Climate Risk Projection and Economic Vulnerability Assessment of Outdoor Mass Culture of S-Type Rotifer Under Warming Scenarios

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ABSTRACT

S-type rotifer (*Brachionus rotundiformis*) is an essential live feed in marine aquaculture. Rising global temperatures may impair its growth and production capacity. This study established a quantitative climate risk framework to evaluate the economic vulnerability and resilience of outdoor rotifer production under warming scenarios. A climate-adjusted production model was developed to simulate economic performance under projected temperature increases of +1.5°C, +2°C, and +4°C, with the objective of identifying economically optimal and climate-resilient stocking densities for rotifer cultivation. Under baseline thermal conditions (26.39-27.07°C), a stocking density of 10 ind./mL yielded the highest net return (430.19 THB per 1,000 L), followed by 5 ind./mL (397.31 THB per 1,000 L). In contrast, higher densities (15-20 ind./mL) exhibited signs of overstocking, characterized by reduced productivity, elevated production costs, and negative economic returns. However, under warming scenarios, all production systems shifted toward economic losses beginning at +1.5°C. High-density systems (15-20 ind./mL) exhibited the greatest vulnerability, with probability of loss exceeding 95% and strongly negative economic resilience ratio (ERR) values. At +4°C, economic risk intensified across all densities, as net return distributions shifted substantially toward negative values and value at risk ($VaR_{5\%}$) indicated amplified downside risk. Monte Carlo simulations further demonstrated that loss probability increased progressively with temperature, approaching certainty (~100%) at +4°C. Overall, rising temperature reduced both biological productivity and economic stability. Stocking densities of 5-10 ind./mL demonstrated comparatively greater resilience than higher-density systems, underscoring the importance of climate-informed density optimization to sustain live feed production under warming conditions.

Keywords: Adaptive aquaculture production strategy/ Climate resilience/ Live feed culture

1. INTRODUCTION

Climate change resulted in a continuous increase in the average global temperature. The Intergovernmental Panel on Climate Change (IPCC) projected that global surface temperatures would increase by approximately 1.5-4.0°C within this century, depending on greenhouse gas emission scenarios [1]. This rise in temperature directly affected aquatic ecosystems, including many aquaculture systems that were highly sensitive to fluctuations in temperature and water quality [2, 3].

In marine aquaculture, S-type rotifer, particularly *Brachionus rotundiformis*, were recognized as a critical live feed for the larval rearing of many economically important fish, crab, and shrimp species [4-7]. Consequently, the consistency and yield of rotifer production directly influenced the stability of the aquaculture supply chain. However, large-scale outdoor rotifer culture systems were highly sensitive to temperature fluctuations, which affected growth rates and carrying capacity, thereby influencing production stability and economic viability. Although numerous studies had examined the effects of initial stocking density on rotifer yield [8-10], limited attention had been given to integrating these findings within the context of climate change, particularly with respect to economic risk under future temperature uncertainty. Climate change exerted not only biological impacts but also economic consequences on aquaculture systems, as energy costs, production volumes, and the risk of financial losses varied under changing climatic conditions [11].

Therefore, this study aimed to investigate the effects of rotifer stocking density under projected temperature increases associated with climate change, incorporating scenario-based projection modeling to evaluate the vulnerability and resilience of the production system. This approach was intended to support the development of adaptive aquaculture production strategies. Specifically, the objectives were to develop a predictive model for rotifer production under temperature increase scenarios (+1.5°C, +2°C, and +4°C) and to determine the economically optimal and climate-resilient initial stocking density. These objectives were aligned with the Blue Economy framework and climate adaptation strategies in aquaculture, which had become critical issues in recent years.

2. METHODOLOGY

2.1 Experimental design and set-up

This experiment was conducted using a completely randomized design (CRD) to evaluate the effects of four stocking densities on rotifer cultivation under outdoor mass culture conditions: low (5 rotifers/mL), medium (10 rotifers/mL; control), high (15 rotifers/mL), and intensive (20 rotifers/mL). Each treatment consisted of 10 replicates (n=10). The study was carried out from January to March 2026.

A microalgal starter culture was obtained from the Klongwan Fisheries Research Station laboratory, Faculty of Fisheries, Kasetsart University and *Nannochloropsis* inoculated into a 200-L plastic tank at a ratio of 1:25 (starter culture to water), with salinity adjusted to 20 ppt. Appropriate fertilizer was added to support the growth of marine green microalgae. The culture was maintained until it reached the exponential growth phase (about 2 days). It was then transferred to a 2,000-L tank and further cultured for an additional 2-3 days until the cell density reached approximately 1-2 × 10^6 cells/mL. The resulting *Nannochloropsis* culture was subsequently used as feed for S-type rotifers.

The large-scale microalgal culture was transferred into 2,000-L rotifer mass culture tanks, each containing 1,500 L of microalgae. Rotifer starter cultures were then introduced at the designated initial stocking densities (low, medium, high, and intensive). The rotifers were allowed to grow for 3 days, after which the entire culture was harvested.

For rotifer harvesting, the valve located at the bottom of the culture tank was opened to allow the water to drain by gravity. A two-layer hand-net system was used during harvesting. The first layer, with a 350 µm mesh size, prevented sediment from mixing with the rotifer. The second layer, a 75 µm mesh harvest net, collected the rotifer as the water flowed from the tank. Both hand nets measured 30 cm in diameter and 25 cm in height. After complete harvesting, the rotifer retained in the 75 µm net were transferred to a 5-L plastic container and rinsed with clean seawater. The rotifer was then filtered again through the 75 µm net to obtain a concentrated sample (wet weight), following the method described by Arkronrat et al. [5] (Figure 1).

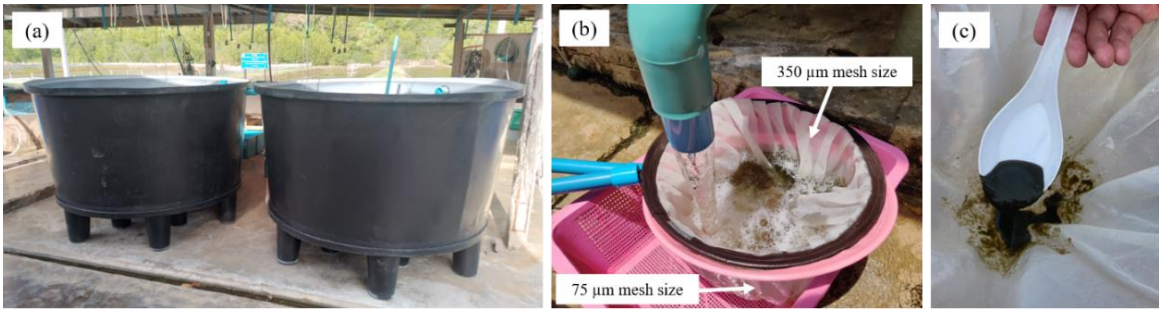


Figure 1. Mass culture tank (2,000 L, 1.7 m diameter, 1 m height) for rotifers under outdoor conditions (a), rotifer harvesting method (b), and rotifers in concentrated form (c).

2.2 Bioeconomic considerations

During the experiment, rotifer samples were collected every 12 h to estimate rotifer density (rotifers/mL). The samples were fixed with 5% formalin and subsequently counted using a Sedgewick-Rafter counting chamber under a compound microscope at 40× magnification. Population growth parameters, including specific growth rate (μ), division rate (K), and doubling time (D), were calculated for each culture according to the methods described by Ashraf et al. [12] and Matha et al. [6], using Equations 1, 2, and 3, respectively.

$$\mu = \ln N_2 - \ln N_1 / t_2 - t_1 \quad (1)$$

$$K = \mu / \ln(2) \quad (2)$$

$$D = 1 / K \quad (3)$$

Where; μ=the specific growth rate (day^{-1}), K=division rate (day), D=doubling time (day), N_1=the density count at time t_1 (rotifers/mL), N_2=the density count at time t_2 (rotifers/mL), t_1=the first sampling time (day), t_2=the second sampling time (day), and ln indicates the Napierian logarithm.

In addition, at the end of the 3-day culture period, the total yield of rotifer production from the mass culture tanks was calculated using Equations 4 and 5.

$$\text{Gross yield (g/tank)} = \text{rotifer production (g)/tank} \quad (4)$$

$$\text{Net yield (g/1,000 L)} = \text{rotifer production (g)/1,000 L of tank} \quad (5)$$

2.3 Profitability factors

For profitability assessment, several economic indicators were evaluated. The total cost (TC) of rotifer production was divided into production cost (PC), environmental cost (EC) and marketing cost (MC). PC comprised fixed costs (FC), including land cost, labor cost, tools and equipment depreciation, as well as variable costs (VC), such as seed stock, feed, and transportation. MC covered expenses related to distribution, packaging, and advertising. Total revenue (TR) and net return (NR) represented the sales value, with net return calculated as the difference between total revenue and total cost at the various initial stocking densities [13]. TC, PC, TR, and NR were calculated using Equations 6, 7, 8, and 9, respectively.

$$TC = PC + MC \quad (6)$$

$$PC = TFC + TVC \quad (7)$$

$$TR = P \times Q \quad (8)$$

$$NR = TR - TC \quad (9)$$

Where; TFC is the total fixed costs, TVC is the total variable costs, P is the price per unit of rotifer/kg, Q is the total quantity of rotifer in kg and VCU is the variable cost per unit of yield = TVC / Q measured in cost per kg, where all costs are in THB.

2.4 Modeling the effects of temperature on mass rotifer production

This study examined the effects of rotifer culture density under baseline conditions derived from Studies 2.1-2.3 across three temperature increase scenarios (ΔT: +1.5°C, +2°C, and +4°C), based on projections from the IPCC [1].

Baseline yield (Y_0) and total cost (TC_0) obtained at each rearing density (d) were used to develop a climate-adjusted yield model following Hultgren et al. [14]. Climate-adjusted cost and net return

models were constructed based on Amorim et al. [15]. Risk analysis was performed using Monte Carlo simulation as described by Mahmudiono et al. [16] and Amorim et al. [15], and risk indicators were evaluated according to Puttanapong [17] and World Bank [18].

2.4.1 Climate-adjusted yield model

To evaluate the impact of temperature on yield, a temperature sensitivity coefficient (β) was defined to represent the rate of change in yield per 1°C increase in temperature. The climate-adjusted yield model was formulated as presented in Equation 10:

$$Y(c,d) = Y(0,d) \times (1 - \beta\Delta T) \quad (10)$$

Where; Y(c,d) represented the climate-adjusted yield at density d, ΔT denoted the temperature increase (+1.5°C, +2°C, +4°C), and β represented the rate of yield reduction per 1°C increase.

In this study, β was estimated using reported population growth rate responses to temperature from three literature sources: Gama-Flores et al. [19], Paraskevopoulou et al. [20] and Tran-Nguyen et al. [21]. The reported changes in growth rate or yield were converted into β values expressed as percentage decreases per 1°C increase, resulting in an average estimate of 0.03 (3% per °C).

2.4.2 Climate-adjusted cost model

Under increasing temperature conditions, energy expenditures were expected to rise. Accordingly, a cost effect coefficient (γ) was defined to represent the rate of cost increase per 1°C, as specified in Equation 11:

$$TC(c,d) = TC(0,d) \times (1 + \gamma\Delta T) \quad (11)$$

Where; TC(c,d) represented the climate-adjusted total cost at density d, ΔT denoted the temperature increase (+1.5°C, +2°C, +4°C), and γ represented the rate of cost increase per 1°C

In this study, γ was estimated from the relationship between baseline production cost and temperature-related cost changes across the available production scenarios. The reconstructed estimate was approximately 0.05 (5% increase in total cost per 1°C increase), and this value was applied consistently across the three temperature scenarios.

2.4.3 Climate-adjusted net return model

$$NR(c,d) = (P \times Y(c,d)) - TC(c,d) \quad (12)$$

Where; NR(c,d) represented the net profit under the climate scenario at density d, P represented the price per kilogram of rotifers, Y represented the yield under the climate scenario at density d, and TC(c,d) represented the total cost under the climate scenario at density d.

2.4.4 Monte Carlo simulation model

Probability distributions were specified for the following variables: simulated output variability (Y_{sim}), price volatility (P_{sim}), and energy cost volatility (TC_{sim}), using the corresponding random variables described below.

$$Y_{sim} \sim N(Y(c,d), \sigma Y)$$

$$P_{sim} \sim Triangular(P_{min}, P_{mode}, P_{max})$$

$$TC_{sim} \sim N(TC(c,d), \sigma TC)$$

Where; σY and σTC represented the standard deviations of total output and total cost, respectively, and N denoted the normal distribution. For the Monte Carlo simulation, σY was set at 0.20 kg and σTC at 300 THB, while, the minimum (P_{min}), most likely (P_{mode}), and maximum (P_{max}) prices of rotifer were set at 1,000, 1,200, and 1,400 THB/kg, respectively. A total of 1,000 iterations were performed for each density and temperature scenario.

Subsequently, net profit from each iteration of the Monte Carlo simulation (NR_{sim}) was calculated based on the randomly sampled values according to Equation 13:

$$NR_{sim} = (P_{sim} \times Y_{sim}) - TC_{sim} \quad (13)$$

2.4.5 Risk assessment (Risk indicators)

Estimate the probability of loss (Pr_{loss}), value at risk ($VaR_{5\%}$), climate vulnerability index (CVI), and economic resilience ratio (ERR) according to equations 14, 15, 16, and 17, respectively:

$$Pr_{loss} = P(NR_{sim} < 0) \quad (14)$$

$$VaR_{5\%} = 5\text{th percentile of } NR_{sim} \quad (15)$$

$$CVI_d = Pr_{loss} \times \left(\frac{Y_{0,d} - Y_{c,d}}{Y_{0,d}}\right) \quad (16)$$

$$ERR_d = \frac{Mean(NR_{sim})}{SD(NR_{sim})} \quad (17)$$

2.5 Data analysis

Statistical analyses were performed using IBM SPSS Statistics for Windows. Group differences were evaluated by one-way ANOVA followed by Duncan's multiple range test at the 95% confidence level. Data are presented as mean ± standard deviation. Economic characteristics were summarized using descriptive statistics (average, percentage, and ratios), and profitability was assessed quantitatively. Climate impact modeling and Monte Carlo simulations were conducted in Python (version 3.x) using open-source libraries to ensure reproducibility. Climate-adjusted models were computed using scenario-based temperature increments, and risk indicators were derived from simulated outputs for each temperature scenario.

3. RESULTS AND DISCUSSION

3.1 Optimal density and profitability of rotifer cultivation under the current temperature conditions

In this study, S-type rotifer was cultured in outdoor mass production tanks under ambient environmental conditions. Dissolved oxygen ranged from 5.42±1.18 to 5.61±1.13 mg/L, total ammonia from 0.38±0.17 to 1.09±1.22 mg-N/L, and nitrite from 0.06±0.01 to 0.07±0.22 mg-N/L. The mean water temperature during the cultivation period ranged from 26.39±1.22 to 27.07±1.46°C. At different initial stocking densities, bioeconomic analysis indicated that the low-density treatment exhibited a significantly higher μ and a lower K compared with the other densities ($P<0.05$). However, no statistically significant differences were observed among treatments in terms of maximum density, D, or total yield ($P>0.05$) (Table 1).

Table 1. Bioeconomic data (mean±SD) in terms of maximum density, specific growth rate (μ), division rate (K), doubling time (D) and total yield of S-type rotifer (*Brachionus rotundiformis*) production from the mass culture tanks under outdoor condition (n=10).

Parameter	Rotifer density				P-value
	Low (5 ind./mL)	Medium (10 ind./mL)	High (15 ind./mL)	Intensive (20 ind./mL)	
Maximum density (ind./mL)	15±5[a]	20±8[a]	19±15[a]	26±19[a]	0.342
μ (day^{-1})	0.51±0.17[a]	0.33±0.18[b]	0.20±0.19[b]	0.18±0.19[b]	0.002
K (day)	0.73±0.25[a]	0.47±0.26[b]	0.29±0.28[b]	0.26±0.27[b]	0.001
D (day)	1.54±0.66[a]	2.08±1.48[a]	1.34±1.29[a]	3.43±4.27[a]	0.215
Gross yield (g/tank)	667.60±336.74[a]	701.08±451.23[a]	569.26±522.27[a]	608.81±641.31[a]	0.936
Net yield (g/1,000 L)	333.80±168.37[a]	350.54±225.61[a]	284.63±261.13[a]	304.40±320.65[a]	0.936

Means in each row followed by different letters indicate a significant difference ($P<0.05$).

From an economic perspective, a stocking density of 10 ind./mL generated the highest net profit (+430.19 THB per 1,000 L), followed by 5 ind./mL. At densities above 15 ind./mL, signs of overstocking were observed, resulting in reduced unit productivity, increased production costs, and negative net returns. Therefore, under baseline conditions, the economically optimal stocking density was identified as 10 ind./mL (Table 2).

Table 2. Costs, production output, and economic returns at a production capacity of 1,000 L per tank per month for S-type rotifer (*Brachionus rotundiformis*) cultured in outdoor mass production systems under different stocking densities (in THB).

Parameter	Rotifer density			
	Low (5 ind./mL)	Medium (10 ind./mL)	High (15 ind./mL)	Intensive (20 ind./mL)
Total fixed cost (TFC)	148.56	148.56	148.56	148.56
Total variable cost (TVC)	2,559.73	2,727.73	2,904.13	3,072.13
Production cost (PC)	2,708.29	2,876.29	3,052.69	3,220.69
Environmental cost (EC)	400.00	400.00	400.00	400.00
Marketing cost (MC)	500.00	500.00	500.00	500.00
Total cost (TC)	3,608.29	3,776.29	3,952.69	4,120.69
Price per unit of rotifer/kg (P)	1,200.00	1,200.00	1,200.00	1,200.00
Total quantity of rotifer in kg (Q)	3.34	3.51	2.85	3.04
Total revenue (TR)	4,005.60	4,206.48	3,415.56	3,652.86
Net return (NR)	397.31	430.19	-537.13	-467.83

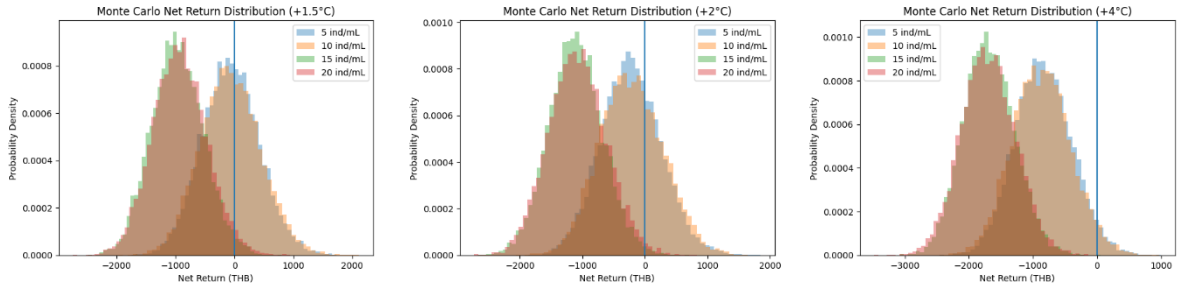
Note: (1) The study assumed a production capacity of 1,000 L per tank per month. (2) Labor costs were not included in the fixed cost category, as production was estimated based on a capacity of one tank per month. (3) Annual depreciation was calculated using the straight-line method: (Cost of asset − Salvage value) / Useful life, assuming a service life of 3 years. (4) EC was estimated from monthly water quality analysis, specifically measuring total ammonia and nitrite concentrations in wastewater from the rotifer cultivation system prior to discharge. (5) MC was calculated based on online advertising fees through Google Ads at a flat rate of 2,000 THB per campaign. A marketing promotion plan was implemented for 3 campaigns per year; therefore, the annual marketing cost amounted to 6,000 THB, equivalent to an average of 500 THB per month.

3.2 Predicting the impact of global warming on rotifer production

Based on projections derived from the present data, all initial stocking densities (5, 10, 15, and 20 ind./mL) exhibited economic deterioration under warming scenarios beginning at +1.5°C. Net returns became negative across all densities, with the smallest loss (-55 THB) observed at 10 ind./mL. As temperature increased further, financial losses intensified, reaching a maximum loss of -864 THB under the +4°C scenario (Table 3).

Monte Carlo simulations indicated that the probability of economic loss increased substantially with rising temperature (Figure 2). Under the +1.5°C scenario, the probability of loss exceeded 55% at low stocking densities and 97% at high densities. At +4°C, the probability of loss approached certainty (approximately 100%) across all densities. High-density systems (15-20 ind./mL) consistently exhibited

higher $VaR_{5\%}$ and CVI values. Although the ERR was negative under all scenarios, densities of 5–10 ind./mL showed ERR values closer to zero compared with 15–20 ind./mL, indicating relatively greater economic resilience to global warming. In contrast, higher densities were associated with greater downside risk and structural vulnerability (Table 3).



(a) (b) (c)

Figure 2. Probability distributions of simulated net returns for rotifer production under temperature increase scenarios: (a) +1.5°C, (b) +2°C, and (c) +4°C. The vertical line at zero represents the break-even threshold. Higher stocking densities exhibit pronounced leftward shifts and heavier lower tails, indicating greater downside risk and increased economic vulnerability under climate warming.

Table 3. Predicting the impact of global warming in terms of climate-adjusted net return (NR), probability of loss (Pr_{loss}), value at risk ($VaR_{5\%}$), climate vulnerability index (CVI), and economic resilience ratio (ERR) on rotifer production under temperature increase scenarios.

Rotifer density	Scenario	NR (THB)	Pr_{loss} (%)	$VaR_{5\%}$ (THB)	CVI	ERR
Low (5 ind./mL)	+1.5°C	−65	55	−845	0.04	−0.12
	+2°C	−220	68	−993	0.06	−0.45
	+4°C	−837	97	−1,537	0.19	−1.87
Medium (10 ind./mL)	+1.5°C	−55	56	−888	0.04	−0.12
	+2°C	−217	67	−1,014	0.06	−0.42
	+4°C	−864	97	−1,593	0.19	−1.89
High (15 ind./mL)	+1.5°C	−971	98	−1,686	0.07	−2.20
	+2°C	−1,116	99	−1,805	0.09	−2.59
	+4°C	−1,695	100	−2,329	0.20	−4.23
Intensive (20 ind./mL)	+1.5°C	−927	97	−1,674	0.07	−2.04
	+2°C	−1,080	99	−1,828	0.09	−2.35
	+4°C	−1,693	100	−2,380	0.20	−4.01

3.3 Climate risk and economic vulnerability of outdoor rotifer production

The analysis revealed that, under baseline conditions, a stocking density of 10 individuals/mL generated the highest net return. However, under increasing temperature scenarios, all production systems tended to incur losses beginning at +1.5°C, particularly at higher densities (15-20 individuals/mL), which exhibited a Probability of Loss exceeding 95% and a substantially negative ERR, indicating structural economic vulnerability. At +4°C, economic risk increased markedly across all stocking densities, with net returns showing a distinctly negative distribution and a more severe $VaR_{5\%}$, reflecting the pronounced sensitivity of outdoor rotifer production systems to climate change. Overall, rising temperatures not only reduced biological yield but also amplified economic risk through higher production costs and increased uncertainty in financial returns.

These findings were consistent with those reported by Nhinh et al. [22], who demonstrated that the growth rate of *Brachionus* spp. increased within the optimal temperature range, whereas temperatures exceeding this range resulted in higher mortality and reduced carrying capacity. Similarly, Gao et al. [23] reported that a temperature increase of 2–3°C shortened reproductive duration and

increased population instability, supporting the present observation of reduced bioproduction under +1.5 to +4°C warming scenarios.

In outdoor mass culture systems, temperature sensitivity was likely more pronounced due to the absence of closed-loop environmental control. Rahman et al. [2] and Boyd et al. [24] identified externally dependent culture systems as highly vulnerable to climate variability, particularly in tropical and subtropical regions.

From an economic perspective, the results indicated that rising temperatures significantly increased financial risk, as reflected by a more negative VaR, suggesting greater downside tail risk. This pattern was consistent with Sriskanthan & Funge-Smith [25], who reported that climate change not only reduced productivity but also increased cash flow volatility. Moreover, Collins et al. [26] report noted that aquaculture systems characterized by high fixed costs and intensive bioproduction were more sensitive to environmental fluctuations than more cost-flexible systems. This observation corresponded with the present finding that high-density cultures (15–20 individuals/mL) exhibited a probability of loss exceeding 95%. The observation that, at +4°C, all density levels demonstrated a clearly negative distribution of net returns indicated the presence of systemic risk rather than solely operational risk. This trend was consistent with the IPCC [1], which reported that tropical aquaculture systems were highly vulnerable to declines in productivity and economic returns under warming scenarios. Accordingly, the findings supported the hypothesis that climate warming affected not only biological performance but also economic stability through (1) increased management costs (e.g., water quality control), (2) greater productivity volatility, and (3) heightened uncertainty in financial returns.

4. CONCLUSIONS

Based on the experimental findings and data analysis, the following conclusions were drawn:

1. The results indicated that low to medium stocking densities (5–10 individuals/mL) provided greater economic resilience compared with higher densities (15–20 individuals/mL). Accordingly, adjustments to production strategies should be considered to reduce climate-related risks associated with global warming.

2. Under the +1.5°C, +2°C, and +4°C warming scenarios, economic risk increased progressively across all rearing densities. The distribution of net returns became increasingly skewed toward negative outcomes, while the value at risk ($VaR_{5\%}$) indicated escalating downside exposure as temperature levels rose. These results underscored the pronounced sensitivity of outdoor rotifer production systems to projected climate change.

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