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Climate Change Effects on Aquaculture: A Case Study of Latvia

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***Abstract* – Aquaculture is one of the fastest growing food production sectors, but the imminent impact of climate change puts aquaculture at risk. In the production of aquaculture products in ponds, the production process is significantly affected by climatic conditions, in particular climate change resulting in changes in average air and water temperatures, rainfall, changes in the hydrological regime and groundwater levels. At the same time, ponds are an essential element of environmental services, also contributing to the conservation of biodiversity and habitats. The research problem is the multidimensional impact of climate change on Latvia's aquaculture sector, which threatens its sustainability, competitiveness, and ecological balance. The aim of the study is to determine the potential impact of climate change on aquaculture production in Latvia. A partially structured questionnaire was used to collect data. Bottom-up descriptive approach and Indicative methods were used for statistical analysis of the data collected. Collected data was analysed using frequency distributions, mean ranks and Mann-Whitney U test. The results showed that in order to balance the public interest in environmentally sustainable and biodiversity-preserving aquaculture production with ensuring the competitiveness of producers, it is necessary to continue to provide public support to cover revenue foregone or additional costs incurred by enterprises. Climate change has a significant impact on air and water temperatures, not only on open fish farming systems, but also on closed systems, which incur higher production costs in order to maintain and ensure optimal breeding conditions for fish species.**

***Keywords* – Aquaculture farms; biodiversity conservation; climatic environments; sustainability.**

1. INTRODUCTION

Aquaculture is one of the fastest-growing food production sectors worldwide, providing essential food resources and livelihoods. However, the sector is increasingly vulnerable to climate change, which affects its productivity, sustainability, and ecological balance [1]. Key climatic factors – including changes in air and water temperatures, rainfall patterns, hydrological regimes, and groundwater levels – directly influence aquaculture production, particularly in pond-based systems [2]. Additionally, ponds contribute to environmental services, supporting biodiversity and habitat conservation [3].

The impacts of climate change on aquaculture are multifaceted, encompassing physical, biological, and socio-economic dimensions [4]. Rising temperatures can alter metabolic rates in aquatic species, affecting growth, disease susceptibility, and mortality [5]. Extreme weather events, such as floods and droughts, disrupt growth cycles and reduce productivity

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in both freshwater and marine systems [6]. Ocean acidification further threatens shellfish production, although selective breeding shows potential to enhance resilience [7].

Socio-economic factors also play a critical role. Communities dependent on aquaculture are vulnerable due to limited financial resources, institutional support, and social capital [8]. Adaptive strategies, such as climate-smart practices and GIS-based site selection, are being explored to mitigate these risks [9]. Declining fish stocks and adverse climatic conditions can pose serious food security challenges [10].

Latvia's aquaculture sector is emerging, with significant opportunities and challenges. Abundant freshwater resources provide favourable conditions for fish farming, but the sector has been slow to adopt technological innovations, limiting competitiveness and sustainability [11]. The Latvian Aquaculture Development Plan (2021–2027) aims to improve efficiency, productivity, and knowledge exchange among stakeholders, fostering responsible aquaculture practices [12].

Modern feeding practices and innovative formulations, including probiotics, have been shown to enhance fish health and growth [13], [14]. Technological advancements, such as wireless sensor networks for monitoring water quality, are being implemented to improve both productivity and environmental sustainability [15], [16]. Waste management, including biogas production from aquaculture waste, provides circular economy [17], [18]. Ecological sustainability remains a concern, particularly regarding biodiversity and the introduction of non-native species [19]. Nevertheless, innovative practices and strategic planning present opportunities for growth and resilience in the Latvian aquaculture sector [20].

Robust climate information services and integration of adaptation measures into national policy are critical for enabling aquaculture operators to respond to climate variability [23]. In Latvia, environmental communication and sustainable practices are essential to align aquaculture development with climate adaptation goals [24]. Research indicates that temperature fluctuations and altered precipitation patterns negatively impact production, highlighting the urgency of adaptation strategies [25].

The central research problem is the multidimensional impact of climate change on Latvia's aquaculture sector, which threatens its sustainability, competitiveness, and ecological balance. This study focuses on assessing these climate change effects in the Latvian context, with the aim of identifying adaptive strategies to enhance resilience and ensure sustainable aquaculture development.

2. METHODS AND METHODOLOGY

This study is based on data collected from fish farmers across various regions in Latvia. A structured survey designed specifically for Latvian aquaculture farmers was used to collect the data. In 2024, there were 66 economically active aquaculture entrepreneurs in Latvia. From this population, 20 entrepreneurs (n = 20) participated in the survey, representing approximately 30 % of the total Latvian aquaculture entrepreneurs.

The survey included a combination of structured and open-ended questions on the impacts of climate change in aquaculture, focusing on key aspects such as fish growth performance, fish health and quality, feed conversion ratio (FCR), reproductive performance, fish survival, weather conditions, feed availability and costs, production costs, employment, community dependence, competition for space and with substitutes, sustainability, market opportunities, and coherent policies for sustainable production.

Participants were selected using a purposive sampling approach, targeting active aquaculture farmers with diverse farm sizes, types of aquaculture systems, and geographic locations to ensure representation of the sector. Potential respondents were identified through the Latvian Aquaculture Association, regional aquaculture networks, and public directories of licensed fish farms. Invitations were sent via email and phone calls, and participation was voluntary.

Interview procedures: Surveys were administered through a combination of online questionnaires and in-person interviews, depending on respondent preference and accessibility. In-person interviews were conducted at the fish farms to observe production conditions and to allow for follow-up questions. Each interview lasted approximately 30–60 minutes. Respondents were briefed about the purpose of the study, confidentiality measures, and their right to withdraw at any time.

Survey questions: The survey was designed to capture both quantitative and qualitative data. Structured questions included multiple-choice and Likert-scale items about farm characteristics, feed types, and production metrics. Open-ended questions explored respondents' perceptions of climate change impacts, adaptation strategies, challenges faced, and opportunities for improving sustainability. Example questions included:

- 'How have recent changes in weather patterns or temperature affected the growth and health of the fish in your farm?'
- 'Have changes in feed availability or costs influenced how efficiently your fish convert feed into growth, and if so, how?'
- 'In your experience, how have climate-related changes impacted your production costs and your ability to access or compete in the market?'
- 'Do you perceive that climate change has affected employment in your farm or the wider community dependent on aquaculture?'

This combination of structured and open-ended questions allowed for a comprehensive understanding of both measurable trends and farmers' experiential insights regarding climate change impacts on Latvian aquaculture.

Fig. 1 illustrates the methodological framework of the study, which was implemented in three consecutive phases. In Phase 1, methods for assessing the impacts of climate change on aquaculture were reviewed through an extensive literature analysis. In Phase 2, a detailed review of non-parametric methods was conducted, also based on literature and methodological assessment. In Phase 3, the most appropriate method was selected to test for significant differences in perceptions between two aquaculture sector groups regarding climate change–aquaculture interactions, which led to the application of the Mann–Whitney U test.

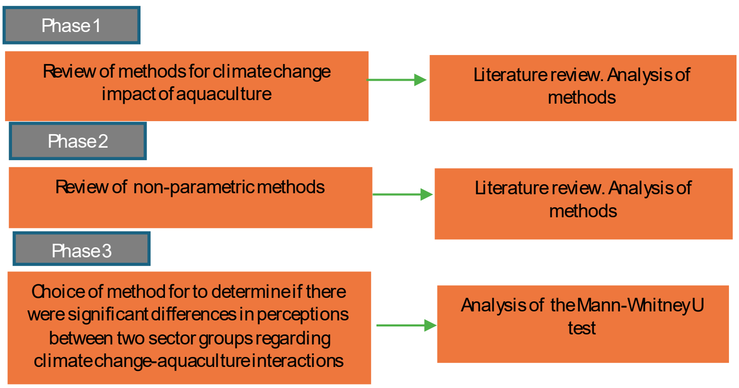


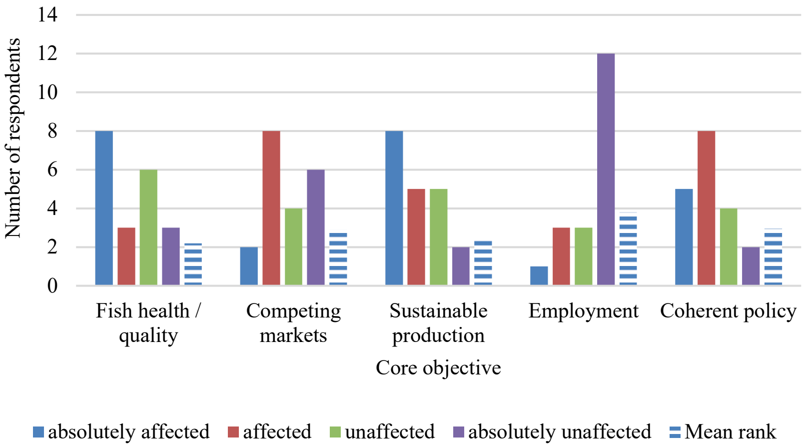
Fig. 1. Methodological framework of the study.

The collected data underwent both descriptive and inferential statistical analysis. The primary data types were nominal and ordinal, necessitating non-parametric methods for analysis. The study utilised frequency distributions, mean ranks, and the Mann-Whitney U test for the analysis. Mean ranks represent average importance rankings assigned to items by the participants, serving as a recognised descriptive statistic for comparing items in ordinal data cases. The Mann-Whitney U test, a non-parametric hypothesis test, was applied to investigate significant differences in dependent variable scores between two distinct groups. Its non-parametric nature accommodates dependent variable scores that are non-normally distributed or ordinal. The Mann-Whitney U test was employed to determine if there were significant differences in perceptions between two sector groups regarding climate change-aquaculture interactions.

3. Results

In the initial section of the questionnaire, the participants ranked several core objectives based on their significance for the future performance of their enterprises. Fig. 2 presents the importance ranks (1st – absolutely affected, 2nd – affected, 3rd – unaffected, 4th – unaffected) assigned to the core objectives.

Fish health and quality emerged as the top core objective, identified by eight participants, with three ranking it second and six ranking it third. Employment received the highest rank from only one participant, but was ranked second and third by eight and five participants, respectively. Mean ranks indicated that fish health and quality are the most critical objectives (mean rank = 2.20), while employment ranked lowest (mean rank = 3.79). Sustainable production, competing markets, and coherent policy were also recognised as significant objectives.



Note: Absolutely unaffected – respondents who selected this category believe that climate change does not affect the respective aspect at all. Unaffected – respondents who selected this category believe that climate change has little effect on the respective aspect. Affected – respondents who selected this category believe that climate change affects the respective aspect. Absolutely affected – respondents who selected this category believe that climate change significantly affects the respective aspect.

Fig. 2. Importance ranks of core objectives.

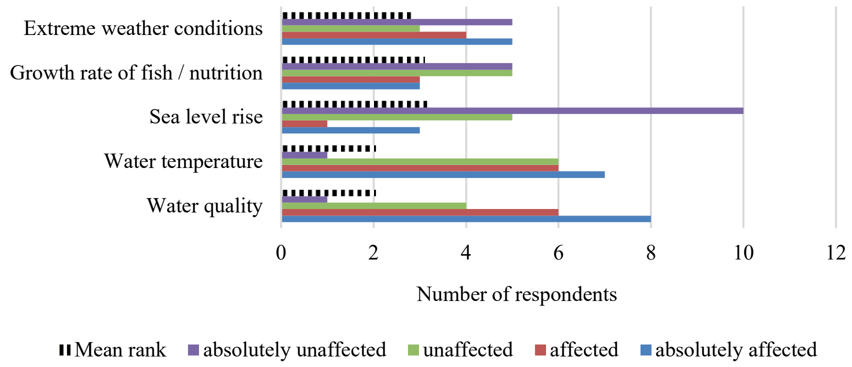
In addition to frequency distributions and mean ranks, the Mann-Whitney U test was conducted to assess significant differences in importance rankings of core objectives between the participants involved in pond and recirculation aquaculture systems. As indicated in Table 1, there were no significant differences in the importance rankings of core objectives between individuals engaged in freshwater pond farming and those in recirculation aquaculture systems, as all p-values were above the 0.05 threshold. This finding suggests similar prioritisation of core objectives among both groups.

TABLE 1. MANN-WHITNEY U TEST FOR THE IMPORTANCE RANKS OF CORE OBJECTIVES BETWEEN PARTICIPANTS ENGAGED IN PONDS AND RECIRCULATION AQUACULTURE SYSTEMS

Core Objectives	**Mann-Whitney U Test Statistic**	**Z-value**	**p-value**
Fish health / quality	12.0	−0.973	0.331
Competing markets	10.0	−1.290	0.197
Sustainable production	8.5	−1.491	0.136
Employment	12.0	−0.586	0.558
Coherent policy	13.0	−0.376	0.707

Z-value – standardized Mann–Whitney U test statistic showing how many standard deviations the observed result differs from the expected value under the null hypothesis, used to calculate the p-value. p-value – probability of obtaining the observed result if there is no difference between groups; a smaller p-value indicates stronger statistical significance.

The results of the Mann-Whitney U test indicate that respondents' evaluations are not statistically different, suggesting that opinions on the impact of climate change on these aspects in Latvia are currently relatively uniform. However, higher absolute Z-values (e.g., for sustainable production) point to potential group differences, indicating that some farms experience the effects of climate change more strongly. This data emphasizes that while developing adaption strategies and policies, considerations including fish health, sustainable production, and market competition should be given top priority. The participants were asked to assess the prominence of climate change indicators, the results are shown in Fig. 3.



Note: Absolutely unaffected – respondents who selected this category believe that climate change does not affect the respective aspect at all. Unaffected – respondents who selected this category believe that climate change has little effect on the respective aspect. Affected – respondents who selected this category believe that climate change affects the respective aspect. Absolutely affected – respondents who selected this category believe that climate change significantly affects the respective aspect.

Fig. 3. Notability ranks of climate change signs.

The most frequently observed signs were water quality and temperature (mean rank = 2.05), while the least observed sign was sea level rise (mean rank = 3.16). Extreme weather conditions and fish growth/nutrition were ranked 2nd–3rd, respectively.

To determine if the notability rankings of climate change signs differed significantly between the participants in pond and recirculation aquaculture systems, the Mann-Whitney U test was applied to the collected data. Table 2 shows no significant differences in notability rankings between the two groups, with all p-values exceeding 0.05, indicating a similar ranking approach among both groups. The Mann-Whitney U test results show no statistically significant differences in respondents' perceptions of climate change indicators, as all p-values are above 0.05. However, the relatively higher absolute Z-value for fish growth rate and nutrition suggests some variation among farms, indicating that certain respondents perceive stronger effects of climate change on production performance.

TABLE 2. MANN-WHITNEY U TEST FOR THE NOTABILITY RANKS OF CLIMATE CHANGE SIGNS

Signs of Climate Change	Mann-Whitney U Test Statistic	Z-value	p-value
Water quality	17.0	–0.085	0.932
Water temperature	16.0	–0.260	0.795
Sea level rise	13.5	–0.316	0.752
Growth rate of fish / nutrition	7.0	–1.488	0.137
Extreme weather conditions	10.5	–1.159	0.246

Z-value – standardized Mann–Whitney U test statistic showing how many standard deviations the observed result differs from the expected value under the null hypothesis, used to calculate the p-value. p-value – probability of obtaining the observed result if there is no difference between groups; a smaller p-value indicates stronger statistical significance.

In another section of the survey, the participants expressed their perceptions regarding the potential impacts of climate change on various aquaculture performance parameters. The number of participants who think climate change would affect these parameters negatively, neutrally, or favourably is shown in Table 3. For instance, nine participants anticipate a negative impact on fish growth, while two and nine believe it will have no effect or a positive effect, respectively.

The Mann-Whitney U test results in Table 4 reveal no significant differences in climate change impact assessments between the participants in pond and recirculation aquaculture systems ($p > 0.05$). The participants generally agree on the direction of these impacts, regardless of species or sector, particularly regarding the potential effects of climate change on fish health, weather conditions, availability and pricing of fish meal/oil and market opportunities ($p = 1$). When inquired about their strategies for managing climate change impacts, only three participants (15 %) reported having a plan, while 17 participants (85 %) did not. The predominant adaptive strategy mentioned was the use of recirculating aquaculture systems (RAS). The Mann-Whitney U test results indicate that respondents' perceptions of the potential impacts of climate change on various aspects of aquaculture are generally uniform, as all p-values exceed 0.05. Relatively higher absolute Z-values for fish growth performance ($Z = -1.418$) and fish survival ($Z = -1.183$) suggest that some farms may experience stronger effects than others. In contrast, aspects such as sustainability ($Z = -0.125$, $p = 0.901$) and market opportunities ($Z = 0$, $p = 1.000$) show complete agreement among respondents, indicating a high level of uniformity in perceptions and no detectable differences between groups.

TABLE 3. POTENTIAL IMPACTS OF CLIMATE CHANGE ON PERFORMANCE OF AQUACULTURE

Potential Impact of Climate Change	Absolutely unaffected	Unaffected	Affected	Absolutely affected
Fish growth performance	9	2	9	0
Fish health	19	0	1	0
Feed conversion ratio (FCR)	12	1	7	0
Reproductive performance	14	2	3	1
Fish survival	18	0	1	1
Weather conditions	19	0	1	0
Availability and price of fish meal / oil	19	0	1	0
Production costs	18	1	1	0
Employment in the sector	9	5	4	2
Community depending on the sector	15	2	3	0
Competition for space	13	1	3	3
Competition with fish substitutes	10	3	6	1
Sustainability	17	1	1	1
Market opportunities	10	1	4	5

Absolutely unaffected – respondents who selected this category believe that climate change does not affect the respective aspect at all. Unaffected – respondents who selected this category believe that climate change has little effect on the respective aspect. Affected – respondents who selected this category believe that climate change affects the respective aspect. Absolutely affected – respondents who selected this category believe that climate change significantly affects the respective aspect.

While these differences are not statistically significant, the trends highlight areas of concern, emphasizing the importance of focusing on fish health, sustainable production practices, and market competitiveness in adaptation strategies and policy development for Latvian aquaculture.

TABLE 4. MANN-WHITNEY U TEST FOR THE POTENTIAL IMPACT OF CLIMATE CHANGE

Potential Impact of Climate Change on	Mann-Whitney U Test Statistic	Z-value	p-value
Fish growth performance	9.5	–1.418	0.156
Fish health	17.5	0.000	1.000
Feed conversion ratio (FCR)	16.0	–0.324	0.746
Reproductive performance	15.5	–0.428	0.669
Fish survival	14.0	–1.183	0.237
Weather conditions	17.5	0.000	1.000
Availability and price of fish meal / oil	17.5	0.000	1.000
Production costs	15.0	–0.845	0.398
Employment in the sector	11.5	–1.051	0.293
Community depending on the sector	12.0	–1.073	0.283
Competition for space	13.0	–0.959	0.337
Competition with fish substitutes	14.5	–0.586	0.558
Sustainability	17.0	–0.125	0.901
Market opportunities	17.5	0.000	1.000

Z-value – standardized Mann–Whitney U test statistic showing how many standard deviations the observed result differs from the expected value under the null hypothesis, used to calculate the p-value. p-value – probability of obtaining the observed result if there is no difference between groups; a smaller p-value indicates stronger statistical significance.

Additionally, respondents indicated a need for a more proactive role from the public sector in forecasting climate changes, developing scenarios, identifying risks associated with climate for the aquaculture sector, and formulating adaptation and mitigation policies and strategies.

4. CONCLUSION

This study demonstrates that climate change poses a multidimensional challenge for Latvian aquaculture, affecting environmental, biological, and socio-economic aspects, consistent with previous research [1]–[10]. Fish health and quality emerged as the most critical objective, reflecting the sector's sensitivity to rising temperatures, disease susceptibility, and growth performance [5]. Water quality and temperature were identified as the most notable climate indicators, highlighting the central role of environmental conditions in aquaculture productivity [2], [3].

Mann-Whitney U tests showed no statistically significant differences between pond and recirculation aquaculture systems in perceptions of climate impacts, core objectives, or observed indicators ($p > 0.05$). This uniformity indicates that farmers, regardless of system type, share similar priorities and concerns. Nevertheless, relatively higher absolute Z-values for fish growth performance and survival suggest that some farms may experience more pronounced effects, emphasizing the need for farm-specific adaptation measures [9], [23], [24].

Sustainability and market opportunities showed complete agreement among respondents ($Z \approx 0$, $p \approx 1$), reflecting a shared recognition of long-term sector priorities. However, only 15 % of participants reported having formal adaptation strategies, with the use of recirculating aquaculture systems (RAS) as the most common measure, aligning with research advocating technological solutions to buffer climate impacts [15], [16].

Overall, these findings indicate that while climate change impacts are widely recognized, practical adaptation remains limited. The results underscore the importance of policy support, climate information services, and knowledge exchange to enable effective responses, enhance sustainability, and strengthen market competitiveness in Latvian aquaculture. In conclusion, targeted strategies focusing on fish health, sustainable production practices, and adaptive management are essential to improve resilience and secure the sector's long-term viability under climate change.

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