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Projected climate change scenarios and their effects on the nutritional quality of *P. segnis* muscle: Macromolecular and fatty acid transformations

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Abstract

This work presents the effects of increasing temperature on the physiological changes of *Portunus segnis* in natural environments (*in situ*) and under controlled conditions (*in vivo*). Following the increase in temperature from 19°C to 30°C and 40°C, physicochemical analyses showed that the percentages of oxygen consumption increased and the quantities of dissolved oxygen decreased. Under the effect of natural and controlled thermal stresses (19°C, 30°C and 40°C), the water and ash contents in the muscles of blue crabs decreased with increasing temperature. For protein, glycogen and lipid contents, a decrease was observed with increasing water temperature. Saturated fatty acids (SFAs) significantly increased compared to polyunsaturated fatty acids (PUFAs), mainly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which gradually decreased with increasing temperature. These results highlight the need to closely monitor climate change, particularly temperature increases, due to their potential impact on the structure and stability of biological macromolecules. Such alteration can compromise essential physiological functions of aquatic organisms. These findings open new avenues for future research aimed at better understanding adaptation and resilience mechanisms to thermal stress in a warming climate.

Keywords: *Portunus segnis*, globl warming, temperature, macro-molecules, fatty acids

Introduction

The world's oceans, representing nearly 71% of the Earth's surface, are experiencing the effects of pollution, eutrophication, and over-exploitation of their resources [1]. Moreover, this marine environment plays a significant role in human society, as over 50% of the global population lives within 60 km of the coast. On the other hand, oceans and seas constitute the largest source of biodiversity on the planet [2]. Many human activities such as fishing, tourism, and aquaculture depend on marine biodiversity and the overall health of seas and oceans, but these activities alter the chemical composition of aquatic ecosystems [3]. It is highly probable, according to the commonly accepted understanding by the intergovernmental panel on climate change, that the accelerating global temperature rise since the late 1970s is a result of the increased concentration of greenhouse gases in the atmosphere, such as carbon dioxide and methane, which have continued to rise [4]. The global CO_2 emissions level increased from 30.4 gigatonnes in 2010 to 33.3 gigatonnes in 2019. The increase in emissions has led to a widespread reduction of the cryosphere (areas of the planet where water is frozen), a continuous rise in ocean temperatures, a decrease in ocean pH and oxygen levels, changes in currents, and an increase in extreme events such as heatwaves [5].

In addition to direct issues related to pollution, eutrophication, over-exploitation, and the invasion of exotic species, the rise in carbon dioxide concentration and temperature poses a risk of causing major modifications to biodiversity, structure, and functioning of marine ecosystems [6]. Climate change poses a growing threat to marine ecosystems, directly affecting species distribution, physiology, and population dynamics. Rising seawater temperatures disrupt the thermal tolerance limits of many species, leading to geographical shifts toward the poles or to greater depths. The gradual rise in

ocean temperature is altering the environmental conditions essential for the survival of marine organisms, causing range shifts toward colder areas, mainly toward the poles or at depth [7; 8]. Climate change is also influencing the physiology of ectothermic species, reducing their metabolic performance, growth, reproduction, and survival [9]. Increasingly frequent extreme marine heat events, such as ocean heatwaves, are leading to mass mortalities and local population collapses [10; 11]. These rapid thermal changes often exceed the adaptive capacities of species, particularly those with low mobility or a narrow ecological niche, increasing the risk of local or global extinction.

It is urgent to place these systems under surveillance in order to detect, better understand, and anticipate changes in biological and ecological systems in the face of global climate change. Climate warming is detected in numerous functional units of the Earth's system. The signature of warming is identified in the ocean and the terrestrial and aquatic biosphere. Global temperatures have risen by 0.76°C between the periods 1850-1899 and 2001-2005 [4]. This temperature increase has mainly affected the oceans, which have absorbed 84% of the heat added to the climate system over the last four decades [12]. The increase in heat stored by the ocean has contributed to thermal expansion by 25% since the 1950s [13]. The warming projected by ocean-atmosphere general circulation models varies between 1.1°C (Scenario B1, rapid introduction of efficient and clean technologies) and 6.4°C (Scenario A1FI, intensive consumption of fossil carbon) by the end of this century [4]. Indeed, the exposure of aquatic organisms to higher temperatures could also reduce the metabolic rate, decreasing physiological energy costs and providing short-term tolerance above the critical temperature. Among the numerous species affected by this phenomenon, crustaceans are considered significant fisheries in many countries, and the influence of climate change poses a serious environmental and economic threat.

Global climate change is perhaps the most concerning anthropogenic impact currently, not only for the ocean but also for the entire planet. These manifestations will directly act through the effects of temperature on marine organisms. However, this disturbance will also indirectly influence marine ecosystems through its impact on regional climate and hydrology (atmospheric oscillation and ocean currents). Organisms' responses will be differential, and abrupt and unexpected ecosystem balance changes are to be feared. Despite existing uncertainties, our level of knowledge is sufficient to urge policies to reduce greenhouse gas emissions into the atmosphere and also to consider the other consequences of human activities that go against sustainable development. Furthermore, temperature and climate changes are considered the most important abiotic factors for the biogeographical distribution, abundance, and communities of marine fish. In aquatic environments, several studies also show a change in fish communities in response to climate changes. In fact, an increase in the temperature of the living environment, beyond a tolerance limit that varies by species, leads to the onset of physiological stress,

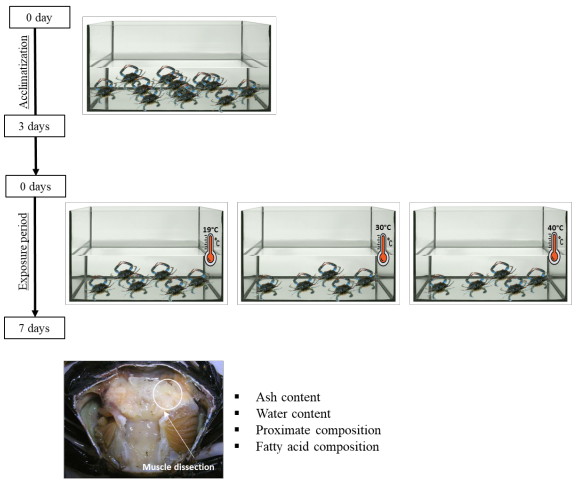

Figure 1. Experimental design for *P. segnis* exposure to increased temperature

especially pronounced when the exposure duration to this temperature is long, and the species are already closer to their upper thermal tolerance limit. If these stresses occur regularly, they can lead either to changes in geographical distribution, modifications in the life cycle, and *in situ* adaptations to new conditions, or, in sessile or less mobile forms, to significant mortality accompanied by epizootics and the substitution of affected species by others more resistant [14]

Therefore, the set of physico-chemical changes induced by climate change leads to the evolution of distribution areas, phenology, migratory movements, abundance, and interspecific interactions for many marine, freshwater, and terrestrial species [7]. These modifications, of course, have repercussions on biodiversity and can significantly alter the appearance of underwater landscapes. For this reason, we designed our study to determine the effect of temperature on the physiology of blue crabs (*Portunus segnis*). This current work focuses on the effect of increased temperature on the biochemical composition of *P. segnis*. The main objective is to analyze macromolecules (proteins, lipids, and glycogens) as well as the fatty acid composition and the nutritional quality of blue crab meat under controlled conditions.

Materials and methods

Samples and Experimental design

The individuals of blue crabs were collected from the Ghar el Melh lagoon during the summer season. Once collected, the specimens were immediately transported to the laboratory of the Higher Institute of Fisheries and Aquaculture of Bizerte (ISPAB) in a ventilated cooler. The specimens were acclimatized for three days in a 200 L cylindro-conical basin, in a closed circuit, containing filtered natural seawater, under continuous aeration and under strictly controlled physicochemical conditions: temperature (19°C), oxygen content (62 μ g/L), salinity (35 psu), and photoperiod (12 h/12 h), reproducing those of the sampling area.

After three days of acclimatization, the crabs were divided

into three tanks and subjected to different temperatures. For the control group, specimens were exposed to an ambient temperature of 19.81 ±0.14°C. In the second tank, the temperature was raised to 30.18 ±0.36°C using a thermostat. Regarding the third tank, two thermostats were installed to increase the temperature to 40.03 ±0.56°C. The temperature gradually increased to reach the desired values after approximately 2 hours of thermostat installation. During the one week of the experiment, the physicochemical parameters of the water, such as temperature and dissolved oxygen levels, were measured daily (every 24 hours) using a multimeter **Figure 1**.

Crabs dissection and muscles preparation

After exposure to increasing temperature, each individual from the crabs sampled from the natural environment and the controlled condition was weighed (170.04 ±16.51 g), measured using a caliper (60.44 ±6.51 mm), and subsequently dissected with a scalpel. The muscles from each batch were carefully extracted using forceps and weighed with a precision electronic balance. The choice of the organ taken from individuals is based on the fact that muscles are the edible tissues for living beings.

Table 1. Proximate composition of *P. segnis* muscle under increasing temperature

Parameter	19°C	30°C	40°C
Ash (%)	20.23 ±1.25^{a}	19.98 ±1.45^{a}	19.52 ±1.00^{a}
Moisture (%)	80.00 ±2.82^{a}	82.66 ±3.26^{a}	80.66 ±3.26^{a}
Protein (mg/g)	66.08 ±6.62^{a}	62.49 ±7.90^{a}	10.75 ±1.46^{c}
Lipid (mg/g)	11.14 ±2.35^{a}	11.82 ±2.56^{a}	1.97 ±0.48^{c}
Glycogen (mg/g)	2.03 ±0.25^{a}	1.77 ±0.22^{b}	0.37 ±0.07^{c}

Note: Values are expressed as mean ±standard deviation. Different superscript letters (a, b, c) in the same row indicate significant differences between temperature conditions at the 0.5% level.

Determination of water, ash, and proximate composition content

Using an electronic balance, 0.5 g of crab muscle was weighed to determine the initial wet weight. After drying in an oven at a temperature of 105°C for 24 hours, the samples were weighed again to determine the dry weight. To determine the ash content in crab muscles, the AOAC method was employed [15]. In brief, approximately 0.5 g of muscles were weighed and then dried at a temperature of 400°C for 24 hours. Lipid analysis was performed according to the method of [16], using vanillin solution. Glycogen extraction was performed according to the enzymatic method of [17], with glucose solution (100 mg/L). Protein determination

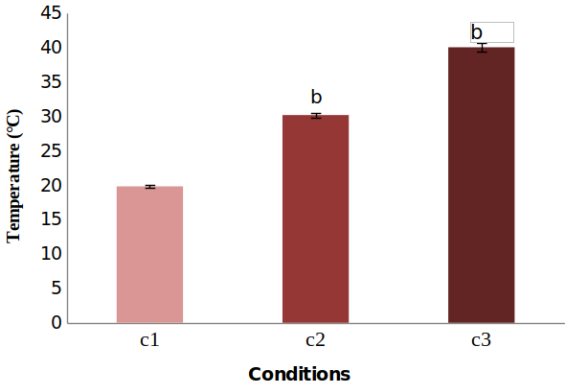

Figure 2. Temperature measurement in aquariums subjected to different temperatures **Note:** The difference between C1 and C2, C3 is significant at 0.5%.

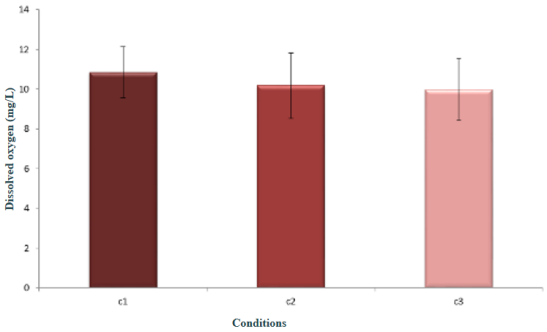

Figure 3. Measurement of dissolved oxygen in aquariums subjected to different temperatures

was carried out according to the method of [18], using bovine serum albumin as a standard.

Fatty acid composition analysis

Lipid extraction is a method for isolating these compounds using organic solvents, including a mixture of chloroform and methanol, according to the technique described by [19]. This process consists of grinding 0.5 g of flesh in a mortar with 15 mL of this mixture (2:1, v/v). In order to facilitate phase separation, 1 mL of sodium chloride (NaCl 15%) is then added to each sample. The homogenate obtained is subjected to centrifugation at 4000 rpm for 15 minutes, thus allowing the separation of the chloroform phase (containing the lipids) from the aqueous phase. The lower phase, containing the lipid extract, is then carefully recovered using a Pasteur pipette. From this extract, 20 μL are collected and placed in test tubes, to which 1 mL of hexane, 500 μL of an internal standard (C19:0), 500 μL of sodium methylate, 200 μL of sulfuric acid and 1.5 mL of sodium chloride are added. After methylation, the tubes are centrifuged under the same conditions, then the upper phase is recovered and stored

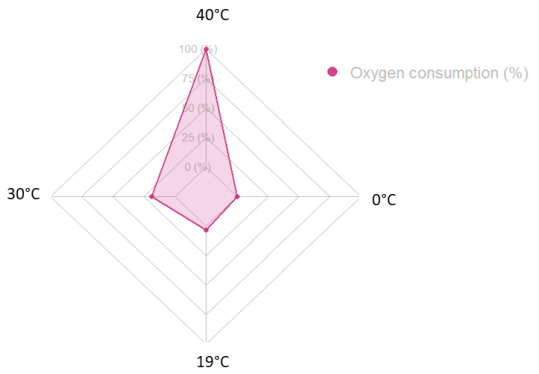

Figure 4. Oxygen consumption by *P.segnis* in aquariums subjected to different temperatures

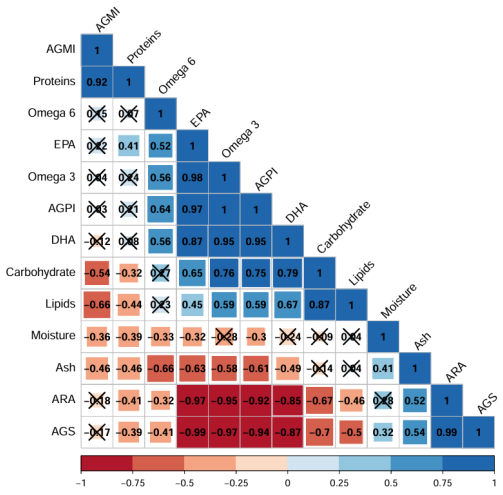

Figure 5. Correlation matrix illustrates the relationships between essential fatty acids and the biochemical composition of *P. segnis* subjected to different temperatures

at −30 °C, according to the method of [20]. The identification of fatty acids is based on the comparison of their retention times with those of a reference mixture of methyl esters (SUPELCO PUFA-3). The analysis of the chromatographic peaks is carried out using HP ChemStation software, and the relative amount of each fatty acid is expressed as a percentage of total fatty acids. The calculation of the percentage of each group of fatty acids (FA) was carried out according to the method of [21], using the following formula: %FA = (FAA × 100) / (total FA), where %FA corresponds to the relative surface area of a fatty acid (FAA) expressed as a percentage of the total surface area of the fatty acids detected.

Statistical analysis

The results of the biochemical parameters are expressed as means ± standard error (SD). Statistical analysis of the data was performed using R software (version 4.2.2), which was also used to generate the illustrative graphs. The normality of the distribution was checked by the Shapiro–Wilk test. A one-way analysis of variance (ANOVA) was then performed, followed by the Tukey test to identify significant differences between the means of the control and experimental groups. The significance threshold was set at 0.05. Finally, a correlation matrix was established to assess the significance of the Pearson correlation coefficients.

Results

Temperature and oxygen variation during the experiment

During the experiment, the temperature of the ponds was measured every 24 hours **Figure 2**. The control pond maintained a stable temperature of 19.81 ± 0.14 °C, whereas the ponds exposed to elevated temperatures reached significantly higher values of 30.18 ± 0.36 °C and 40.03 ± 0.56 °C, respectively ($p < 0.001$). Dissolved oxygen levels followed a similar pattern **Figure 3**, with the control pond showing 10.8 mg/L, while the ponds at 30 °C and 40 °C recorded 10.18 mg/L and 9.8 mg/L, respectively. Furthermore, oxygen consumption increased with prolonged exposure to higher temperatures **Figure 4**. A significant rise in oxygen consumption was observed in the tanks at 30 °C and 40 °C compared to the control at 19 °C, with consumption doubling in all tanks within the first 24 hours.

Water, ash, protein, lipid, and glycogen content

As shown in **Table 1**, water and ash contents exhibited similar trends across all temperature groups, with no statistically significant differences detected. In contrast, protein content varied significantly, with higher values observed in crabs exposed to 19 °C (66.08 mg/g) and 30 °C (62.49 mg/g), while a markedly lower protein concentration was recorded at 40 °C (10.75 mg/g) ($p < 0.001$). Lipid analysis revealed that crabs exposed to 40 °C had the lowest lipid levels (1.9 mg/g), whereas significantly higher concentrations were measured in crabs from the 19 °C and 30 °C groups ($p < 0.001$). Similarly, glycogen content was highest in the control group at 19 °C (2.03 mg/g), followed by the 30 °C group (1.77 mg/g), and was significantly reduced in crabs exposed to 40 °C (0.37 mg/g) ($p < 0.001$).

Fatty acid composition

Table 2 presents the fatty acid composition of *P. segnis* muscles exposed to temperatures of 19 °C, 30 °C, and 40 °C. Our results show that crabs exposed to 30 °C and 40 °C had significantly higher contents of saturated fatty acids (SFA), reaching 43.64 ± 2.64% and 75.50 ± 1.15%, respectively, compared to the control group at 19 °C ($p < 0.001$). This increase is mainly attributed to the rise in the major fatty acids C16:0 and C18:0, which reached 33.71 ± 0.007% and 5.843 ± 0.013% at 30 °C, and 63.82 ± 1.28% and 9.66 ± 0.02% at 40 °C, respectively.

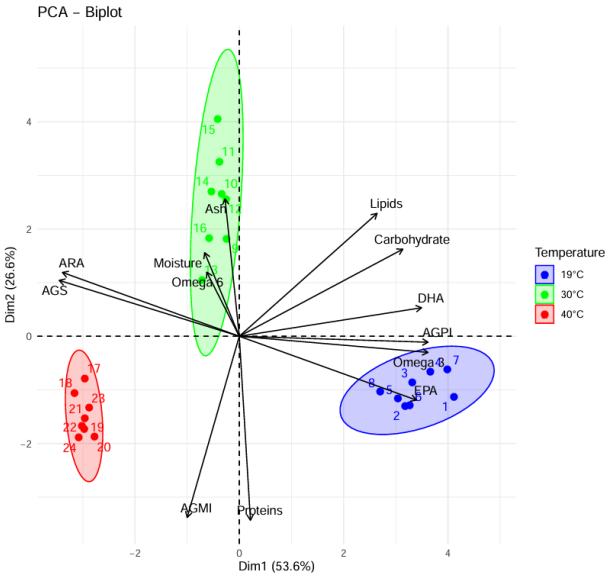

Figure 6. Principal component analysis (PCA), performed using two factors (F1 = 57.4% and F2 = 24.4%), allowed us to examine the variations of biochemical parameters (ash, humidity, lipids, proteins, carbohydrates) and essential fatty acids in the muscle of *P. segnis* subjected to different temperatures

Exposure to higher temperatures also resulted in a significant reduction in monounsaturated fatty acids (MUFAs) in crabs exposed to 30 °C compared to those maintained at 19 °C and 40 °C ($p < 0.01$). Crabs exposed to 40 °C showed the lowest concentrations of C16:1 and C20:1 and the highest concentration of C18:1 compared to the 19 °C and 30 °C groups ($p < 0.05$).

Polyunsaturated fatty acids (PUFAs) varied significantly between temperature groups. The control group (19 °C) exhibited a high PUFA content (80.53%), which was significantly greater than those observed at 30 °C and 40 °C ($p < 0.001$). A similar trend was found for omega-3 and omega-6 fatty acids, with higher percentages in the muscles of crabs maintained at 19 °C compared to those exposed to 30 °C and 40 °C ($p < 0.05$). This was confirmed by the high concentrations of docosahexaenoic acid (DHA, 39.99%) and eicosapentaenoic acid (EPA, 31.65%) in the 19 °C group, which significantly decreased in the muscles of crabs at higher temperatures ($p < 0.01$). Finally, arachidonic acid (ARA) showed an opposite trend, with significantly lower concentrations in crabs exposed to 19 °C compared to those at 30 °C and 40 °C ($p < 0.001$).

Correlation and Principal Component Analysis

The Pearson correlation coefficient matrix highlights the relationships between the levels of biochemical composition and the main fatty acids present in *P. segnis* muscle under different temperature exposures. A significant positive correlation ($p < 0.05$) was observed between essential fatty acids, proteins, and glycogen, with coefficients greater than 0.62. Conversely, monounsaturated fatty acids (MUFAs) showed a negative correlation with glycogen ($r = -0.54$), lipids ($r = -0.66$), water content ($r = -0.36$), and ash content ($r = -0.46$). Furthermore, an increase in arachidonic acid (ARA) and saturated fatty acid (SFA) levels appeared to be associated with a reduction in essential fatty acids, as evidenced by a strong negative correlation ($r < -0.85$), also illustrated in **Figure 5**.

Each cell of the matrix represents the Pearson correlation coefficient (r) for a pair of parameters. Positive correlations ($0 < r < 1.0$) are shown in blue, while negative correlations ($-1.0 < r < 0$) are shown in red. The intensity of the colors corresponds to the absolute values of the correlation coefficients. Statistical significance is indicated as follows: $*p < 0.05$, $**p < 0.01$, $***p < 0.001$; values not statistically significant ($p > 0.05$) are represented by a checkbox symbol.

Principal component analysis (PCA) biplot was employed to analyze the variation in measured parameters in *P. segnis* muscle samples exposed to different temperatures **Figure 6**. The first two principal components explained 81.8% of the total variance, with PC1 contributing 53.6% and PC2 26.6%. This analysis revealed a clear separation between the groups of crabs subjected to 30 °C and 40 °C compared to those exposed to 19 °C. The 19 °C group was associated with high levels of lipids, glycogen, DHA, PUFA omega-3, and EPA. In contrast, the 30 °C and 40 °C groups showed strong associations with elevated SFA, ARA, ash, omega-6, and moisture contents.

Discussions

Climate change, which occurs over time through natural variability, is also exacerbated by human activity. These activities, responsible for the increase of greenhouse gases in the atmosphere, have led to an increase in water temperatures. The impact of climate change represents a serious environmental threat to fisheries, especially to economically exploited species, such as crabs. Indeed, temperature, as a major abiotic factor, significantly influences the biochemical, metabolic and physiological processes of these species [22]. Studies have shown that natural temperature variation can induce alterations in the fish *Carassius auratus* [23], indicating that the increase in temperature generates molecular stress and increased energy demand, probably explaining the decrease in the organism's energy reserves. In addition, it has been reported that increased temperature causes molecular disruptions in proteins, lipids, and fatty acids in fish [24].

With this knowledge, an *in vivo* study was conducted to assess the effects of increased temperature on the physiology and biochemical composition of ectothermic organisms. Analyses of the biochemical composition of muscles, after exposure to elevated temperatures, revealed a decrease in protein and lipid contents compared to the control group. Similar results were reported for the blue swimmer crab, *P. pelagicus*, where an elevated temperature of 30 °C affected the protein content [25]. Similarly, it was shown that increased temperature alters lipids in *Carassius auratus* [26]. These decreases can be explained by the energy production resulting from the complete oxidation of

Table 2. Fatty acid composition of *P. segnis* muscle under increasing temperature

Fatty Acid	19°C	30°C	40°C
C16:0	5.760 ±0.106	33.712 ±0.007***	63.829 ±1.287$^{***\#\#\#}$
C18:0	1.001 ±0.044	5.843 ±0.013***	9.661 ±0.022$^{*\#\#}$
C20:0	3.136 ±0.069	4.090 ±0.000**	1.019 ±0.148$^{***\#\#\#}$
SFA	9.898 ±0.220	43.645 ±2.639***	74.509 ±1.159$^{***\#}$
C16:1	4.649 ±0.052	0.239 ±0.004***	1.198 ±0.154$^{***\#\#}$
C18:1	0.073 ±0.014	2.380 ±0.002***	9.661 ±0.022$^{***\#\#\#}$
C20:1	4.841 ±0.059	3.860 ±0.001***	1.019 ±0.148$^{***\#}$
MUFA	9.563 ±0.126	6.479 ±0.768**	11.878 ±0.279$^{**\#\#}$
C18:3n3	0.759 ±0.046	0.796 ±0.001	2.186 ±0.156$^{**\#\#}$
C20:5n3	31.657 ±0.180	26.800 ±0.003***	5.456 ±0.056$^{***\#\#\#}$
C22:6n3	39.995 ±0.362	15.810 ±0.003***	0.993 ±0.162$^{***\#}$
Omega-3	72.411 ±0.496	43.406 ±2.031***	8.635 ±0.375$^{***\#}$
C18:2n6	5.472 ±0.052	4.510 ±0.002***	1.688 ±0.161$^{***\#\#}$
C18:3n6	1.994 ±0.101	0.492 ±0.002***	0.241 ±0.197**
C20:4n6	0.658 ±0.004	1.462 ±0.000***	2.972 ±0.144$^{**\#\#}$
Omega-6	8.125 ±0.149	6.464 ±1.009**	4.901 ±0.503**
PUFA	80.537 ś 0.346	49.871 ś 2.756***	12.938 ś 0.879$^{***\#}$

Note: Results are presented as means ±standard deviation. Significant differences in saturated fatty acids between: 19 °C vs 30 °C and 19 °C vs 40 °C are denoted by: $p < 0.001$ ***, and between 30 °C vs 40 °C by: $p < 0.05$. For monounsaturated fatty acids, significant differences between: 19 °C vs 30 °C and 19 °C vs 40 °C are denoted by: $p < 0.01$ **, and the difference between 30 °C vs 40 °C is indicated by: $p < 0.05$ $^{\#}$. Regarding polyunsaturated fatty acids, significant differences between: 19 °C vs 30 °C and 19 °C vs 40 °C are noted by: $p < 0.001$ ***, and between 30 °C vs 40 °C by: $p < 0.05$ $^{\#}$.

macromolecules in response to temperature variations. Concerning glycogen contents, a highly significant decrease was observed with increasing water temperature. The study by [27], on glycogen concentrations and agonistic behavior of swimming crab (*Portunus trituberculatus*) subjected to temperatures of 16 °C, 24 °C and 32 °C, shows that glycogen concentrations decrease as temperature increases.

Higher temperatures enhance ROS production and consequently increase the risk of lipid peroxidation [28]. This hypothesis was observed in our work through the alteration of fatty acid composition of *P. segnis* subjected to different temperatures. Fatty acid analyses revealed that in response to heat stress, saturated and monounsaturated fatty acids significantly increase, while polyunsaturated fatty acids decrease in the muscles of crabs exposed to high temperatures. Heat stress is well established as a factor with physiological repercussions on poikilothermic organisms, eliciting a series of adaptive cellular responses. Among these, one of the most notable is the modification of membrane lipid composition, particularly through FA remodeling. This process involves changes in the proportions of SFA and UFA fatty acids, as well as changes in carbon chain length, with an increased predominance of SFA, or longer chains, in response to temperature elevation, to counterbalance the increase in membrane fluidity. For example, alterations in polyunsaturated fatty acids, mainly DHA and EPA, were observed in the gastropod *Lymnaea* [29]. Similarly, in *Trematomus bernacchii*, increased temperature induced lipid remodeling, with a decrease in C18:3n-3 and C22:6n-3 fatty acids [30]. Similar results have been reported in different bivalves where warming caused marked modifications in their fatty acid profiles illustrated by the depletion of essential FA such as DHA and EPA [31]. In our study, the observed changes in fatty acid profiles indicate an adjustment in lipid metabolism. Although significant changes were noted in the proportions of some fatty acids, the strong alterations observed in our analysis suggest that *P. segnis* is relatively affected by an increase in temperature of 30 and 40 °C and manages to deteriorate its lipid composition, indicating its high thermal sensitivity.

In general, the multivariate analysis, particularly the Princi-

pal Component Analysis (PCA) performed on the entire dataset, clearly highlighted distinct patterns associated with increasing thermal stress. The PCA revealed a clear clustering of the physiological responses of *Portunus segnis* across different temperature treatments *in vivo*, consistently separating the effects of low (19 °C), moderate (30 °C), and high (40 °C) temperatures. This separation underscores the substantial impact of temperature on key biochemical parameters such as protein, lipid, glycogen, and fatty acid profiles. The discriminative power of PCA not only confirms the robustness of the observed trends but also emphasizes the high sensitivity of this species to thermal fluctuations. The results obtained clearly indicate that proteins and lipids play a crucial role in the metabolic mechanisms that enable organisms to cope with thermal stress, while changes in fatty acid compositionparticularly the decrease in polyunsaturated fatty acids such as EPA and DHAcan be considered reliable indicators of thermal variation in aquatic organisms. This study confirms that global warming significantly affects the physiological state and biochemical composition of *P. segnis* under both natural and experimental temperature conditions. From a practical perspective, these findings provide valuable insights for aquaculture stakeholders, including breeders and shellfish farmers, by identifying physiological thresholds and stress markers essential for monitoring the health and viability of crustacean stocks. Furthermore, this work supports the development of adaptive and sustainable management strategies in response to climate-induced thermal stress, thus contributing to the long-term resilience and productivity of benthic resources.

Conclusions

This study investigates the effects of elevated temperatures on the physiological and biochemical responses of the blue crab (*Portunus segnis*) under *in vivo* conditions, following a three-day exposure to thermal stress. The analysis focused on key biochemical parameters in muscle tissue, including moisture, ash, protein, lipid, glycogen, and fatty acid composition. The results yielded several noteworthy findings. After 72 hours of exposure to high temperatures, no significant differences in water and ash content were observed compared to the control group. However, a marked decrease in glycogen, protein, and lipid levels was recorded with increasing temperature, indicating altered energy metabolism. In terms of fatty acid composition, a significant rise in saturated and monounsaturated fatty acids was detected, while polyunsaturated fatty acids, particularly those essential for maintaining membrane fluidity, decreased substantially. Physicochemical measurements also showed a reduction in dissolved oxygen levels in the rearing tanks, alongside an increase in oxygen consumption, pointing to elevated metabolic demand and thermal stress. Overall, these findings enhance our understanding of the physiological and biochemical responses of *P. segnis* to thermal variation and underscore the potential impacts of global warming on aquatic organisms, particularly regarding biochemical degradation and metabolic disruption.

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