AQUATIC RESEARCH
E-ISSN 2618-6365

Aquatic Research 9(4), 291-302 (2026) • https://doi.org/10.3153/AR26023 *Research Article*

Population structure, temporal allometry status of *Neotrapezium sublaevigatum* (Lamarck, 1819) (Family: Trapezidae) in the Vellar estuary, India

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Cite this article as:
Anbuselvan, S., Sanjaikumar, V., Jana, G., Nabisha, S., Arundathy, A., Thirupathi, G., Srihari, B., Shamkumar, E., Thangaraj, M. (2026). Population structure, temporal allometry status of *Neotrapezium sublaevigatum* (Lamarck, 1819) (Family: Trapezidae) in the Vellar estuary, India. *Aquatic Research*, 9(4), 291–302. https://doi.org/10.3153/AR26023

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Submitted: 06.03.2026
Revision requested: 02.05.2026
Last revision received: 09.05.2026
Accepted: 05.06.2026
Published online: 08.09.2026

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Available online at
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ABSTRACT

Seasonal variation in growth and condition of *Neotrapezium sublaevigatum* was investigated in the Vellar estuary from August 2024 to July 2025. A total of 926 individuals were examined to evaluate shell morphometry, length–weight relationships, size–frequency distribution, and condition indices across pre-monsoon, monsoon, and post-monsoon seasons. Shell length ranged from 4.70 to 41.10 mm, with the highest mean length and weight recorded during the pre-monsoon. Length–weight analysis revealed consistent negative allometric growth (b = 2.5299–2.7875; $p < 0.05$) in all seasons, indicating that shell length increased proportionally faster than biomass. Stronger morphometric correlations were observed during the monsoon (r^2 up to 0.9164), suggesting enhanced growth consistency under nutrient-enriched conditions. Size–frequency distribution showed dominance of the 16.0–20.9 mm size class, with peak abundance during the monsoon, reflecting active recruitment and favorable growth conditions. Condition indices exhibited clear seasonal trends, with higher relative condition (*Kn*) during the monsoon and elevated Fulton's condition factor (*K*) during the post-monsoon, indicating dynamic energy allocation in response to environmental variability. The bivalve, *N. sublaevigatum,* demonstrates adaptive growth strategies characteristic of tropical estuarine bivalves, with population structure and physiological status closely linked to monsoon-driven hydrological cycles. These findings provide baseline ecological information for future monitoring and management of estuarine bivalve populations.

Keywords: *Neotrapezium sublaevigatum*, Vellar estuary, Allometric growth, Length–weight relationship, Size–frequency distribution, Condition factor

Introduction

Neotrapezium sublaevigatum (Lamarck, 1819), commonly referred to as the trapezid bivalve, was originally described as *Cardita sublaevigata*. This species typically inhabits sheltered environments influenced by freshwater input and protected from strong wave action. It commonly occurs as a nesting species in rocky intertidal and shallow sub-littoral crevices, where salinity may fluctuate considerably and sediment load can be high. The species is frequently recorded from small, protected bays and mangrove ecosystems at depths ranging from 0 to 15 m (Morton, 1979). They exhibit a byssally attached, epifaunal mode of life and are weakly heteromyarian. The shell is medium-sized, oblong, solid, compressed, and quadrangular in outline, lacking a pronounced keel on the posterior dorsal margin. The umbo is small and positioned anteriorly. The dorsal margin slopes posteriorly, while the ventral margin remains nearly straight. The shell surface displays purplish rays over a dull white background, and the periostracum is greenish-brown. The morphology of the mantle cavity, visceral mass, and pericardium is broadly comparable to that of other veneroid bivalves (Morton, 1979; Siddiqui et al., 2007). The species is widely distributed throughout the Indo-West Pacific region, including Hong Kong, Singapore, and the Red Sea (Siddiqui et al., 2007). In India, it has been reported from both east and west coast mangrove ecosystems (Preston, 1915; Subba Rao et al., 1991, 1995; Boominathan et al., 2012; Kantharajan et al., 2017; Tudu et al., 2018).

Growth in bivalves is commonly assessed through measurements of shell dimensions, growth rings, or body volume (Nagvenkar et al., 2014). Allometry refers to the study of proportional changes in different parts of an organism as a function of growth (Reiss, 1985). Length–weight and other morphometric relationships are widely used to estimate soft tissue biomass and to understand growth patterns in living bivalves (Dame, 1972). Shell morphology and relative proportions are influenced by various environmental factors, including latitude, depth, shore level, tidal regime, water currents, turbulence, wave exposure, and sediment characteristics (Dame, 1972; Claxton et al., 1998; Akester & Martel, 2000). Condition indices such as the relative condition factor (Kn) and Fulton's condition factor (K) are widely employed to evaluate the physiological status and overall well-being of bivalves. These indices may vary seasonally and are influenced by sex, reproductive stage, and environmental conditions (Watanabe & Katayama, 2010; Sundaram et al., 2011; Isnard et al., 2015).

Globally, numerous studies have examined allometric relationships in bivalves to characterize growth patterns (Gaspar et al., 2001; Çolakoğlu, 2014; Alkaradawe et al., 2014; Mugabe et al., 2019; Ransangan et al., 2019; Bahtiar & Findra, 2025). Along the Indian coast, investigations have addressed population structure, growth patterns, and condition indices of several marine bivalve species (Ramesha & Seetharamaiah, 2009; Sundaram et al., 2011; Thomas, 2013; Tenjing et al., 2013; Nagvenkar et al., 2014; Hemachandra & Thippeswamy, 2017). However, despite the ecological significance of this species in the Vellar estuary, detailed information on its seasonal growth dynamics and morphometric relationships remains scarce. To the best of our knowledge, this is the first seasonal allometric assessment of *N. sublaevigatum* from Vellar estuary. The findings provide baseline information for understanding population structure, seasonal growth dynamics, and ecological adaptation of the species. Therefore, the present study aims to evaluate seasonal variations in shell allometry, length–weight relationships, and condition indices of *N. sublaevigatum* in the Vellar estuary, thereby contributing to a better understanding of its population biology and ecological adaptation in estuarine environments.

Materials and Methods

Study Area

The study was conducted in the Vellar estuary, situated along the southeast coast of India. The estuary is classified as a "true estuary," characterized by a permanently open mouth throughout the year. Based on salinity gradients, it has been divided into four zones: marine, gradient, tidal, and freshwater (Ramamurthy, 1954). The estuarine system is influenced by semi-diurnal tides, with a maximum tidal amplitude of approximately 1 m. Water depth ranges from 2.3 to 5.0 m. The interaction between neritic coastal waters and estuarine conditions facilitates the exchange of biotic and abiotic components, with tidal influence extending up to 16 km upstream. Seasonal fluctuations in chlorinity and freshwater inflow significantly influence nutrient dynamics and elemental cycling within the estuary and adjacent coastal waters (Natarajan et al., 1979). Climatically, the region experiences three distinct seasons: pre-monsoon (May–August), monsoon (September–December), and post-monsoon (January–April), which strongly influence hydrographic parameters and biological productivity.

Sample Collection

Live *Neotrapezium sublaevigatum* specimens were collected fortnightly from August 2024 to July 2025 from the intertidal oyster beds covering an area of approximately 200 m² in the

Vellar Estuary (11°29'25"N, 79°45'60"E) (Figure 1) using 2 m² quadrats. To minimize depth-related variability, all samples were collected at a uniform depth of 0.5-1feet. During each sampling event, three quadrats were randomly placed within the study site, covering a total sampling area of 6 m² per observation. The collected monthly data were subsequently pooled and categorized into seasonal groups for comparative analysis.

Individuals attached to edible oyster beds were carefully detached manually to avoid shell damage and rinsed with estuarine water to remove adhering sediment and debris. For each specimen, morphometric parameters, including shell length (SL), shell height (SH), and shell width (SW), were recorded. Shell length was measured as the maximum anterior–posterior dimension, shell height as the maximum dorsal–ventral dimension, and shell width as the maximum lateral thickness. Measurements were taken using a digital vernier caliper (Myuto**,** Japan) with a precision of 0.02 mm, while total shell weight (SWt) was measured using a digital balance (Sartorius BT224S) with an accuracy of 0.01 g. Water quality parameters such as temperature, salinity, DO, and pH at the collection site were observed during the sampling period and are presented in Table 1.

Data Analysis

The length–weight relationship (LWR) was assessed using the following non-linear equation: $W=aL^b$ where W is the total weight (g), L is the shell length (mm), a is the intercept (initial growth coefficient), and b is the slope or growth exponent (Ramesha & Seetharamiah, 2009; López et al., 2018; Petetta et al., 2019; Nahar et al., 2019; Bouzaidi et al., 2020). The equation was log-transformed and analyzed using the Linear Allometric Model (LAM): $logW = Log^a + bLog^L$

The b value indicates the nature of growth: $b = 3$ implies isometric growth, $b > 3$ indicates positive allometric growth, and $b < 3$ suggests negative allometric growth. One-way analysis of variance (ANOVA) was performed to evaluate seasonal differences in the LWR and condition factor values.

The physiological condition of the mussels was assessed using Fulton's condition factor (K) and the relative condition factor (Kn), which are commonly used indicators of organismal well-being and habitat suitability (Simon & Mazlan, 2008; Isnard et al., 2015; Hashim et al., 2017).

Fulton's Condition Factor: $K = 1000W/L^3$

Relative Condition Factor: $Kn = W/aL^b$

where W is the total body weight (g), and L is the shell length (mm). Higher values of K and Kn indicate better nutritional status and overall condition. Seasonal variations in condition were statistically analyzed to determine the potential influence of environmental factors.

Figure 1. Map showing the sampling site in the Vellar estuary

Results and Discussion

A total of 926 individuals of *N. sublaevigatum* were examined for morphometric analysis during the study period (Table 2). Shell length (SL) ranged from 4.70 to 41.10 mm. The highest mean SL was recorded during the pre-monsoon season (20.93 ±5.70 mm), followed by the post-monsoon (19.63 ±6.68 mm), whereas the lowest mean SL was observed during the monsoon (18.95 ± 5.92 mm). No significant difference was detected between the monsoon and post-monsoon seasons ($p > 0.05$).

Body weight varied from 0.012 g to 9.640 g. The highest mean body weight occurred during the pre-monsoon (1.69 ±1.44 g), followed by the post-monsoon (1.59 ±1.61 g). Shell height (SH) showed clear seasonal variation, with the highest mean value during the pre-monsoon (11.79 ±1.29 mm) and the lowest during the monsoon (7.24 ± 2.45 mm). In contrast, shell width (SW) was highest during the monsoon (11.29 ±3.72 mm) and lowest during the pre-monsoon (8.79 ±3.00 mm).

The smallest individual (4.7 mm SL) was recorded in the monsoon season, while the largest specimen (41.1 mm SL) occurred during the post-monsoon. A similar seasonal trend was observed for body weight. The maximum shell height (23.6 mm) and shell width (23.8 mm) were recorded in the post-monsoon season, whereas the minimum values for height (1.2 mm) and width (2.0 mm) were observed during the monsoon. Since this species is not commercially exploited or harvested for consumption, market-based size classification and minimum landing size regulations have not been established in Tamil Nadu. However, understanding its natural size distribution is ecologically significant, as it reflects population stability, environmental adaptation, and may serve as an indicator.

The length–weight relationship (LWR) and other morphometric relationships exhibited negative allometric growth in all seasons, as indicated by *b* values significantly lower than 3 ($p < 0.05$) (Table 3). For the LWR, the growth exponent (*b*) ranged from 2.5299 (pre-monsoon) to 2.7875 (monsoon). The highest coefficient of determination ($r^2 = 0.9065$) was observed during the post-monsoon season, indicating a strong relationship between shell length and body weight. Since $b<3$ in all seasons, growth was negatively allometric, suggesting that shell length increased proportionally faster than body weight.

Table 1. Water quality parameters in Vellar estuary during the study period (Values in the column sharing a common superscript is not significantly different at the *P*=0.05 level)

Season	Temperature (ºC)	Salinity (ppt)	pH	DO (mg/L)
Pre monsoon	29.7 ± 2.5[a]	30.3 ± 3.5[a]	7.5 ± 0.5[a]	4.81 ± 0.53[a]
Monsoon	26.5 ± 2.3[b]	22.1± 12.2[b]	7.9 ± 0.3[b]	5.85 ± 0.64[b]
Post monsoon	27.8 ± 2.1[a]	24.3 ± 5.7[c]	7.6 ± 0.2[a]	5.14 ± 0.71[b]

Table 2. Morphometric variables in *N. sublaevigatum* at Vellar estuary (Values in the row sharing a common superscript is not significantly different at the *P*=0.05 level)

Parameter	Central tendency and data range	Pre monsoon	Monsoon	Post monsoon
Total Length (mm)	Mean±SD	20.93 ±5.70[a]	18.95 ±5.92[b]	19.63 ±6.68[b]
	Min	5.9	4.7	6.2
	Max	36.4	38.1	41.1
Body Weight (g)	Mean±SD	1.69 ±1.44[a]	1.32 ±1.29[a]	1.59 ±1.61[a]
	Min	0.109	0.012	0.028
	Max	8.31	8.654	9.641
Total height (mm)	Mean±SD	11.79 ±1.29[a]	7.24 ±2.45[b]	9.53 ±3.78[c]
	Min	3.7	1.2	1.9
	Max	23.3	16.7	23.6
Total Width (mm)	Mean±SD	8.79 ±3.0[a]	11.29 ±3.72[b]	9.82 ±4.17[c]
	Min	2.8	2	2.5
	Max	20.3	26.1	23.8

Table 3. Descriptive statistics and allometric relationships in *N. sublaevigatum* at Vellar estuary in different seasons

Relationship	Season	*n*	*a*	*SE of a*	*b*	*SE of b*	r^2	Allometric relationship
Length – Weight	Pre monsoon	209	0.0006	0.2318	2.5299	0.1091	0.8040	Negative
	Monsoon	403	0.0002	0.1407	2.7875	0.0499	0.8700	Negative
	Post monsoon	314	0.0005	0.1747	2.6040	0.0818	0.9065	Negative
Length – Width	Pre monsoon	209	0.4702	0.0977	0.9583	0.0561	0.5501	Negative
	Monsoon	403	0.6055	0.0588	0.9920	0.0208	0.8532	Negative
	Post monsoon	314	0.5621	0.0930	0.9500	0.0435	0.6180	Negative
Length – Height	Pre monsoon	209	0.9819	0.1101	0.8124	0.0632	0.8705	Negative
	Monsoon	403	0.3575	0.0636	1.0194	0.2257	0.8353	Negative
	Post monsoon	314	0.6452	0.1068	0.8952	0.0500	0.7511	Negative
Height – Weight	Pre monsoon	209	0.2003	0.1582	1.7012	0.0886	0.7464	Negative
	Monsoon	403	0.0062	0.0965	2.5855	0.0307	0.9164	Negative
	Post monsoon	314	0.0151	0.2295	1.9386	0.0973	0.8968	Negative
Width – Weight	Pre monsoon	209	0.0211	0.1794	1.9184	0.0822	0.7038	Negative
	Monsoon	403	0.0017	0.1125	2.6500	0.0370	0.8816	Negative
	Post monsoon	314	0.0189	0.1465	1.8230	0.0099	0.7586	Negative
Width - Height	Pre monsoon	209	0.7063	0.1339	0.7090	0.0614	0.7529	Negative
	Monsoon	403	0.6815	0.0541	0.9728	0.0178	0.8536	Negative
	Post monsoon	314	0.5124	0.1360	0.7193	0.0547	0.8584	Negative

The length–width relationship yielded *b* values ranging from 0.9500 (post-monsoon) to 0.9920 (monsoon), with the strongest correlation during the monsoon (r^2 = 0.8532). Similarly, the length–height relationship showed *b* values between 0.8124 and 1.0194, with r^2 values ranging from 0.7511 to 0.8705. In all cases, the growth pattern remained negatively allometric. In the height–weight relationship, the highest *b* value was recorded during the monsoon (2.5855), followed by post-monsoon (1.9386) and pre-monsoon (1.7012). The monsoon season also exhibited the strongest correlation (r^2 = 0.9164). Overall, the morphometric relationships consistently demonstrated negative allometric growth across seasons.

The length-frequency distribution showed distinct seasonal patterns (Figure 2). The 16.0–20.9 mm size class was dominant in all seasons, with the highest abundance recorded during the monsoon (*n* = 132), followed by the post-monsoon (*n* = 97) and pre-monsoon (*n* = 72). The monsoon season exhibited greater abundance across most size classes, particularly within the 6.0–35.9 mm range. In all seasons, frequency increased progressively from the 6.0–10.9 mm class to the 26.0–30.9 mm class, followed by a decline in larger size classes. The smallest size class (1.0–5.9 mm) was poorly represented in all seasons. Individuals larger than 36.0 mm were rare, and specimens exceeding 41 mm were absent in the pre-monsoon and monsoon samples.

Fulton's condition factor (*K*) ranged from 0.00036 to 0.02856, with higher values generally observed during the post-monsoon season (Figure 3). The relative condition factor (*Kn*) ranged from 0.03576 to 1.64521, with peak values recorded during the monsoon season. Seasonal variation in both *K* and *Kn* indicates fluctuations in physiological condition, potentially associated with environmental variability and reproductive cycles.

The relationship between morphology and life-history strategies of aquatic organisms is well established, as shell form and size reflect growth patterns, ecological adaptation, and population dynamics. Estimation of growth rates and secondary production in aquatic ecosystems is possible when information on organismal size, shape, differential growth, and population structure is available. The morphometric data obtained in the present study clearly demonstrate that shell length, height, and width of *N. sublaevigatum* vary with size. However, individuals of similar shell length often exhibited differences in shell height and width, resulting in shape variability, a phenomenon previously described by Nahar (2020).

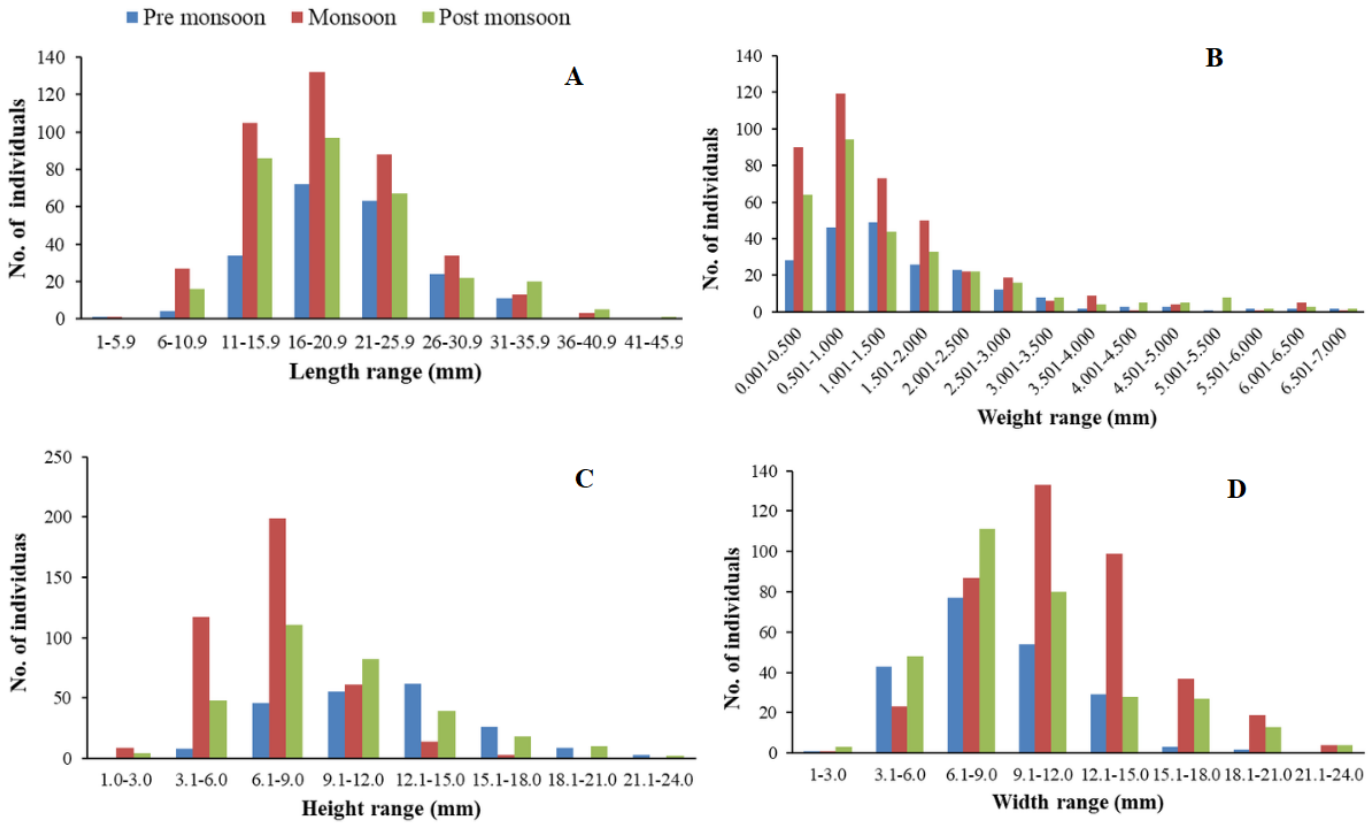

Figure 2. Temporal variation of (A) length, (B) weight, (C) height, and (D) width frequency of *N. sublaevigatum* in the Vellar estuary during the study period

Shell form in bivalves is influenced by a range of environmental factors, including salinity, food availability, hydrodynamics, and substrate type. Earlier studies have shown that shell size is generally more responsive to environmental fluctuations than shell shape (Seed, 1968; Wilbur & Owen, 1964). Consequently, shell shape may provide more stable information on dimensional relationships, potentially reflecting genetic control, whereas shell size is more strongly regulated by ambient environmental conditions. The ecological relevance of allometric relationships lies in their ability to describe growth and metabolic scaling across a wide range of organism sizes and taxa (West & Brown, 2005).

The present investigation revealed consistent negative allometric growth ($b < 3$ for length–weight relationships and $b < 1$ for linear dimensions) in *N. sublaevigatum* across pre-monsoon, monsoon, and post-monsoon seasons in the Vellar estuary. Such growth patterns are characteristic of estuarine bivalves inhabiting environments with pronounced salinity and nutrient fluctuations. Comparable negative allometry has been reported in tropical bivalves such as *Meretrix meretrix*, *Meretrix casta*, and *Perna viridis* from Indian estuaries, where shell elongation exceeds biomass accumulation under variable environmental conditions (Narasimham, 1991; Vakily, 1989; Sawanth, 2012; Takar et al., 2022). Similar trends have also been documented in estuarine populations of *Crassostrea madrasensis* and *Tegillarca granosa*, in which salinity variation and seasonal food availability influence somatic growth (Amin et al., 2008; Uddin et al., 2024).

The b values obtained in the present study (2.52–2.78) fall within the commonly reported range (2.0–3.0) for tropical estuarine mollusks. According to Le Cren (1951) and Ricker (1975), deviations from isometric growth are frequently associated with environmental variability, reproductive investment, and ontogenetic changes. In estuarine systems such as Vellar, monsoon-driven freshwater inflow alters salinity and nutrient regimes, thereby affecting tissue deposition and shell accretion. Comparable seasonal variability in b values has been reported for *Anomalocardia flexuosa* from estuarine intertidal flats, where monsoon conditions enhanced growth consistency without producing isometric scaling (Silva-Cavalcanti et al., 2018). Negative allometry in length–width and length–height relationships observed in this study further

supports earlier findings on estuarine bivalves. Morphometric plasticity in response to hydrodynamic stress and substrate characteristics has been documented in species such as *Donax cuneatus* and *Tellina* spp., where shell elongation is favored over thickening in dynamic habitats (Stanley, 1970; Ansell, 1983). The relatively higher r^2 values recorded during the monsoon season are consistent with observations by Nagarajan et al. (2006), who reported stronger morphometric correlations during periods of enhanced food availability. Nutrient enrichment following freshwater inflow may promote more uniform growth increments, leading to improved regression fits.

The negative allometry observed in height–weight and width–weight relationships is also in agreement with previous studies on tropical estuarine mollusks. Vakily (1989) emphasized that biomass accumulation in bivalves is often constrained by reproductive investment and salinity stress, resulting in reduced proportional weight gain relative to shell dimensions. In Indian estuaries, studies on *V. cyprinoides* (Vijaya Krishna & Ammini, 2018) and *M. casta* (Durve, 1971) demonstrated that seasonal reproductive cycles strongly influence weight increments, particularly during spawning when tissue mass declines despite continued shell growth. The relatively higher *b* and r^2 values observed during the monsoon in the present study may therefore reflect improved feeding conditions associated with detrital enrichment and phytoplankton blooms (Qasim, 2003). The persistent negative allometric growth observed in *N. sublaevigatum* is consistent with adaptive strategies of estuarine bivalves exposed to fluctuating salinity gradients. According to Clark et al. (2020), estuarine bivalves often prioritize shell elongation to maintain stability and functional efficiency in soft sediments, while tissue deposition varies in response to energy availability and reproductive demand. Morphometric variability in estuarine populations is thus more frequently attributed to environmental heterogeneity than to genetic differentiation (Stanley, 1970). The relatively high r^2 values obtained in this study (0.7038–0.9164) indicate that the regression models reliably describe growth patterns despite seasonal environmental variability.

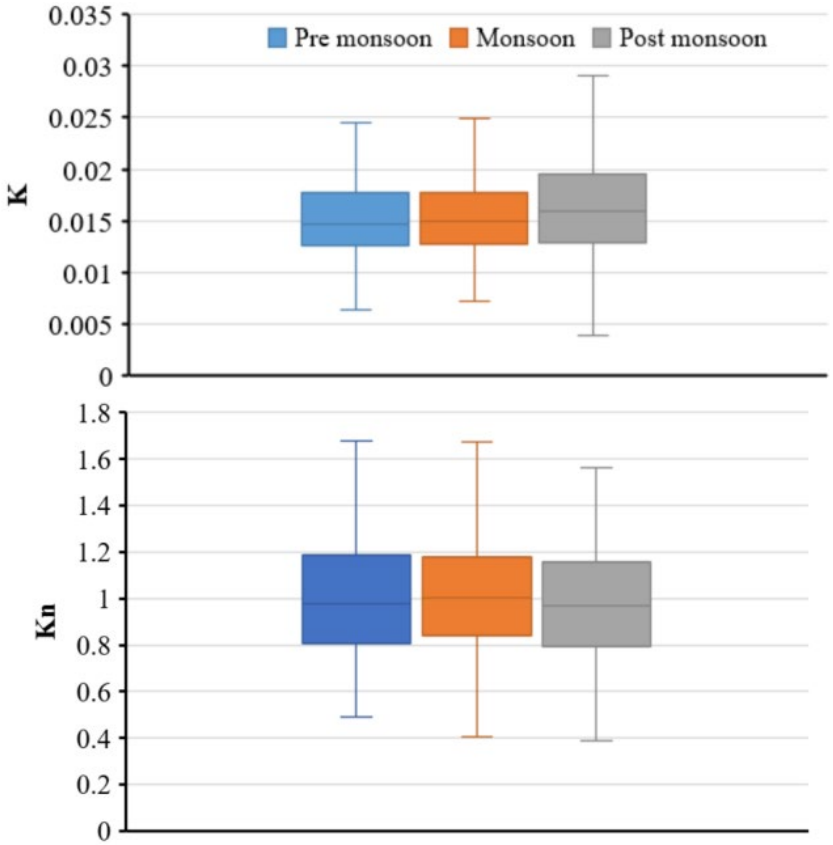

Figure 3. Box–plots of Fulton's condition factor (*K*) and relative condition factor (*Kn*) of *N. sublaevigatum* in the Vellar estuary. (Line = median, box = 25th and 75th percentile, whiskers = 10th and 90th percentile)

Seasonal variation in size-frequency distribution further reflects the dynamic population structure of *N. sublaevigatum*. The dominance of the 16.0–20.9 mm size class across all seasons, particularly during the monsoon, suggests that this size group represents either a rapidly growing cohort or the most ecologically stable life stage. The marked increase in abundance during the monsoon, especially within the 6.0–35.9 mm size range, indicates enhanced recruitment and juvenile survival. Similar monsoon-driven recruitment peaks have been reported for estuarine bivalves such as *M. casta* and *V. cyprinoides*, where freshwater influx enhances nutrient availability and primary productivity, supporting larval settlement and early growth (Durve, 1971; Vijaya Krishna & Ammini, 2018). The progressive increase in frequency from smaller to intermediate size classes, followed by a decline in larger size groups, represents a typical cohort progression pattern in estuarine molluscs with extended or continuous spawning (Seed, 1976). The reduced abundance of larger individuals may reflect cumulative mortality, predation pressure, or environmental constraints limiting attainment of larger sizes, as reported for *T. granosa* and *C. madrasensis* (Amin et al., 2008; Uddin et al., 2024). The poor representation of the smallest size class (1.0–5.9 mm) may result from habitat segregation of early juveniles, cryptic settlement behavior, or sampling bias (Ansell, 1983; Narasimham, 1991).

Temporal variation in condition indices provides further insight into the physiological status of *N. sublaevigatum*. Fulton's condition factor (*K*) attained higher values during the post-monsoon season, whereas the relative condition factor (*Kn*) peaked during the monsoon. Elevated *K* values during the post-monsoon suggest improved tissue accumulation and physiological recovery following the monsoon period, when salinity and temperature conditions become relatively stable. Similar post-monsoon peaks in condition factor have been reported for *M. casta* and *T. granosa* (Durve, 1971; Uddin et al., 2024). The higher *Kn* values during the monsoon indicate that individuals were heavier than expected for their shell length, reflecting active feeding and rapid tissue deposition under nutrient-rich conditions. Unlike Fulton's *K*, *Kn* accounts for deviations from the predicted length–weight relationship and is therefore more sensitive to short-term physiological changes (Le Cren, 1951). Monsoon-associated phytoplankton blooms and organic matter enrichment in tropical estuaries (Qasim, 2003) likely contributed to enhanced biomass accumulation. The contrasting seasonal peaks of *K* (post-monsoon) and *Kn* (monsoon) highlight the dynamic balance between growth, energy storage, and reproductive investment. Environmental stress during extreme pre-monsoon conditions may suppress feeding efficiency and metabolic balance, resulting in lower condition values. The relatively high condition indices recorded during monsoon and post-monsoon seasons indicate that *N. sublaevigatum* benefits from seasonal nutrient enrichment in the Vellar estuary, although the wide range in *Kn* values suggests individual variability related to age, reproductive stage, and microhabitat conditions.

The present findings improve ecological understanding of *N. sublaevigatum* by providing baseline information on its seasonal growth dynamics and morphometric variations in the Vellar Estuary. Seasonal allometric relationships help in understanding how environmental factors influence shell growth and population structure. Such information is valuable for monitoring population health, identifying periods of environmental stress, and supporting conservation strategies for estuarine habitats. In addition, these results can serve as reference data for future population assessments and ecological monitoring programs in mangrove-associated coastal ecosystems.

Conclusion

This study provides a comprehensive evaluation of seasonal growth dynamics, morphometric relationships, population structure, and physiological condition of *N. sublaevigatum* in the Vellar estuary. The species consistently exhibited negative allometric growth across pre-monsoon, monsoon, and post-monsoon seasons, indicating that shell elongation progresses more rapidly than biomass accumulation. The observed *b* values (2.5299–2.7875) fall within the expected range for tropical estuarine mollusks and reflect adaptive growth responses to fluctuating salinity, nutrient availability, and reproductive investment. Seasonal patterns in morphometric relationships and relatively high coefficients of determination, particularly during the monsoon, suggest that nutrient enrichment associated with freshwater influx promotes more uniform somatic growth. The dominance of intermediate size classes and the marked increase in abundance during the monsoon indicate active recruitment and successful cohort progression, characteristic of opportunistic estuarine life-history strategies. The limited representation of early juveniles and larger individuals further highlights habitat partitioning, cumulative mortality, and environmental constraints typical of dynamic estuarine systems.

Condition indices revealed distinct seasonal trends, with higher relative condition (Kn) during the monsoon and improved Fulton's condition factor (K) during the post-monsoon. These fluctuations underscore the dynamic balance between growth, energy storage, and reproductive processes under monsoon-driven environmental variability. Enhanced

food availability during the monsoon likely supports rapid tissue deposition, whereas post-monsoon stability favors improved overall somatic condition. The findings demonstrate that *N. sublaevigatum* exhibits pronounced ecological plasticity, with growth and physiological performance tightly coupled to seasonal hydrological cycles. This study contributes to a better understanding of the species' ecological plasticity and provides baseline information for future monitoring, management, and conservation of estuarine bivalve populations in the region.

Compliance with Ethical Standards

Conflict of interest: The author(s) declare no actual, potential, or perceived conflict of interest for this article.

Ethics committee approval: The authors declare that this study does not involve experiments with human or animal subjects, and therefore, ethics committee approval is not required.

Data availability: The data will be made available upon request from the author.

Funding disclosure: The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Acknowledgments: The authors are highly grateful to the Authorities of Annamalai University for providing facilities and encouragement.

Disclosure: -

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