate (TIMR) protocol proposed by Paschke et al. (2018). This method quantifies the difference between high and low metabolic rates (HMR and LMR) at extreme but sublethal temperatures to evaluate aerobic capacity. Using the TMS approach, we identified the temperature within our experimental conditions at which *C. viridis* juveniles exhibited a maximum TMS. This peak is interpreted as the temperature that maximizes the aerobic capacity available beyond basal maintenance, i.e. a proxy for the energetic margin potentially available for growth and other functions; conversely, low TMS values indicate reduced aerobic capacity and increasing thermal stress (Paschke et al. 2018, Larios-Soriano et al. 2020, Alvarez-Lee et al. 2023).

The HMR and LMR of fish from each acclimation treatment were measured. HMR was measured after stimulating fish metabolism by exposing them to water temperatures equivalent to 90% of the average CT_{max} (defined as $TIMR_{max}$), whereas LMR was measured at 110% of the average CT_{min} ($TIMR_{min}$), where metabolic activity is suppressed. A total of 80 fish were used (40 for HMR and 40 for LMR), with 5 temperatures, 2 replicates, and 4 fish per condition. To minimize specific dynamic action during respirometry, fish were fasted for 48 h before HMR and LMR measurements. Measurements were carried out using an intermittent flow respirometry system equipped with an aquarium containing nine respirometry chambers, each equipped with valves to control the flow of water from the aquarium into the chambers. Each chamber contained a mini optical oxygen sensor (fiber-optic optodes; Loligo Systems) connected to a multi-channel transmitter (OXY-10 mini, PreSens, Germany). The temperature of the aquarium and the chambers was the $TIMR_{max}$ and $TIMR_{min}$ previously calculated for the juveniles of each acclimation temperature treatment. A juvenile was individually placed in eight chambers, and oxygen consumption was measured every 30 s for 5 min. One chamber served as a control to account for microbial respiration in the seawater.

The oxygen consumption rate (OCR) was calculated using Equation 1, and the HMR, LMR, and TMS were expressed in mg O_2 h^{-1} kg^{-1} wet weight. For each acclimation temperature:

$$\mathrm{OCR} = \frac{([O_2]_{\mathrm{initial}} - [O_2]_{\mathrm{final}}) \times V}{(W \times T)} \quad (1)$$

where $[O_2]_{\mathrm{initial}}$ - $[O_2]_{\mathrm{final}}$ was the difference in the initial concentration minus the final concentration of dissolved oxygen (mg O_2 L^{-1}); V was the volume (in liters) of the chamber where the measurements were made minus the volume displaced by the fish; W was the wet weight of the individuals in grams; and T was the time in hours during which oxygen consumption was measured.

TMS was calculated by pairing each of the seven HMR individuals with one of the eight LMR individuals based on measurement order and similar body mass, and computing the difference (HMR-LMR) for each pair, which yielded eight independent TMS values per acclimation temperature. This pairing approach, based on similar body mass and measurement order, allowed the calculation of eight independent TMS values per acclimation temperature, enabling subsequent statistical comparisons across groups. This methodology has already been employed in other studies (e.g. Larios-Soriano et al. 2021).

Data analysis

The T_{pref} data were summarized using box-and-whisker plots. To estimate the confidence intervals (CI) of the median, Equation 2 was applied:

$$\mathrm{CI} = \mathrm{M} \pm \left(\frac{1.58 \times \Delta \mathrm{H}}{\sqrt{\mathrm{N}}}\right) \quad (2)$$

where M is the median, 1.58 is a constant, ΔH is the interquartile range (75% quartile-25% quartile), and N is the sample size.

All physiological data (thermal tolerance limits, T_{pref}, and metabolic rates) were tested for normality using the Shapiro-Wilk test and for homoscedasticity using Levene's test. As the assumptions were met ($P > 0.05$), the data were analyzed using one-way ANOVA to evaluate the effect of acclimation temperatures.

When significant differences were detected ($P < 0.05$), Tukey's *post-hoc* test was applied for pairwise comparisons. Finally, we used linear models to assess the effect of fish mass and acclimation temperature on the thermal tolerance limits ($CT_{\max}$ and $CT_{\min}$). All analyses and graphics were performed using SigmaPlot v.14 and GraphPad Prism v.10.2.

RESULTS

Thermal tolerance limits were significantly affected by acclimation temperatures (Table S1). $CT_{\max}$ values increased from 36.9 ± 0.5°C (mean ± SD) to 41.9 ± 0.3°C (Fig. 1a), while $CT_{\min}$ values increased from 9.9 ± 0.6 to 16.4 ± 0.7°C (Fig. 1b) as the acclimation temperature increased from 20 to 32°C, respectively. Based on these $CT_{\max}$ and $CT_{\min}$ values, the thermal window area was 228°C (Fig. 1c). Linear model analyses revealed that acclimation temperature had a significant effect on both $CT_{\max}$ and $CT_{\min}$. In contrast, body mass had no significant effect on either $CT_{\max}$ or $CT_{\min}$ (Table S2).

The T_{pref} of *C. viridis* juveniles also varied significantly with acclimation temperature (Table S1), increasing from 22.6 ± 1.1 to 29.0 ± 1.4°C as the acclimation temperature increased from 20 to 32°C; the overall T_{pref} was 27.3°C (Fig. 2).

Acclimation temperature significantly affected HMR and TMS but had no significant effect on LMR in *C. viridis* juveniles (Table S3). HMR increased from 534.7 ± 78.5 to 1,321.0 ± 109.2 mg O_2 h^{-1} kg^{-1} as acclimation temperature increased from 20 to 29°C, then declined to 845.1 ± 106.2 mg O_2 h^{-1} kg^{-1} at 32°C (Fig. 3a). LMR remained stable throughout the thermal gradient (Fig. 3b). Peak TMS (1,005.8 ± 44.1 mg O_2 h^{-1} kg^{-1}) occurred at 29°C (Fig. 3c). Consistent with this peak, a secondary endpoint-growth over the 30-day acclimation-was also greatest at 29°C. Juveniles acclimated at 29°C showed the highest mass gain (37.7 ± 5.8 g), followed by 32°C (31.0 ± 9.4 g) and 26°C (30.9 ± 7.3 g) (Fig. 4).

DISCUSSION

Despite the commercial and economic importance of *C. viridis*, studies on its thermal physiology remain limited. To our knowledge, this is the first study to characterize the thermal tolerance limits ($CT_{\max}$ and $CT_{\min}$), T_{pref}, and the temperature associated with maximal TMS in juveniles. These physiological metrics serve as operational benchmarks for the aquaculture of *C. viridis* juveniles by delimiting temperature ranges to guide husbandry set points, acclimation protocols, and contingency planning. Beyond aquaculture applications, these results also provide mechanistic insight into the potential vulnerability of *C. viridis* to warming-specifically, increased exposure to temperatures above T_{pref}/optimal ranges and closer to $CT_{\max}$. Under such conditions, ectotherms typically increase metabolic rates and reduce aerobic scope (Pörtner 2001, Paschke et al. 2018), with downstream effects that include slower growth, greater susceptibility to hypoxia during warm episodes, and higher stress-related morbidity (Pörtner 2010, Assan et al. 2020, Jutfelt et al. 2021, Liu et al.

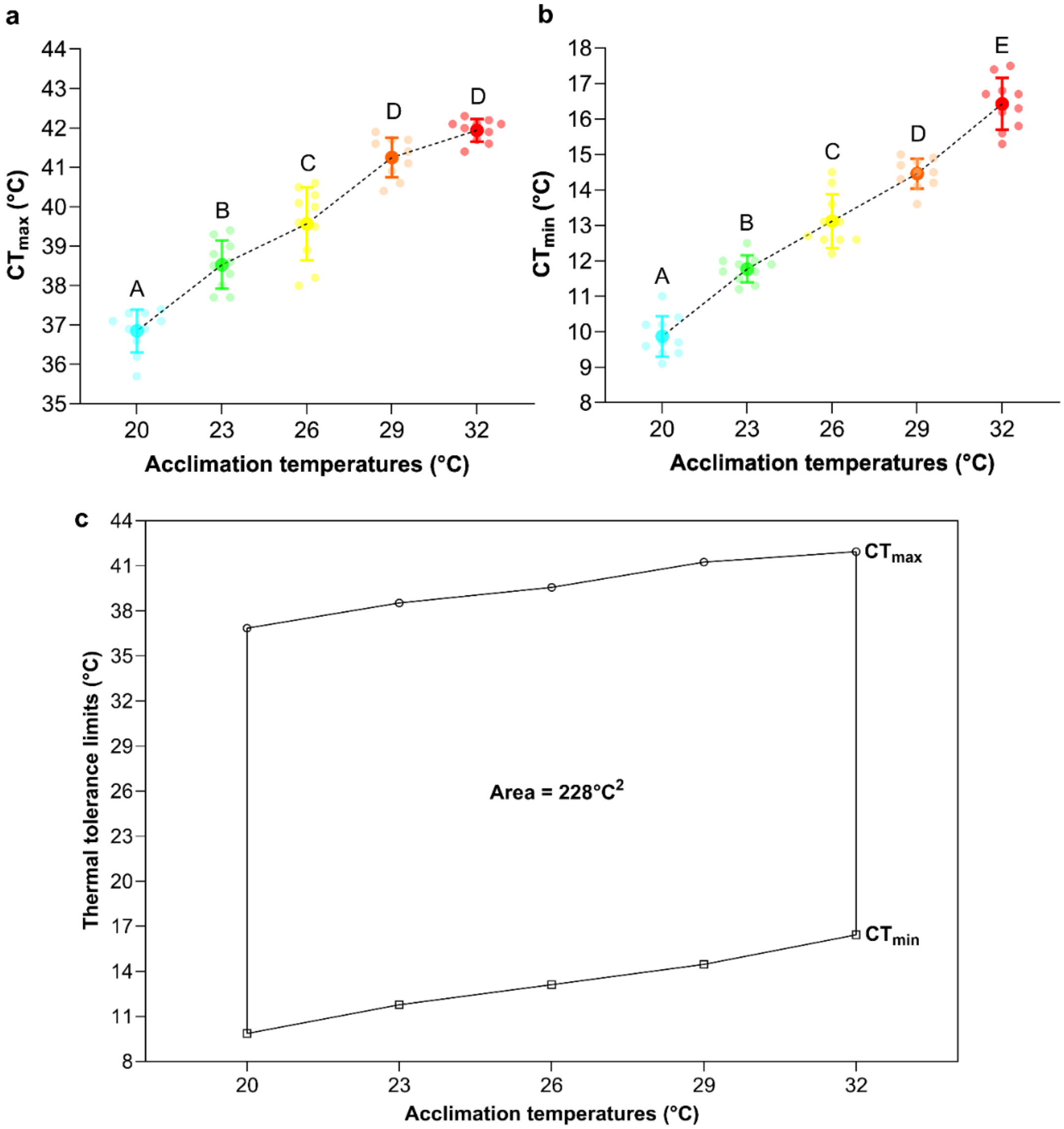

Figure 1. Thermal tolerance limits of *Centropomus viridis* juveniles acclimated to 20, 23, 26, 29, and 32°C. a) CT_{max} values, b) CT_{min} values, c) thermal window. Dark points represent the mean for each group, error bars indicate the standard deviation, and individuals are represented by small transparent points (n = 10). Letters indicate Tukey's *post-hoc* groups. Groups that do not share a letter are significantly different. CT: critical thermal.

2025b). Anticipating these responses is relevant for aquaculture site selection and seasonal management (e.g. choosing cooler intake waters, shading, or aeration) and it also has implications for natural populations, given projections of more frequent and intense marine heatwaves in the eastern tropical Pacific (Qiu et al. 2021, Capotondi et al. 2024). Enhancing the physiological understanding of *C. viridis* is therefore essential for both optimizing aquaculture practices and anticipating climate-related risks to wild stocks.

Determining the critical thermal limits (CT_{max} and CT_{min}) provides key information for managing fish outside stressful thermal zones during the hatchery and grow-out phases, thereby helping to establish proper aquaculture industry management (Desforges et al. 2023, Debnath 2024, De Bonville et al. 2025). According to Beitinger & Bennett (2000), as the acclimation temperature increases, both upper and lower thermal limits shift upward. The former indicates a gain in heat tolerance, while the latter indicates a loss in cold

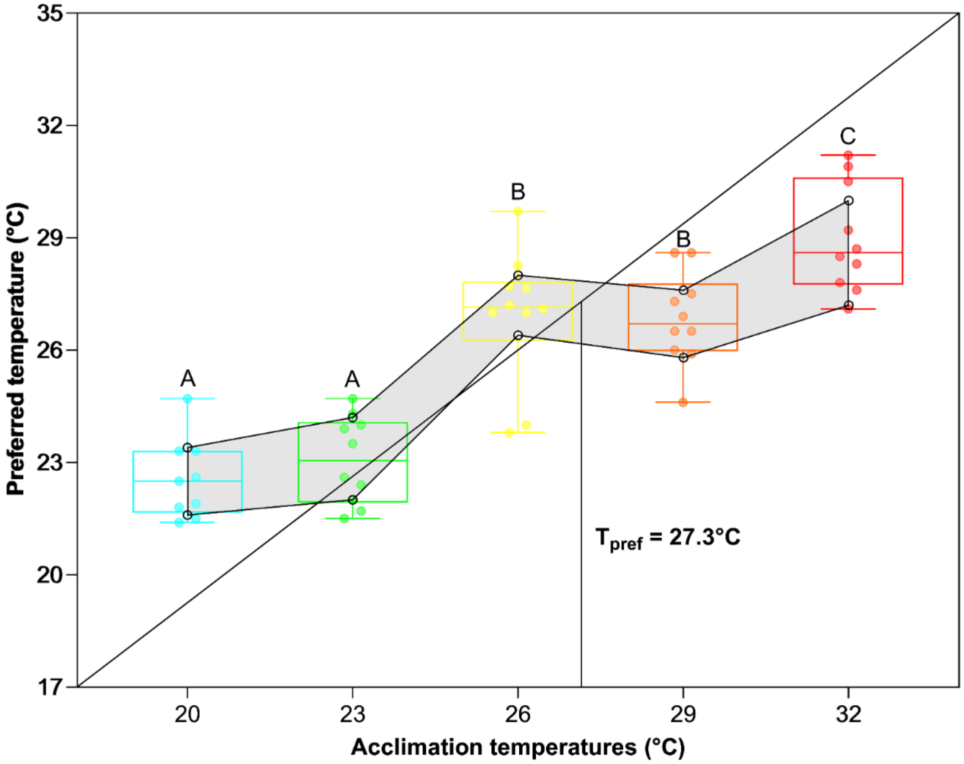

Figure 2. Preferred temperature (T_{pref}) of *Centropomus viridis* juveniles acclimated to 20, 23, 26, 29, and 32°C. The gray shaded area represents the 95% confidence intervals of the median. The boxes represent the 50% distribution of the data, the T-shaped whiskers represent the maximum and minimum values, and the solid horizontal line within the boxes is the median. Individuals are represented by small transparent points (n = 10). Letters indicate Tukey's *pos-hoc* groups. Groups that do not share a letter are significantly different.

tolerance. Our results for *C. viridis* juveniles were consistent with this pattern; however, juveniles acclimated at 29 and 32°C exhibited similar CT_{max} values (41.3-41.9°C, respectively), indicating diminished capacity for further heat tolerance. The CT_{max} values reported in the present study fall within the range observed in other species of tropical marine fish (34.7-45.3°C; Heath et al. 1993, Noyola et al. 2015, Vinagre et al. 2015, Cereja 2020). Species near the tropics-where temperatures are generally high and relatively stable-often tend to live closer to their CT_{max} and have reduced acclimation capacity to further temperature increases (Somero 2010, Dowd et al. 2015, Cereja 2020). Therefore, we consider that *C. viridis* juveniles should not be cultured at temperatures above 32°C to avoid thermal stress that exceeds their acclimation capacity.

Thermal windows represent the difference between CT_{max} and CT_{min} and describe the organism's tolerance range and offer a comparative index of thermal breadth among species (Beitinger et al. 2000). They also provide an overview of the thermal niche that ectothermic organisms, such as fish, can occupy in their habitat (Fry 1947, Bennett & Beitinger 1997). Consequently, thermal windows are used as comparative indices among fish species (Eme & Bennett 2009, Conte et al. 2023). Species with small thermal tolerance polygons have a narrower range of optimal temperatures and a smaller ecological niche, referred to as stenothermal. In contrast, larger polygons indicate species with a broader niche, known as eurythermal (Fangue & Bennett 2003, Dowd et al. 2015, Lattuca et al. 2018, Conte et al. 2023). In this study, the thermal window area of *C. viridis* juveniles (228°C^2) was smaller than that of its western Atlantic congener *Centropomus undecimalis* (288.6°C^2, Noyola et al. 2015) and smaller than ranges reported for other tropical and subtropical fish (258-1380°C^2), suggesting a stenothermal profile with limited ecological flexibility (Bennett & Beitinger 1997, Eme & Bennett

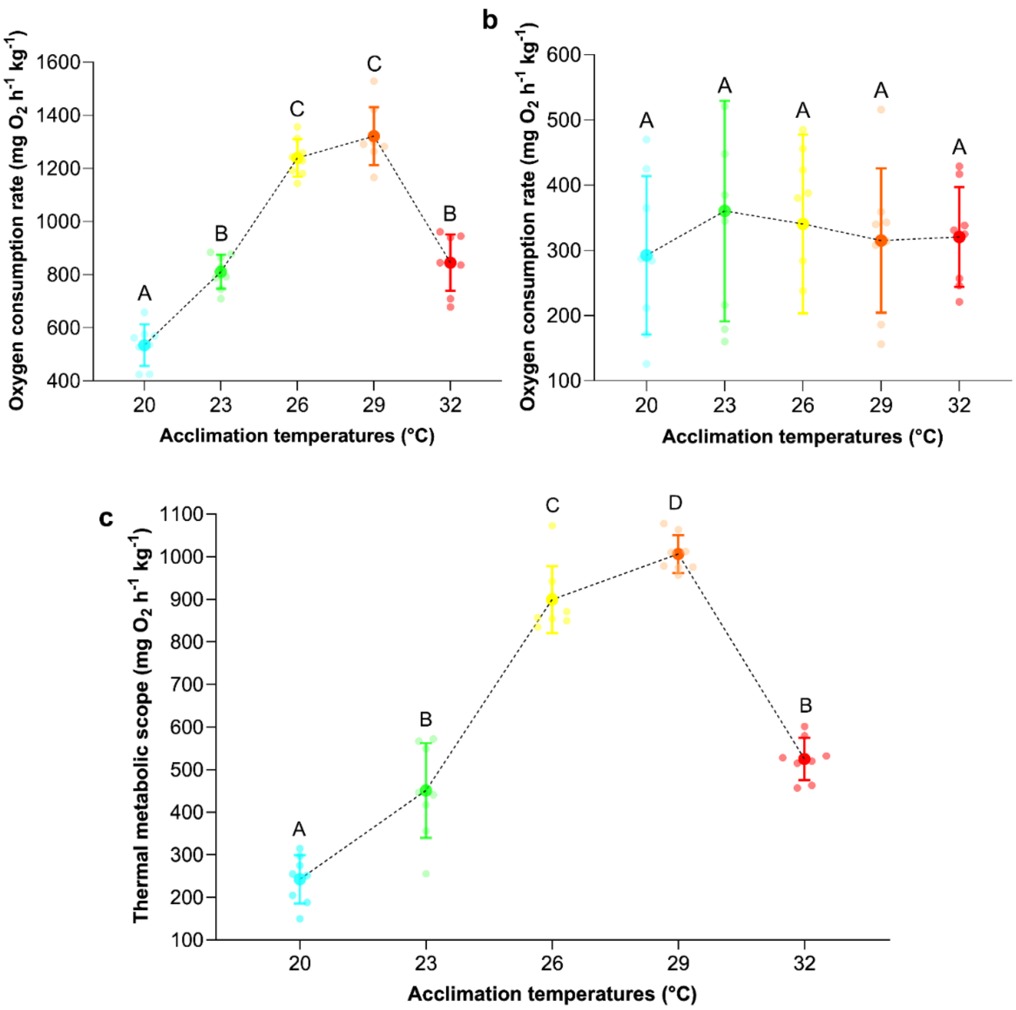

Figure 3. Metabolic rates of *Centropomus viridis* juveniles acclimated to 20, 23, 26, 29, and 32°C. a) High metabolic rate, b) low metabolic rate, c) thermal metabolic scope. Dark points represent the mean for each group, error bars indicate the standard deviation, and individuals are represented by small transparent points (n = 8). Letters indicate Tukey's *post-hoc* comparisons among groups. Groups that do not share a letter are significantly different.

2009, Larios-Soriano et al. 2021, Conte et al. 2023). As the ocean temperature continues to rise, the effective thermal niche of *C. viridis* may shrink further, reinforcing the importance of aquaculture as a conservation and production strategy.

T_{pref} and optimal temperature are typically close in fish, with T_{pref} reflecting thermal comfort (behavioral preference) and optimal temperature maximizing physiological performance (McCauley & Casselman 1980, Jobling 1981, Khan et al. 2014). Noyola et al. (2015) reported that T_{pref} of *C. undecimalis* was between 28.5 and 29.3°C, relatively similar to peak reproductive aggregation temperatures in its natural habitat in southern Florida, USA (27-28°C, Young et al. 2014) and consistent with the greatest growth temperature (26-29°C) in cultured juveniles in northern Brazil (Bendhack et al. 2013). For *C. viridis* juveniles, the T_{pref} (27.3°C) differed by only 1.7°C, consistent with the narrow thermal window and reinforcing its stenothermal nature.

The TMS represents the optimal temperature that maximizes the aerobic capacity available beyond basal maintenance-i.e. a proxy for the energetic margin potentially available for growth, reproduction, and other functions. Low TMS values indicate reduced aerobic capacity and increased thermal stress (Paschke et al. 2018, Larios-Soriano et al. 2020, Alvarez-Lee et al. 2023). Consistent with this framework, TMS increased

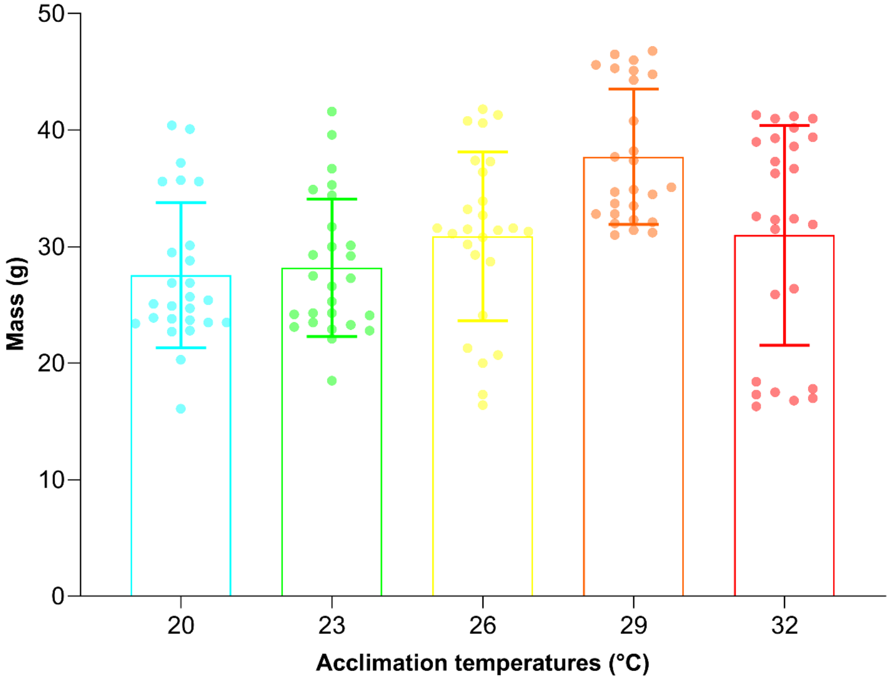

Figure 4. Final body mass of *Centropomus viridis* juveniles after 30 days of thermal acclimation at 20, 23, 26, 29, and 32°C. The boxes represent the mean, the T-shaped whiskers represent the standard deviation, and individuals are represented by small transparent points (n = 26).

with acclimation temperature up to 29°C and declined at 32°C, exhibiting a unimodal pattern; the TMS peak (~29°C) occurred within approximately 2°C of T_{pref} (27.3°C). Above this peak, aerobic capacity declines, narrowing management margins during warm episodes. Mechanistically, this pattern aligns with the oxygen- and capacity-limited thermal tolerance hypothesis: at optimal temperatures, oxygen supply effectively meets metabolic demand, resulting in maximal TMS as temperatures approach the thermal limits, constraints on oxygen delivery to tissues lower TMS and signal a progressive decline in physiological performance (Pörtner 2001, 2010). In our study, although growth rate was not a primary endpoint, juveniles acclimated to 29°C exhibited the greatest growth after the 30-day acclimation period, in agreement with the temperature at which TMS reached its peak. Baldini et al. (2022) indicated that marine-cage grow-out of *C. viridis* juveniles is feasible in tropical and subtropical sites with temperatures of ≥26°C. Looking ahead, long-term experiments under farm-realistic conditions-spanning larval, juvenile, and subadult stages-are needed to validate whether the 29°C optimum and the peak in TMS persist across ontogeny. Such work should quantify production endpoints (e.g. growth, feed conversion, survival) alongside physiological indicators, and test temperature in combination with co-stressors relevant to hatchery and grow-out systems (e.g. salinity and dissolved oxygen), to define truly optimal operating conditions and robust management margins for white snook aquaculture.

CONCLUSION

This study presents a stage-specific physiological profile for juvenile *C. viridis*, including thermal tolerance limits (CT_{min}/CT_{max}), T_{pref}, and an experimentally derived optimum that coincides with the peak TMS (~29°C). These metrics offer operational benchmarks to guide husbandry set points, acclimation protocols, and seasonal planning; moreover, they indicate that rearing above ~32°C may risk thermal stress beyond acclimation capacity. While growth was not a primary endpoint, juveniles held at 29°C exhibited the greatest mass gain over 30 days, consistent with the TMS peak, reinforcing the practical value of these benchmarks. The applicability of these values is restricted to juveniles under the conditions tested; optima and limits may differ for eggs, larvae, and older fish and can be modulated by non-genetically inherited effects (e.g. parental or early-life environmental history). We therefore recommend conducting long-term, farm-realistic trials across various life stages that quantify production endpoints (growth, feed conversion, survival) alongside physiological indicators, and testing temperature with co-stressors (e.g. salinity, dissolved oxygen) to define truly optimal operating conditions for white snook aquaculture.

Credit author contribution

L. Ibarra-Castro: conceptualization, methodology, review, and editing; F. Díaz & A.D. Re-Araujo: conceptualization, methodology, data curation, review, and editing; M. Sánchez-González: conceptualization, methodology, data curation, review, and editing; J.M. Martínez-Brown: conceptualization and methodology; J.P. Sánchez-Ovando: conceptualization, methodology, formal analysis, first draft, writing, review, and editing. All authors have read and accepted the published version of the manuscript.

Conflicts of interest

The authors declare that they have no conflict of interest.

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SUPPLEMENTARY MATERIAL

Table S1. Statistical analyses applied to thermal tolerance limits (CT_{max} and CT_{min}) and preferred temperature (T_{pref}) data of *Centropomus viridis* juveniles acclimated at 20, 23, 26, 29, and 32°C. CT: critical thermal.

Measurements	Statistical analysis
CT_{max}	ANOVA: $F_{(4, 45)} = 178.9$, $P < 0.001$ Tukey's test: $P < 0.05$ in all comparisons, except for 29 *vs.* 32°C ($P > 0.05$)
CT_{min}	ANOVA: $F_{(4, 45)} = 178.9$, $P < 0.001$ Tukey's test: $P < 0.001$ in all comparisons
T_{pref}	ANOVA: $F_{(4, 44)} = 39.3$, $P < 0.001$ Tukey's test: $P < 0.05$ in all comparisons, except for 20 *vs.* 23°C ($P > 0.05$) and 26 *vs.* 29°C ($P > 0.05$)

Table S2. Results of linear models assessing the effects of body mass (continuous predictor) and acclimation temperatures (categorical factor) on thermal tolerance limits (CT_{max} and CT_{min}) in *Centropomus viridis* juveniles. Bolded *P*-values indicate statistically significant effects ($P < 0.05$). d.f.: degrees of freedom. CT: critical thermal.

Response	Predictors	d.f.	*F*-value	*P*-value	$R^2_{adjusted}$
CT_{max}	Mass	1, 44	0.39	0.5336	0.901
	Acclimation temperatures	4, 44	81.56	**<0.00001**	
CT_{min}	Mass	1, 44	0.88	0.3526	0.935
	Acclimation temperatures	4, 44	118.81	**<0.00001**	

Table S3. Statistical analyses applied to high metabolic rate (HMR), low metabolic rate (LMR), and thermal metabolic scope (TMS) data of *Centropomus viridis* juveniles acclimated at 20, 23, 26, 29, and 32°C.

Measurements	Statistical analysis
HMR	ANOVA: $F_{(4, 35)} = 110.6$, $P < 0.001$ Tukey's test: $P < 0.001$ in all comparisons, except for 23 *vs.* 32°C ($P = 0.935$ 0.05), and 26 *vs.* 29°C ($P = 0.351$)
LMR	ANOVA: $F_{(4, 35)} = 0.33$, $P > 0.05$
TMS	ANOVA: $F_{(4, 35)} = 155.6$, $P < 0.001$ Tukey's test: $P < 0.05$ in all comparisons, except for 23 *vs.* 32°C ($P = 0.266$)