



Research article

Climate Change Stressors and Adaptive Responses in Shrimp Farming: A Systematic Review of Emerging Synbiotic Technologies

Saroj Kumar Mistry^{1,2} and Syed Hafizur Rahman^{2*}¹Department of Fisheries, Ministry of Fisheries and Livestock, Bangladesh²Department of Environmental Sciences, Jahangirnagar University, Dhaka-1342, Bangladesh

ABSTRACT

Aquaculture faces significant challenges due to climate change, with shrimp production particularly jeopardized by the vulnerability of shrimp physiology and immune responses to climatic fluctuations. Emerging synbiotic technology in aquaculture combines probiotics and prebiotics to enhance animal health, promote growth, and increase disease resistance. Following a systematic review of the literature, Boolean search method was performed to explore how climate-induced stresses influenced shrimp production performance and synbiotic technology improve shrimp production. This systematic literature review adhered to PRISMA 2020 and employed a Boolean search method within the Scopus database to acquire 161 articles. A systematic thematic synthesis of 80 peer-reviewed articles published between 2015 and 2025 was performed after the application of inclusion and exclusion criteria. The findings indicate that prolonged rainfall, fluctuating salinity, and temperature fluctuations directly hinder shrimp growth, enzyme functionality, and immune responses, destabilize the gut microbiome, and increase susceptibility to illnesses. Environmental stress leading to physiological deterioration primarily stemmed from mineral ion imbalances and oxidative damage. Mitigating adverse conditions by improved aeration, optimized water management, and selective breeding offers partial remedies; however, novel microbial technologies have emerged as particularly promising options. The synbiotics exhibited synergistic benefits by increasing antioxidant defenses, stabilizing gut microbiota, and upregulating immune genes, thereby improving the shrimp's tolerance to climate stress. This review highlights the application of synbiotics as a novel strategy for sustainable and climate-resilient shrimp production.

Introduction

Shrimp farming is among the most rapidly expanding sectors of global food production, significantly enhancing food security and the coastal economy of numerous countries (Ahmed & Diana, 2015; Henriksson et al., 2019). However, climate change progressively jeopardizes its enduring viability. Fundamental climatic stressors, such as temperature variations, salinity intrusion, and rainfall inconsistencies, interact with pond ecosystems, destabilizing water quality, impairing shrimp physiology, and elevating disease outbreaks, thereby threatening productivity and farmer livelihoods (Arnberg et al., 2018; Lahiri et al., 2022; Wagner et al., 2025).

The vulnerability is especially pronounced in Bangladesh due to its low-lying coastal topography, reliance on aquaculture, and susceptibility to sea-level rise,

saline intrusion, irregular precipitation, and extreme weather phenomena, rendering the industry very sensitive to climate change (Uddin et al., 2020; Nandy et al., 2021). The destabilization of shrimp production in this region has compromised both immediate economic performance and long-term sustainability (Nguyen, 2015; Mazumder et al., 2017).

Current literature frequently analyzes temperature and salt stress independently; however, rainfall variability is little addressed, despite its significant impact on pond ecology via nutrient runoff, turbidity fluctuations, salinity dilution, and pH instability. This exclusion constrains our understanding of the entire causal route by which climate drivers influence water chemistry, shrimp physiology and immunology, and ultimately growth, survival, and farm-level resilience.

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Emerging synbiotic technology represents an advanced strategy in aquaculture, integrating probiotics and prebiotics to enhance shrimp health, growth, and disease resistance. This approach exerts synergistic effects by modulating the gut microbiome, improving nutrient assimilation, and upregulating immune-related gene expression, thereby increasing shrimp tolerance to primary climate stressors, including temperature elevation, salinity fluctuations, and rainfall variability (Yang et al., 2018; Uawisetwathana et al., 2021; Skrzypczak et al., 2023). While prior studies have predominantly examined probiotics or prebiotics in isolation, the combined application of synbiotics has demonstrated superior efficacy in enhancing antioxidant defenses, stabilizing gut microbial communities, and mitigating disease susceptibility under environmental stress conditions.

This review followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 framework to ensure methodological rigor, transparency, and reproducibility. A Boolean search strategy identified 80 peer-reviewed articles published between 2015 and 2025, specifically addressing the three primary climate stressors and their effects on shrimp production, health, and the effectiveness of synbiotic interventions. This approach ensures the synthesis of recent, relevant, and context-specific evidence, particularly applicable to Bangladesh's coastal aquaculture systems.

Prior reviews often address shrimp physiology and microbial therapies in isolation, neglecting their interrelations under climatic stress. A comprehensive synthesis integrating the impacts of temperature, salinity, and rainfall variability with alterations in water quality, physiological responses, immunity, and microbial therapies is still absent. In countries with significant exposure like Bangladesh, this absence of integration obstructs the formulation of effective, evidence-driven adaptation plans (De Almeida et al., 2024; Missionario et al., 2022).

This review aims to objectively assess the impact of three primary climate-related stressors—temperature increase, salinity fluctuations, and rainfall variability on shrimp farming, with particular attention to water quality, shrimp physiology, immunology, and adaptive technology.

This review further explores publication trends, citation patterns, and significant scholarly contributions to identify the leading articles, journals, authors, and countries in this area. The review examines how these stressors affect shrimp production performance, water quality, and immune resilience, while assessing the effectiveness of adaptive technologies such as probiotics, prebiotics, and synbiotics in mitigating climate-induced challenges and improving shrimp health and survival. Additionally, it identifies existing knowledge gaps and

proposes strategies to promote sustainable and climate-resilient shrimp farming, with special consideration for sensitive areas like Bangladesh.

Materials and Method

Systematic Literature Search

The systematic literature review was structured according to the PRISMA 2020 guidelines, which are widely regarded as improving transparency, reproducibility, and methodological rigor in literature-based studies (Page et al., 2021). The review aimed to synthesize empirical studies to assess the effects of climate change on shrimp farming and immunity, as well as to evaluate the role of adaptive technologies, including probiotics, prebiotics, and synbiotics, in promoting sustainable shrimp cultivation practices. This review integrates peer-reviewed findings via a systematic and comprehensive selection process to offer an evidence-based perspective on climate resilience in aquaculture systems.

The investigation began using Scopus, a multidisciplinary database featuring high-impact journals. A Boolean search strategy was developed to improve relevance and accuracy, employing targeted thematic keywords associated with aquaculture, shrimp species, climate change, oxidative stress, immunology, and sustainable solutions. The employed Boolean expression was '(climate change OR global warming OR climate stress) AND (shrimp OR prawn OR *Litopenaeus vannamei* OR *Penaeus monodon*) AND (growth OR SGR OR FCR OR digestive enzymes OR immune response OR hematological OR oxidative stress)'

Data Collection

This study resulted in 161 articles, which were carefully examined based on established inclusion and exclusion criteria (Figure 1). Studies published prior to 2015 were eliminated ($n = 36$) to maintain recency and relevance, yielding 125 articles for initial screening. Five further data were eliminated due to their irrelevance to aquaculture or climate-induced stress. Out of the remaining 120 articles, 33 were deleted for being non-peer-reviewed sources (e.g., conference proceedings, book chapters, reports), and an additional 7 were excluded following full-text assessment due to thematic irrelevance ($n = 5$) or non-English language ($n = 2$). This procedure included 80 articles that fulfilled all eligibility requirements and were incorporated into the final synthesis. To mitigate selection bias, only peer-reviewed articles published in English were considered. Multiple researchers independently assessed titles, abstracts, and complete texts to guarantee uniformity in eligibility determinations. Disputes were settled via dialogue. Grey literature and non-journal sources were deliberately omitted to guarantee data dependability and methodological precision.

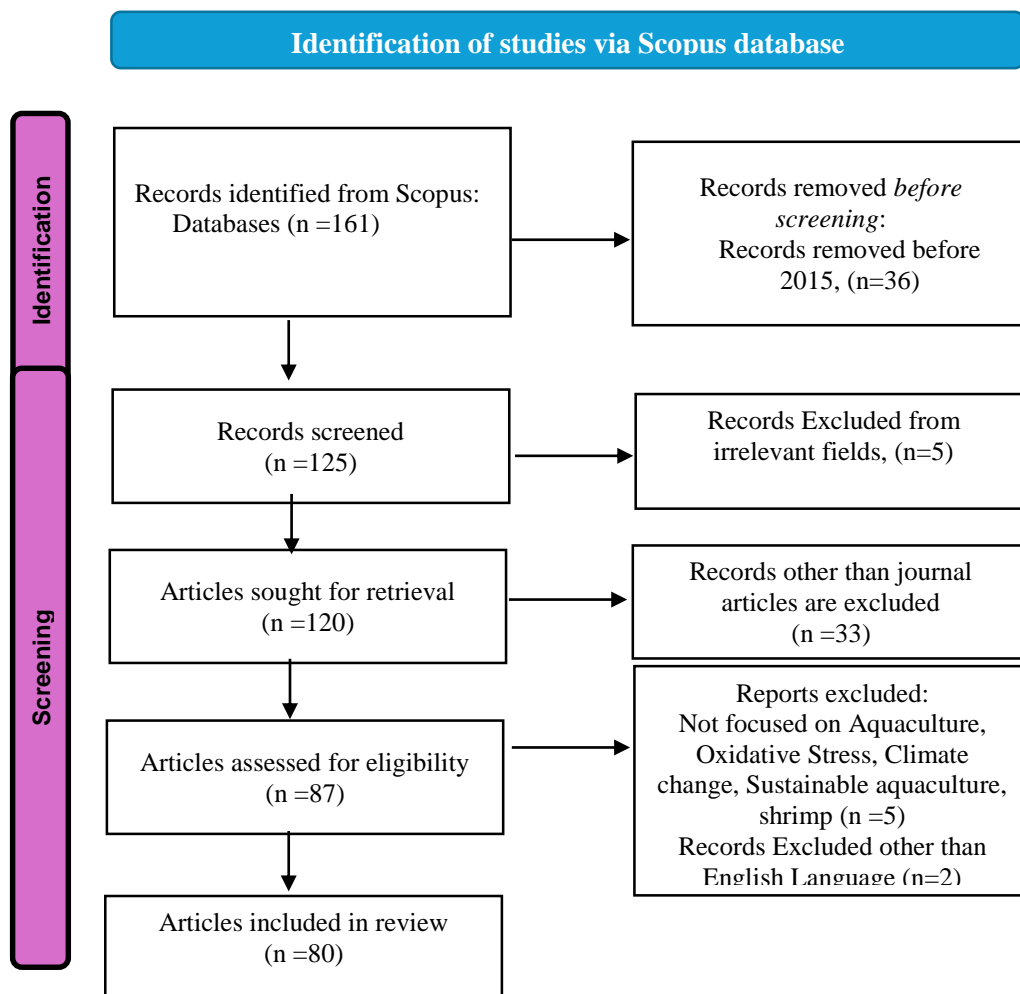


Figure 1: PRISMA Framework 2020 diagram showing steps for the systematic literature search during this study.

A fundamental risk-of-bias assessment was conducted by examining each paper for clarity of objectives, methodological transparency, alignment with the review's purpose, and relevance to the climate change–shrimp nexus. Studies that lacked methodological rigor or did not present empirical results were removed. A comprehensive internal checklist was utilized to evaluate study quality and minimize the inclusion of inadequately designed or ambiguous research, despite the absence of a formal rating method (e.g., ROBIS). The complete process—from identification and screening to eligibility and inclusion—is illustrated through a PRISMA 2020 flow diagram (Figure 1), ensuring transparency and facilitating the replication of the review approach.

Results

This systematic review organized 80 peer-reviewed publications into four interrelated themes that delineate the impacts of climate change on shrimp farming and the potential of adaptive technologies to mitigate these effects. The results are presented in both narrative and tabular formats, ensuring a coherent thematic overview while maintaining analytical rigor.

Current Publications Pattern Trends of Publications

Figure 2 illustrates the annual trends in publications and citations related to climate change and shrimp farming from 2015 to 2025. The number of publications fluctuate over the years, ranging from 1 to 16 publications per year, while citations peak at 446 in 2016. The fitted linear trend line ($R^2 = 0.2503$) indicates moderate but steady research activity over the ten-year period.

Citations experienced a large increase in 2016, reaching 446, followed by a substantial reduction. They stabilized from 2020 to 2022 before seeing another decrease in 2024 and 2025. This pattern indicates that a limited number of seminal articles published early in the period especially from 2015 to 2017—have exerted considerable academic influence, functioning as essential references in the discipline. The years 2023 to 2025 exhibit an increase in the volume of articles; yet, they have not yet garnered substantial citation counts, presumably owing to a temporal delay in citation accumulation.

The disparity between increasing publication production and decreasing citations in subsequent years also indicates a change in research emphasis. This may signify a transition from fundamental conceptual research to more technical and applied investigations, including studies on probiotics, prebiotics, and improvements in IoT (internet of things)-based shrimp farming. Furthermore, the prevailing tendency signifies an increasing scholarly

focus on mitigating climate hazards to aquaculture, while the enduring effects of current studies remain ambiguous. This publication-citation dynamic highlights the growth of the field from initial problem identification to increasingly solution-focused research and emphasizes the necessity for longitudinal impact assessments of emerging technology and management methods in shrimp farming amid climate stress.

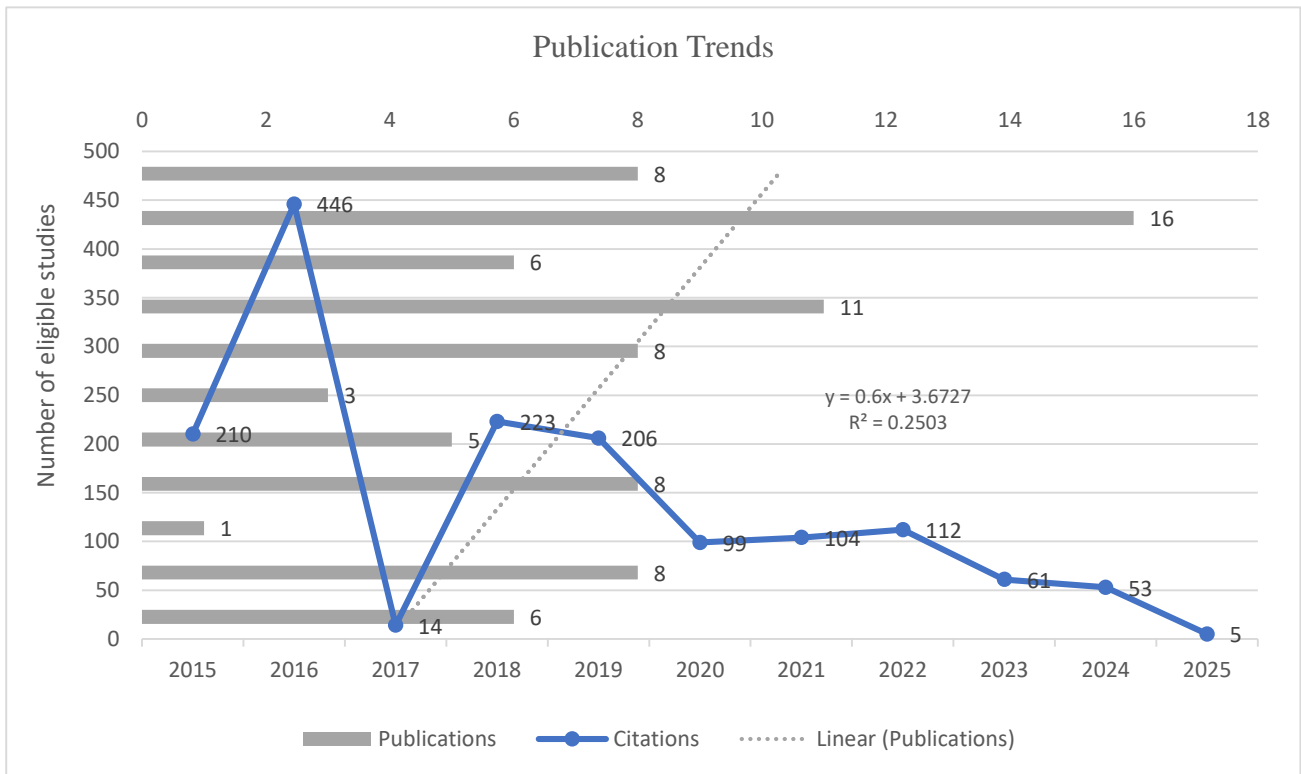


Figure 2: Publication years of the eligible studies on climate change and shrimp farming.

Leading Journals in the Field

Figure 3 illustrates the predominant academic journals that contribute to the scientific field of climate change and shrimp farming, determined by the volume of publications and total citations. It emphasizes the periodicals that have been most pivotal in communicating impactful discoveries within this interdisciplinary domain.

The findings indicate that 'Fisheries Oceanography' and 'Science of the Total Environment' are the most cited journals, with 170 and 165 citations, respectively, reflecting their significant impact and prominence in this academic domain. Conversely, journals such as 'Aquaculture' and 'PLOS ONE' published a greater number of articles (53 and 58, respectively), yet exhibit comparatively lower citation counts, indicating that although they function as significant publication venues,

not all papers attain substantial academic impact. This comparison highlights a distinction between quantity and academic influence; wherein niche journals may yield high-impact ideas despite a reduced output volume.

The journal spread illustrates the interdisciplinary nature of shrimp farming research in the context of climate stress, integrating environmental sciences, marine biology, and practical aquaculture. The incorporation of general scientific magazines such as Scientific Reports alongside specialized publications underscores the increasing scholarly focus on this subject across several fields. This pattern indicates that future researchers should prioritize publishing in journals that effectively balance visibility and academic impact to enhance the influence of their results on scientific knowledge and aquaculture practices.

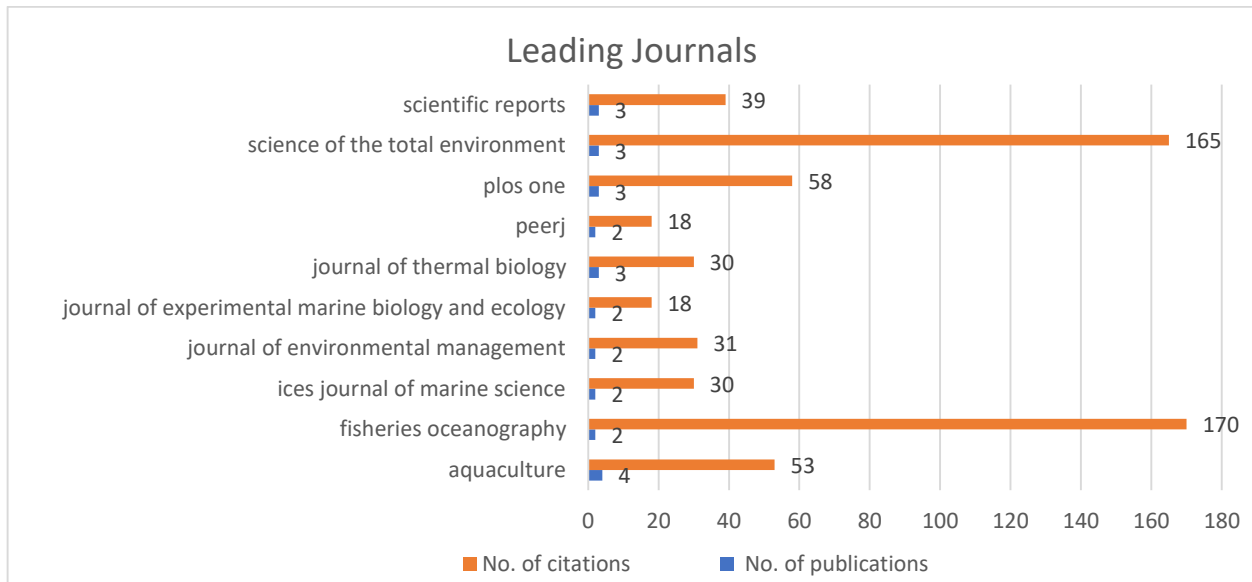


Figure 3: Leading academic journals published articles on climate change and shrimp farming from 2015 to 2025.

Major Contributing Countries

Figure 4 depicts the regional distribution of academic contributions to the study of shrimp farming and climate change, highlighting the nations with the greatest publishing output. The major contributor countries are the United States possesses 17 papers, followed by China with 13, Brazil 5, Norway 5, France 4, Indonesia 4, India with 3, and Australia with 4. European nations, including the United Kingdom, are also listed among the contributors. This pattern indicates a significant concentration of research in industrialized countries, where academic infrastructure and financing capabilities facilitate extensive publication. Nonetheless, it also highlights the increasing involvement of prominent Asian nations—

particularly China and India—where shrimp farming holds substantial economic significance.

Although developed countries currently dominate the research outputs; the rising number of publications from Asian countries represents a significant shift. Countries most susceptible to climate change effects on aquaculture, particularly in South and Southeast Asia, are progressively engaging in the scientific discourse on sustainable methods. This emerging tendency indicates that the research landscape is progressively conforming to the geographies of shrimp production and climate vulnerability. Enhancing local research capabilities and fostering cross-border collaboration may effectively narrow the divide between global scientific knowledge and region-specific aquaculture resilience methods.

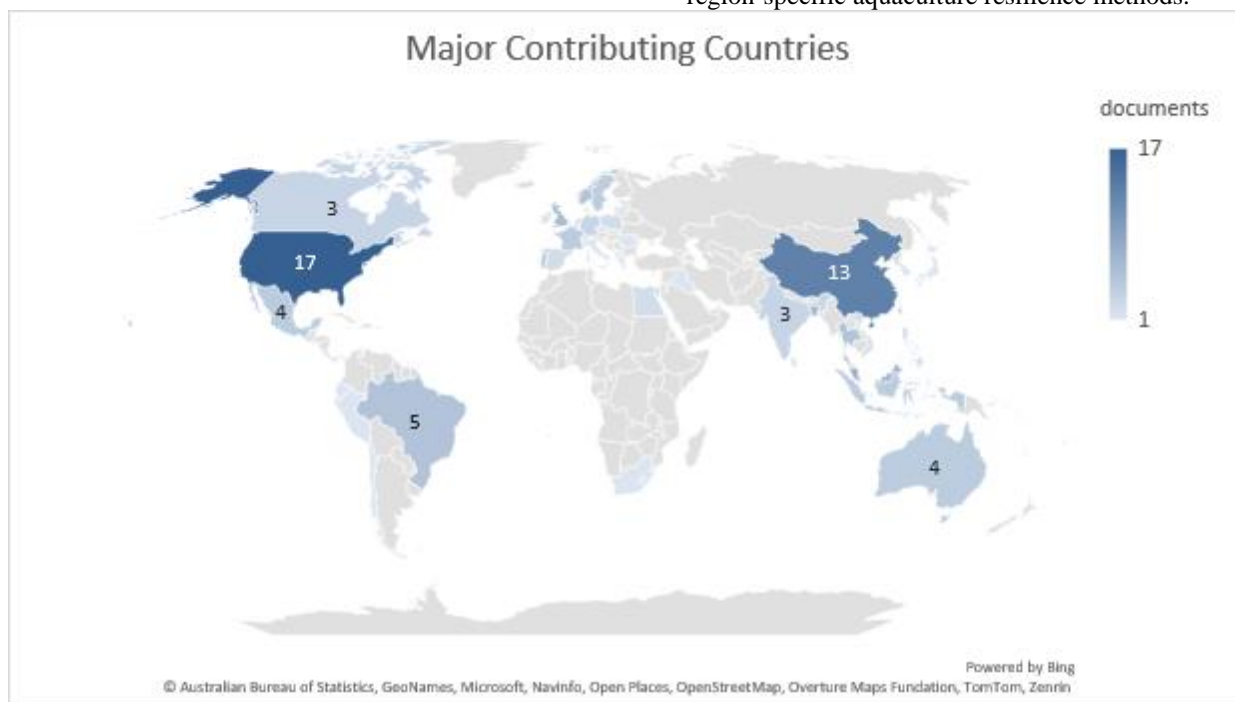


Figure 4: Major contributing countries in climate change and shrimp farming research.

Thematic Findings

Climate Change Impacts on Shrimp Farming

A conceptual framework is proposed to generalize the thematic evidence, illustrating the complex connection of climate change, shrimp culture, and farming households (Figure 5). Climatic factors such as rising temperatures, alterations in salinity, extreme weather events, and fluctuations in rainfall directly affect shrimp production systems, while also creating a ripple effect on farming households. Conversely, there exists a correlation between the socioeconomic vulnerabilities of households and the feedback loops that further influence the resilience of production. This paradigm will support the topic address on shrimp physiology, shrimp immunity, water quality, and sustainable adaptation techniques.

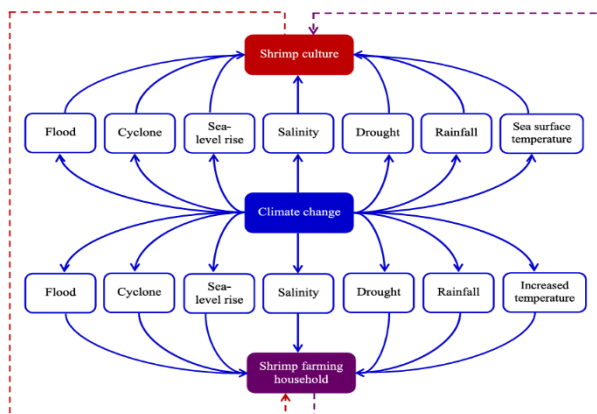


Figure 5: Climate change impacts on shrimp farming and households (Adapted from Ahmed & Diana, 2015).

Climate Change Impacts on Water Quality and Chemistry

The aquatic ecosystem in shrimp farming is particularly susceptible to climatic fluctuations, with water quality

serving as the primary conduit for the impact of these stressors. Rainfall variability, in conjunction with temperature increase and salinity changes, significantly contributes to the destabilization of pond systems. Intense monsoon events result in fertilizer runoff, increased turbidity, and abrupt salinity dilution, whereas extended drought leads to stagnation, fluctuating pH levels, and oxygen depletion. These extremes collectively induce chronic stress conditions that render shrimp susceptible to disease outbreaks and seasonal crop failures (Farha et al., 2024; Hasan et al., 2024).

The increase in temperature exacerbates these effects by diminishing Dissolved Oxygen (DO) levels due to elevated metabolic oxygen requirements. Increased temperatures enhance microbial activity, leading to accelerated accumulation of ammonia and nitrite, which induces hypoxia, oxidative stress, and heightened mortality (Arnberg et al., 2018; Yang et al., 2019).

Salinity intrusion, frequently associated with sea-level rise or variable precipitation, compels shrimp to engage in continual osmoregulatory adaptations. This energy diversion diminishes development efficiency, hinders molting, and compromises immunological function, rendering shrimp more vulnerable to infections (Mazumder et al., 2017; Lahiri et al., 2022).

Ocean acidification exacerbates vulnerability by diminishing carbonate buffering capacity, decreasing alkalinity, and hindering exoskeleton calcification, hence compromising molting and structural integrity (Sánchez et al., 2016; González-Ruiz et al., 2020).

Rainfall variability, temperature extremes, and salinity fluctuations together undermine pond chemistry and water quality, posing a significant danger to sustainable shrimp farming. Table 1 summarizes their collective effects on environmental parameters and the ensuing ramifications for shrimp health and productivity.

Table 1: Water Quality and Chemistry Stressors in Shrimp farming.

Stressor	Parameter Affected	Observed Change	Consequences for Shrimp	Source
Rainfall/Drought	Nutrient & turbidity (extreme rainfall)	Increased runoff, turbidity, and organic load	Ammonia buildup, gill irritation, hypoxia, plankton crashes	Lahiri et al., 2022; González-Ruiz et al., 2020
	DO & pH (prolonged drought)	Decline due to stagnation	Chronic stress, higher pathogen susceptibility, and seasonal crop loss	Lahiri et al., 2022; Farha et al., 2024
Temperature Stress	Dissolved oxygen	Decline due to higher oxygen demand	Hypoxia, reduced feeding, and growth	Arnberg et al., 2018
	Ammonia & nitrite	Increased accumulation via higher microbial metabolism	Toxic buildup, oxidative stress, and mortality	Yang et al., 2019
Salinity Stress	Nutrient & turbidity (heatwaves)	Accelerated microbial activity, ammonia/nitrite buildup	Increased toxicity, immune suppression	Sánchez et al., 2016
	Salinity & ionic balance	Fluctuations beyond the optimal range	Osmoregulatory stress, reduced survival	Mazumder et al., 2017
	Total dissolved solids	Increased variation	Reduced osmoregulation efficiency	Rifqi et al., 2022

Alongside significant alterations in water chemistry, climate stressors also disturb the ionic equilibrium of pond ecosystems. Variations in sodium (Na⁺), potassium (K⁺),

calcium (Ca²⁺), and magnesium (Mg²⁺) adversely affect shrimp osmoregulation, metabolism, and exoskeletal development.

Rainfall dilution diminishes Ca^{2+} and Mg^{2+} concentrations, impairing shell calcification and molting processes. Conversely, drought and salinity intrusion elevate salt concentrations beyond acceptable thresholds, resulting in osmotic stress and the diversion of energy from

growth. The increase in temperature intensifies evaporation and disrupts hemolymph ionic control, exacerbating stress responses (Mazumder et al., 2017; Rifqi et al., 2022). Table 2 outlines the principal ionic perturbations and their physiological ramifications.

Table 2: Mineral Ion Imbalance and Physiological Consequences in Shrimp Farming.

Ion / Parameter	Climate Driver	Observed Change	Physiological Effect	Source
Sodium (Na^+)	Rainfall dilution, salinity shifts	Decrease with rainfall; excess under drought/intrusion	Osmotic imbalance, reduced hemolymph stability	Lahiri et al., 2022
Potassium (K^+)	Rainfall dilution, evaporation	Decline in diluted ponds	Weak muscle/nerve function, lower survival	Rifqi et al., 2022
Calcium (Ca^{2+})	Rainfall dilution, acidification	Reduced availability	Weak exoskeleton, poor molting	González-Ruiz et al., 2020
Magnesium (Mg^{2+})	Rainfall & salinity variability	Fluctuating levels	Enzyme dysfunction, poor growth	Mazumder et al., 2017
TDS	Drought, evaporation	Increased beyond tolerance	Osmotic stress, stunted growth	Rifqi et al., 2022

Climate Change Impacts on Shrimp Physiology and Biochemistry

The growth and survival of shrimp rely on the maintenance of physiological and biochemical stability; however, climate-induced stressors like as salinity variation, acidification, hypoxia, and increased temperature disturb this equilibrium. These variables modify ion regulation, diminish calcification, hinder enzyme activity, and destabilize metabolic activities, together undermining energy use, decreasing growth, and elevating mortality risks {Reference(S)}.

Salinity fluctuations influence hemolymph ion equilibrium (Na^+ , K^+ , Ca^{2+} , Cl^-), hinder gill ATPase function, and elevate the energy expenditure for osmoregulation, therefore reallocating resources from growth and immune responses (Rifqi et al., 2022; Dubey et al., 2021). Increased temperature disrupts calcium absorption, impeding molting and exoskeleton calcification, whereas acidification diminishes the availability of carbonate and bicarbonate ions, resulting in acid-base imbalance and compromising structural integrity (González-Ruiz et al., 2020; Vasanth et al., 2016).

Hypoxia, frequently associated with drought or eutrophication, increases death rates and predisposes shrimp to disease outbreaks (Wagner et al., 2025). Heat stress inhibits antioxidant enzymes like Superoxide Dismutase (SOD), Catalase (CAT) and Glutathione Peroxidase (GPx) diminishing the capacity to neutralize reactive oxygen species and exacerbating oxidative damage (Dubey et al., 2021). Acidification and salinity stress reduce digestive enzyme activity, resulting in inadequate food assimilation and stunted growth (Nguyen, 2015; Vasanth et al., 2016).

Figure 6 illustrates that ocean acidification diminishes ingestion efficiency and growth by as much as 12% at pH levels of 7.3–7.8, while increasing metabolic expenses due to compensatory ion regulation. This study demonstrates how acid-base imbalance compromises the shrimp energy budget and increases susceptibility to climate stress. Figure 6 further illustrates the impact of stress conditions on the allocation of energy to growth (P), ingestion (C), metabolism (R), excretion (U), and feces (F), revealing reduced growth allocation under low pH and high salt stress.

Figure 7 illustrates the variation in biomarker responses in relation to temperature and exposure period. Principal coordinate analysis (PCO) indicates that increased temperature (26 °C) and extended exposure (Days 21–28) correlate with elevated oxidative stress markers (GST, GGT) and diminished antioxidant defenses (SOD, TAC), suggesting that climatic stress not only undermines physiological resilience but also hastens cumulative biochemical damage over time. The ramifications of the various temperature treatments (20, 23, 26 °C) and exposure durations (7, 14, 21, and 28 days) indicate a clustering of antioxidant enzymes (SOD, CAT, GST, TAC), stress proteins (HSP-70 and UBI), and biochemical markers (TP, LPO, and weight) (Figure 8). Vectors indicate biomarker responses to variance, resulting in distinct modification of physiological responses under stress. Contrary to conventional wisdom, which has historically intensified experiences and heightened environmental interest, the situation has now reversed (Figure 7).

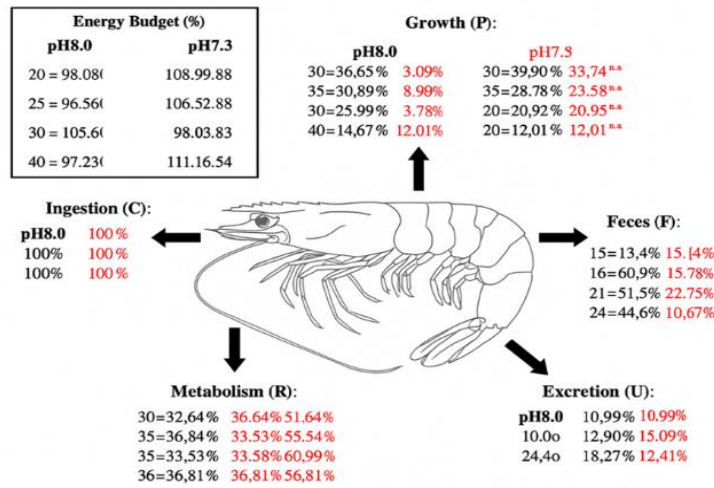


Figure 6: Energy budget allocations (as a percentage of used energy) of *P. vannamei* exposed to varying salinities and pH levels throughout a 30-day duration (Adapted from Ramaglia et al., 2024; with enhancements for labeling and layout clarity).

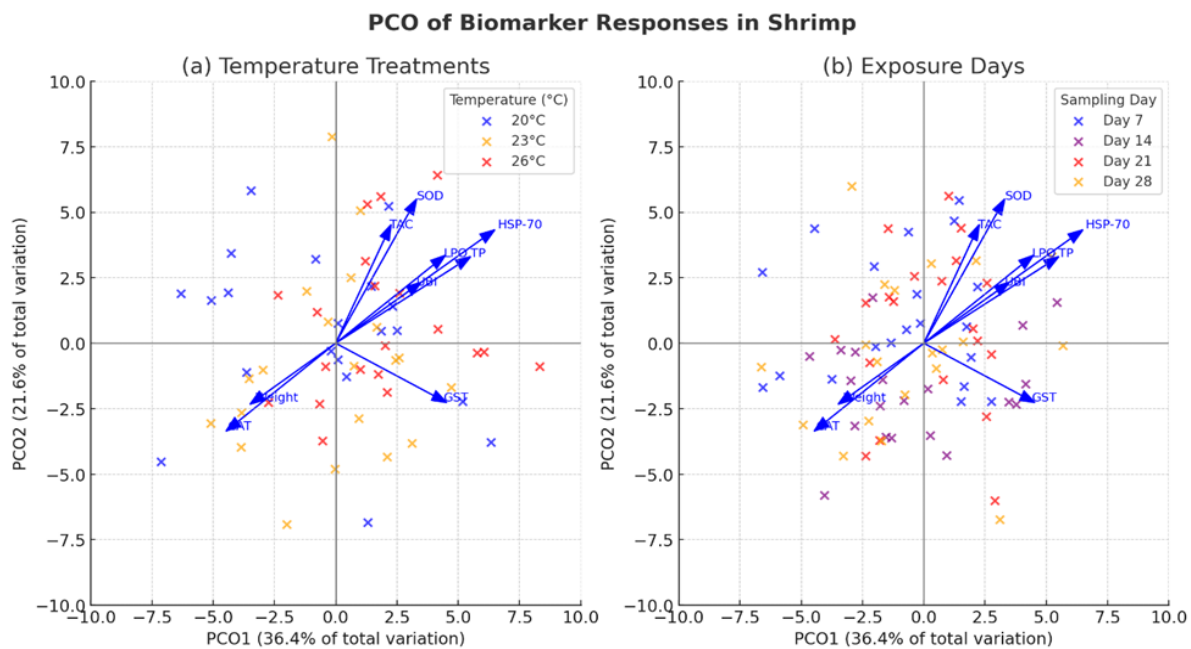


Figure 7: Biomarker response superimposed over Principal Coordinates Analysis (PCO) illustrating the predominance of shrimp (Adapted from Missionario et al., 2022, with simplified formatting and iconographic modifications).

Comprehensive summary of the physiological and biochemical effects of climate stresses on shrimp farming.

Comparative studies indicate that climate stressors temperature rise, salinity fluctuations, and acidification - consistently disrupt shrimp physiology and biochemistry, although the severity of these effects varies with species, exposure duration, and environmental context. Salinity stress impairs hemolymph ionic balance and gill function (Rifqi et al., 2022; Mazumder et al., 2017), while elevated temperatures and acidification compromise calcification and shell formation (González-Ruiz et al., 2020; Vasanth et al., 2016). Heat stress downregulates antioxidant

enzymes, increasing susceptibility to oxidative damage (Dubey et al., 2021; Wagner et al., 2025), and combined stressors further reduce digestive efficiency (Vasanth et al., 2016). These findings indicate that, although the direction of physiological and biochemical responses is consistent, their magnitude depends on both environmental and biological factors. Such disruptions—including impaired ion regulation, reduced antioxidant defenses, and compromised digestive efficiency—trigger a cascade of stress responses that predispose shrimp to immunological suppression and gut microbiota imbalance, as further detailed in Table 4.

Table 3. Physiological and Biochemical Impacts of Climate Stressors in Shrimp farming.

Stressor	Physiological Parameter Affected	Observed Effect	Consequence for Shrimp	Source
Salinity fluctuation	Na ⁺ , K ⁺ , Cl ⁻ balance in hemolymph	Disrupted ionic regulation, impaired gill ATPase	Osmoregulatory stress, reduced survival	Rifqi et al., 2022
Temperature increase	Ca ²⁺ uptake & calcification	Reduced calcium absorption	Molting defects, weak exoskeleton	González-Ruiz et al., 2020
Acidification	Bicarbonate & carbonate ions	Decline in buffering capacity	Acid-base imbalance, impaired shell formation	Vasanth et al., 2016
Drought/Hypoxia	Multiple ions & DO	Stagnation and waste accumulation	Oxidative stress, immune suppression	Mazumder et al., 2017
Elevated temperature	Growth rate & FCR	Poor feed conversion efficiency	Stunted growth, higher production cost	Nguyen, 2015
Hypoxia (low DO)	Survival	Increased mortality under oxygen depletion	Production collapse, disease outbreaks	Wagner et al., 2025
Heat stress	Antioxidant enzymes (SOD, CAT, GPx)	Downregulated activity	Oxidative damage, suppressed immunity	Dubey et al., 2021
Acidification + Salinity	Digestive enzymes (amylase, protease)	Altered enzymatic activity	Reduced nutrient absorption, poor growth	Vasanth et al., 2016

Climate Change Impacts on Shrimp Gut Health, Hematology, and Immune Parameters

Shrimp immunity and gastrointestinal health are acutely responsive to climate disruptions, rendering them essential indications of aquaculture susceptibility. Stressors including temperature variations, salinity discrepancies, rainfall inconsistencies, hypoxia, and acidification undermine hematological equilibrium, immunological function, and microbial balance, hence elevating disease vulnerability (Table 4).

Extreme rainfall exacerbates stress on immunological health. Intense monsoon precipitation enhances nutrient runoff and turbidity, promoting *Vibrio* prevalence in ponds and disrupting gut microbial equilibrium. In contrast,

extended dryness results in stagnant water, diminished hemocyte numbers, and inhibited immune enzyme activity, together increasing shrimp susceptibility to infections (Hasan et al., 2024; Lahiri et al., 2022).

Increased temperatures, alterations in salinity, hypoxia, and acidity exacerbate these problems by diminishing antioxidant enzyme activity (SOD, CAT), hindering calcification, and disturbing hemolymph ionic equilibrium (Yang et al., 2019; Nandy et al., 2021). These data collectively demonstrate that climate-induced stresses impair shrimp immunity via a multi-faceted mechanism: hematological suppression, microbial dysbiosis, and oxidative stress. The principal impacts are encapsulated in Table 4.

Table 4: Climate stressor impacts on gut microbiota, hematology, and immune parameters.

Stressor	Parameter Affected	Observed Effect	Consequences for Shrimp	Source
Rainfall variability (heavy rain / drought)	Hemocytes, gut microbiota	Heavy rainfall: <i>Vibrio</i> dominance, microbial instability; Drought: reduced hemocyte counts, enzyme suppression	Bacterial infections, seasonal mortality, chronic stress	Hasan et al., 2024; Lahiri et al., 2022
Temperature fluctuation	Hemocytes	Reduced total and differential hemocyte counts	Weakened immune defense, pathogen susceptibility	He et al., 2022
Salinity stress	Gut microbiota	Reduced microbial diversity, dominance of <i>Vibrio</i> spp.	Dysbiosis, poor digestion, disease outbreaks	Yang et al., 2019
Hypoxia	Hemolymph Phenoloxidase (PO) activity	Suppressed phenoloxidase activity	Impaired melanization, reduced pathogen resistance	Uawisetwathana et al., 2021
Acidification	Immune-related gene expression	Downregulation of antimicrobial peptide genes	Lowered innate immunity	Nandy et al., 2021
Combined stressors	Antioxidant enzymes & Reactive Oxygen Species (ROS)	Elevated ROS (Reactive Oxygen Species) reduced SOD (Superoxide Dismutase), and CAT (Catalase)	Oxidative stress, tissue damage	Dubey et al., 2021

Adaptive and Microbial Strategies for Climate Resilience

Mitigating climate-induced vulnerabilities in shrimp farming necessitates environmental management and microbiological interventions. Conventional methods like aeration, water exchange, and salinity control sustain pond

conditions by preserving dissolved oxygen levels and mitigating ammonia accumulation. Although effective, these approaches are expensive and provide only little alleviation during major climate fluctuations (He et al., 2022; De Almeida et al., 2024).

Selective breeding of stress-resistant shrimp strains offers a sustainable approach by augmenting tolerance to salinity and temperature variations, therefore raising survival rates and minimizing production losses. Breeding initiatives continue to be constrained in numerous areas and necessitate ongoing investment in genetic resources and farmer education (Missionário et al., 2022).

Microbial interventions are becoming increasingly pivotal for sustainable adaption. Table 5 presents a comprehensive summary of adaptive management approaches and microbial technologies, encompassing symbiotic-specific mechanisms. Probiotics enhance water quality and immune function, whereas prebiotics promote advantageous gut microbiota and improve feed efficiency (Yang et al., 2018; Le et al., 2024). When utilized in

conjunction, they enhance resilience and diminish dependence on antibiotics. Synbiotic, which integrate probiotics and prebiotics, signify the most potential advancement. They regulate gut microbiota, enhance antioxidant enzyme activity and promote immune gene expression, leading to increased survival under salt and temperature stress, improved feed conversion, and diminished pathogen load (Skrzypczak et al., 2023; Awad et al., 2025). Nonetheless, the implementation of synbiotics is constrained by species and contextual heterogeneity, elevated costs, and ambiguous long-term impacts on microbiome stability. Subsequent investigations ought to enhance formulations, assess cost-benefit ratios for smallholders, and corroborate laboratory results in field settings.

Table 5: Adaptive and Microbial Strategies for Climate-Resilient Shrimp farming.

Strategy / Intervention	Mechanism of Action	Observed Effect	Implication for Resilience	Source
Aeration & water exchange	Mechanical aeration, improved circulation	Maintains dissolved oxygen, reduces ammonia buildup	Stabilized pond environment, reduced mortality	He et al., 2022
Salinity regulation	Blending and controlled pumping	Maintains optimal salinity range	Reduced osmotic stress, enhanced survival	De Almeida et al., 2024
Selective breeding	Breeding for stress-tolerant shrimp strains	Improved heat and salinity tolerance	Long-term sustainability, reduced production losses	Missionário et al., 2022
Probiotics	Addition of beneficial bacterial strains	Enhances gut microbiota, boosts immunity	Improved disease resistance, reduced antibiotic use	Yang et al., 2018
Prebiotics	Dietary supplementation (e.g., MOS, FOS, inulin)	Promotes beneficial bacteria, improves digestion	Strengthened gut health, enhanced feed efficiency	Le et al., 2024
Synbiotics (Probiotic + Prebiotic)	Combines microbial and host modulation	Elevated antioxidant enzymes, improved immune gene expression	Comprehensive resilience under temperature/salinity stress	Skrzypczak et al., 2023; Awad et al., 2025
Synbiotic diet integration	Multi-strain probiotics with prebiotic additives	Increased survival, improved FCR, reduced mortality	Holistic resilience against multi-stressor environments	Missionário et al., 2022; De Almeida et al., 2024

Discussion

Climate change presents multifaceted risks to shrimp farming, operating through interrelated mechanisms that disrupt pond ecology, water quality, and shrimp physiology. Elevated temperatures and saline intrusion have been demonstrated to disturb oxygen equilibrium and heighten vulnerability to stress (Islam et al., 2018; Sultana & Hossain, 2023). Variability in rainfall and acidity disrupt pond chemistry, leading to osmotic shock, poor molting, and heightened larval mortality (Amin et al., 2024; Chowdhury & Hossain, 2023). These stressors increase susceptibility to diseases, with occurrences of Acute Hepatopancreatic Necrosis Disease (AHPND), White Spot Syndrome Virus (WSSV) and white feces syndrome documented in stressed conditions (Parvin et al., 2023; Hasan et al., 2024).

In low-income shrimp farming regions, climate stressors—such as rising temperatures, salinity fluctuations, and variable rainfall—substantially compromise shrimp growth, immunity, and survival. Conventional water management, including maintaining adequate water depth or frequent exchanges, is often costly and labor-intensive for small-scale farmers. Synbiotic supplementation offers a cost-effective and sustainable

alternative by improving gut health, immunity, and stress tolerance. When combined with judicious water management, synbiotics provide a practical, scalable adaptation strategy that balances efficacy, affordability, and feasibility. While promising, most evidence remains laboratory-based; therefore, field validation through pilot-pond trials with environmental monitoring, gut microbiome assessment, and immunological metrics is needed. These considerations underpin the adaptive strategies summarized in Table 6, highlighting interventions to enhance shrimp resilience and farm sustainability under climate stress.

The synthesis of information in Table 6 illustrates a sequential process whereby climate drivers affect water quality and physiological responses, resulting in disease outbreaks, diminished productivity, and economic losses. This underscores the pressing necessity for multi-tiered adaptation techniques that concurrently address environmental volatility and the biological robustness of shrimp. Such solutions are particularly crucial for nations like Bangladesh, where aquaculture supports rural livelihoods and susceptibility to climatic fluctuation is severe.

Microbial therapies have promising prospects for augmenting resilience. Probiotics enhance water quality and stimulate the immune system, whereas prebiotics promote advantageous microbial communities that enhance gut health and feed efficiency. Synbiotics, which integrate these two pathways, demonstrate notable efficacy, evidenced by increased antioxidant enzyme activity, augmented immune gene expression, and elevated survival rates under stress (Yang et al., 2018; Skrzypczak

et al., 2023). However, their effectiveness is not universal. Strain–host compatibility, dosage, exposure duration, and environmental context affect outcomes (Le et al., 2024). Financial constraints and supply limitations hinder uptake by smallholders, while commercial availability fluctuates by area. The long-term effects on microbiota stability and immunological tolerance are uncertain, highlighting the necessity for longitudinal studies and comprehensive economic assessments.

Table 6: Climate Change Effects on Shrimp farming.

Climatic Factor	Environmental & Water Quality Changes	Shrimp-Specific Effects	Production Consequences	References
Temperature Rise & Heatwaves	Warmer waters, low DO, increased ammonia/nitrite, stratification	Faster metabolism, smaller harvest size, higher susceptibility	Reduced growth, higher FCR, higher mortality	Islam et al., 2023; Parvin et al., 2023
Rainfall Variability	Erratic monsoons, low salinity, high turbidity, unstable pH	Osmotic shock, seedling mortality, Vibrio outbreaks	Seed loss, seasonal crop failure	Amin et al., 2024; Farha et al., 2024
Salinity Intrusion (Dry Season)	Sea-level rise, very high salinity (30–40 ppt), altered conductivity	Poor molting, slower growth, deformities	Reduced yield, hatchery collapse	Sultana & Hossain, 2023; Chowdhury & Hossain, 2023
Cyclones & Storm Surges	Debris contamination, unstable pH and DO	High stress leading to AHPND/WSSV outbreaks	Total production collapse in affected zones	Islam et al., 2018; Parvin et al., 2023
Dry Season Water Scarcity	Groundwater stress, stagnation, high BOD, high salinity	High larval mortality, slow growth	Lower stocking density, higher PL cost	Hasan et al., 2024; WUR, 2023
Acidification & Runoff Events	Acid rain, low pH (<6.5), algal blooms, toxin build-up	Stress-induced molting issues, white feces syndrome	Sub-lethal infections, reduced growth	Chowdhury & Hossain, 2023; Farha et al., 2024

The economic viability is especially crucial in locations with limited resources. Although synbiotics can reduce disease prevalence and enhance feed efficiency, the elevated costs of fortified feeds and the restricted ability for local formulation hinder adoption (Awad et al., 2025). In Bangladesh's coastal region, where salinity intrusion and heatwaves intensify dissolved oxygen and pH fluctuations, scalable solutions comprise low-energy aeration, climate-resilient shrimp varieties, and locally sourced multi-strain probiotics or synbiotics (De Almeida et al., 2024; Missionário et al., 2022). When included into extension networks and bolstered by quality-assurance standards, such methods could augment resilience among smallholder farmers.

Addressing the Objectives and Remaining Challenges

This review aimed to address four principal research inquiries. The bibliometric purpose of studying publishing dynamics was achieved by investigating temporal patterns, leading nations, and principal journals in the domain of climate change and shrimp farming. A systematic theme synthesis elucidated the impact of climate stressors on shrimp physiology, immunology, and aquaculture performance, based on seven topic strands encompassing environmental stressors, mineral imbalances, gut microbiota, hematological parameters, and adaptation methods. The integration of developing technologies, including probiotics, prebiotics, and synbiotics, directly addressed the goal of identifying sustainable adaption strategies.

Despite these strengths, several limitations should be noted. The review depended exclusively on the Scopus database, perhaps excluding pertinent studies listed in alternative sources. Limiting the scope to English-language, peer-reviewed publications from 2015 to 2025 may have created linguistic and publication bias. Furthermore, although the theme approach offered a comprehensive perspective, it was unable to produce effect-size estimates via meta-analysis. The evidence for adaptable technology is constrained by the paucity of empirical studies across various agricultural contexts, especially in Bangladesh, Southeast Asia, and Latin America. Ultimately, inconsistencies in experimental designs, shrimp species, and production processes posed difficulties in reconciling data.

The review successfully achieved its aims by connecting climate-related stressors to shrimp health and productivity, while delineating adaptive pathways. Simultaneously, these methodological and contextual constraints underscore the necessity for future research that is more comparative, field-oriented, and interdisciplinary.

Conclusion

Climate change poses a multifaceted threat to shrimp farming, especially in susceptible areas like Bangladesh, by destabilizing pond water quality, altering ionic equilibrium, impairing immunological activities, and disturbing gut microbial ecosystems. These factors cumulatively diminish shrimp growth, survival, and production, hence jeopardizing farmer livelihoods and national export potential. Adaptive strategies such as

aeration, enhanced water exchange, and salinity management can mitigate environmental variability, while microbial technologies, specifically probiotics, prebiotics, and synbiotics, demonstrate significant promise to rehabilitate gut microbiota, bolster immunity, and mitigate abiotic stress in shrimp. Nevertheless, their implementation necessitates farmer education, field verification, and economically viable application methods. From a policy standpoint, climate-resilient aquaculture necessitates investment in stress-tolerant shrimp varieties, enhancement of early warning systems, and the transmission of optimal management techniques via extension services to promote best management practices. Collaborative endeavors among researchers, policymakers, and farmers are crucial for converting laboratory findings into applicable field practices. Integrating environmental management with microbial innovations provides a sustainable path toward resilient

shrimp farming that safeguards livelihood and ensures global seafood security.

Author contribution

Saroj Kumar Mistry: Data acquisition, document formulation, composition – evaluation and refinement.

Syed Hafizur Rahman: Composition, critique, review and revision.

Data availability: No datasets were generated or analyzed during the current study.

Declarations

Ethics approval this study does not involve any research conducted on human participants or animals.

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