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Aquaculture and climate change: a data-driven analysis

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Abstract

As climate change increasingly impacts the aquaculture industry, it poses challenges to production quality, management, and sustainability. This study provides a scientometric analysis of 47 years of research on aquaculture and climate change, analysing 4,785 articles and 224,895 references through CiteSpace software. The study highlights enduring themes such as "ocean acidification" and "global warming," alongside emerging concerns like "deforestation" and "nutrient runoff," reflecting new research directions. Notably, "seasonal variations" persist as a key focus due to their significant impact on aquaculture practices. Fourteen research clusters were identified, revealing a diverse array of topics from environmental performance to the effects of blue food systems and ocean acidification on marine life. Clusters related to "carbon sequestration," "seaweed farming," and "integrated multi-trophic aquaculture (IMTA)" emphasise the shift toward innovative practices aimed at mitigating climate impacts and enhancing sustainability. The analysis shows a need for more collaborative research, particularly from leading contributors such as the USA, Europe and Australia with underrepresented regions like Southeast Asia and Africa, to develop resilient aquaculture systems capable of adapting to climatic challenges. It advocates for the integration of new technologies and the exploration of sustainable aquaculture practices that minimise environmental impacts while enhancing global food security. This approach sets a direction for future research to promote adaptive strategies and technological innovations in aquaculture.

Key words: temperature; Marine biodiversity, seasonal variations, hypoxia, ocean acidification

Climate change exerts multifaceted pressures on aquaculture by altering key oceanic parameters and through increased frequency of extreme weather events consequently impacting the sustainability and productivity of aquaculture systems (IPCC, 2022; Barange et al, 2018). These changes manifest through various climatic stressors, including escalated ocean temperatures, intensified ocean acidification, varying salinities and rising sea levels, each contributing significantly to the sector's vulnerability (Maulu et al., 2021; Froehlich et al. 2018). Ocean temperatures have risen by approximately 0.13°C per decade over the past 100 years, significantly affecting the metabolic rates and distribution of aquaculture species (García Molinos et al., 2016). Ocean pH has significantly decreased in approximately 70% of all biomes, by a mean of 0.0018 ± 0.0004/ year for the period 1991–2011, which adversely impacts shellfish calcification rates (Lauvet et al., 2015; Doney et al., 2009). Global sea levels have risen by approximately 3.7 mm per year from 2006 to 2018 (Scambos, 2022), though historically the average rise was slower at 1.5 mm per year, with recent accelerations being linked to thermal expansion and ice loss from Greenland (Frederikse et al., 2020). Some future projections suggest that sea levels could rise by 0.44 to 1.01 metres by 2100, depending on emissions (Scambos, 2022). Climate change brings about higher variability in temperature, salinity and pH in coastal regions compared to the open oceans impacting essential aquaculture habitats (IPCC, 2022; Barange et al., 2018). Warming and acidification have been observed at a rate of 0.2 °C and 0.09 pH units per year in recent studies of coastal estuaries of NE Pacific (Lowe et al., 2019) and Australia (Scanes et al., 2020), an order of magnitude faster than any predicted ocean model. Additionally, extreme weather and changes to upwelling of nutrient-rich and CO_2-rich deep water has implications for aquaculture in coastal regions (Barange et al., 2018). To navigate these challenges, the aquaculture industry is compelled to innovate, adopting strategies like selective breeding for enhanced climate resilience and the development of new management practices aimed at minimising the environmental footprint of aquacultural operations while mitigating some of the aforementioned environmental stressors (Sae-Lim et al., 2017). As natural fish stocks decline and the global population continues to grow, aquaculture is becoming an increasingly important source of high-quality protein, offering a sustainable option that not only keeps up with the demand for protein but also helps preserve wild fish populations (Anderson et al., 2017; Jones et al., 2015). Global research has shown that increased aquaculture production is associated with increased consumption of aquatic foods, and further supports the importance of aquaculture development in vulnerable food-secure areas (Garlock et al., 2022).

Asia accounted for about 90% of total production, followed by Europe in the middle of the 21st century, Africa the fourth, while Oceania ranked last (Chan et al., 2024). In 2012, the industry reached over 90 million tonnes of production, which included nearly 24 million tonnes of aquatic plants, representing nearly half of the total global fish supply (FAO, 2018). By 2018, production surged to 114.5 million tonnes, valued at approximately USD 263.6 billion (FAO, 2022a), and is expected to reach 196 million tonnes by 2025 (Nang et al., 2017). Production is correlated with demand, for example, the global average per capita fish consumption increased from 10 kg in the 1960s to more than 19 kg by 2012 (FAO, 2018), and Canada's aquaculture exports in 2012 exceeded 90,000 tonnes, valued at more than CAD 601 million, primarily to the United States, Japan, and China (Chopin, 2015). In terms of specific sectors, the global production of marine bivalves for human consumption exceeded 15 million tonnes annually, constituting about 14% of total marine production, with 89% originating from aquaculture – primarily from China, which accounted for 85% of global output (Wijsman et al., 2018). The revenue from bivalve shellfish aquaculture alone reached USD 19 billion annually by 2017 (Willer & Aldridge, 2017), while the broader aquaculture sector's revenue from fish and seaweed was estimated at USD 106 billion in 2008 (Alfaro et al., 2014). Geographically, China has maintained its position as the world's largest aquaculture producer, contributing over 60% of global aquaculture volume and approximately 72% of its domestic fish production by 2015, with about 70% of global aquaculture output (Cao et al., 2015). In terms of regional growth, by 2020, China's aquaculture production remained at nearly 70% of the global total, with significant contributions from marine aquaculture including 21.35 million tonnes of mariculture products, primarily macroalgae and mollusks (FAO, 2022a). European production also increased, from 1.34 million tonnes in 2012 to 3.34 million tonnes by 2018, with Norway emerging as the leading producer (Rocha et al., 2022; Bostock et al., 2016). Other countries like Brazil and India have also seen substantial growth; Brazil's production reached 800,000 tonnes in 2019, generating a revenue of USD 1 billion, with main species being Nile tilapia and Pacific white leg shrimp (Valenti et al., 2021), and India continued as a major aquaculture player especially in coastal regions (Thirunavukkarasu et al., 2015). The industry's economic impact is significant, providing numerous jobs and substantial revenue. For instance, the EU aquaculture sector employs between 14,000 and 15,000 enterprises, supporting approximately 80,000 jobs (Bostock et al., 2016). Sustainability efforts have also been enhanced, with initiatives like Integrated Multi-Trophic Aquaculture (IMTA) and Recirculating Aquaculture Systems (RAS) being developed to minimise environmental impacts (FAO, 2022a), with Canada being a leader in adopting these sustainable practices (Chopin, 2015). To ensure that aquaculture continues to grow, it is reliant on continuous advancements in technology and management. These improvements are crucial for reducing environmental harm, making the best use of resources, and maintaining economic stability (Little & Bunting, 2016). However, many of these efforts are overshadowed by the somewhat unpredictable nature of climate change.

A comprehensive grasp of the long-term impacts of extreme weather is still not fully understood. Such impacts potentially include permanent alterations to marine habitats and sustained declines in aquaculture productivity, driving the need for predictive models that span decades (Froehlich et al. 2018). Similarly, the resilience of freshwater aquaculture to hydrological changes induced by climate – such as fluctuations in water flow, temperature, and quality – is not well understood. These factors are pivotal for maintaining the sustainability of freshwater systems, yet there is a scarcity of research on effective long-term water management and species resilience strategies (Handisyde et al. 2017). Additionally, while adaptive management strategies are essential for the continuity of aquaculture in varying climatic conditions, detailed and actionable insights into their efficacy are sparse. Empirical research is critically needed to validate these strategies across diverse climatic zones and aquaculture systems, ensuring their practicality and benefit over the long term (Poloczanska et al., 2016). This article seeks to fill some of these gaps by using a scientometric analysis, mapping the breadth and depth of existing research while highlighting areas scantily explored.

The objective of this scientometric mapping is not only to synthesise a comprehensive picture of the research landscape but also to unearth latent connections between seemingly disparate studies, thereby suggesting avenues for future research. Through this approach, we aim to provide stakeholders—including policymakers, aquaculture practitioners, and the scientific community—with a data-driven foundation to forge resilient and sustainable aquaculture systems in the face of a warming planet.

This article will systematically dissect the trends, impacts, vulnerabilities, and adaptive strategies documented within the scientometric framework to offer a holistic view of how global aquaculture can navigate and thrive amidst the challenges posed by climate change.

Impact of climate variables on aquatic farms

The climate has undergone rapid changes in recent decades, significantly affecting both freshwater and marine aquaculture sectors. These changes have led to considerable economic, ecological, and operational consequences. The primary climate-related challenges for aquaculture include global warming, drought, water scarcity, extreme precipitation, and increased freshwater inflow at coastal areas. These are collectively categorised as extreme weather events. Additional issues are hypoxia, changes in upwelling, coastal acidification, and variations in primary productivity (IPCC, 2022; Barange et al., 2018). This discussion will explore the known impacts of these changes on aquaculture.

Rising temperatures

Rising temperatures have led to geographical shifts in aquaculture, as species once confined to specific thermal niches are now migrating to cooler waters. This shift requires aquaculture practices to adapt and farms to move to areas with more favourable temperatures (Cascarano et al., 2021). At the same time, increased water temperatures have been linked to an increase in the prevalence and severity of diseases and parasites, which thrive under warmer conditions, complicating the management of aquatic farms. For instance, studies have shown that a 1°C increase in water temperature can raise mortality rates due to viral infections by 1.47-8.33% in oysters, and 2.18-5.37% in fish (Combe et al., 2023; Pathirana et al., 2022). Additionally, in Ukraine, warmer years saw infection rates in fish increase to above 25%, correlating with the rise in temperatures, along with increased dissolved organic compounds and corresponding harmful microorganisms (Matvienko et al., 2020). Many marine species have narrow thermal safety margins (TSMs) of less than 5°C, making them vulnerable to minor temperature increases which can lead to a 20-30% reduction in survival rates, compromised immune functions, and greater disease susceptibility (Ma et al., 2021; Adamo & Lovett, 2011). Temperature increases also enhance pathogenic microbes and harmful algal blooms (HABs), causing significant die-offs and disrupting mariculture (Ma et al., 2021). The economic ramifications of these temperature-induced stresses are substantial. For every degree Celsius increase in water temperature, operational costs may rise by 10-15%, driven by the need for additional cooling systems and treatments for heat-related diseases and stress (Ma et al., 2021). To manage these issues effectively, adaptive strategies that consider both thermal tolerance and disease resilience, are required (Rud et al., 2020).

Extreme weather events, drought, and water limitation

Extreme weather events like storms, floods, and droughts cause substantial infrastructure damage, disrupt operations, and result in heavy economic losses (Li et al., 2016). For instance, in coastal Andhra Pradesh, India, cyclones and floods were reported to cause economic losses ranging from 50% to 100%, particularly impacting shrimp aquaculture. Farmers rated the economic risk of floods as high, followed by cyclones, with greater impacts in coastal areas compared to inland (Muralidhar et al., 2021). In Vietnam, the recovery period following storm surges and tropical cyclones can extend up to two years, emphasising the long-term productivity losses in aquaculture (Nguyen et al., 2022). Cyclones Idai and Kenneth in 2019 devastated the aquaculture sector in Mozambique, with losses including hundreds of fish ponds and hundreds of thousands of fish fry in Zambézia and Sofala provinces (Muhala et al., 2021). Furthermore, extreme weather in Central Vietnam has led to projected economic losses for agriculture and fishery enterprises that could range from VND 3,597.72 billion to VND 18,891.2 billion under various climate change scenarios (Do et al., 2021). In Greece, simulations (ClimeGreAq), which use biological models such as Dynamic Energy Budget theory along with other climate models, indicate potential significant losses in biomass and farm profits for finfish aquaculture due to extreme weather events, and this threaten the industry's viability depending on the severity of these events (Stavrakidis-Zachou et al., 2021).

Freshwater aquaculture faces significant challenges from climate-induced hydrological variability, including the effects of droughts and floods which disrupt operations and ecological balances. Droughts reduce water volumes in critical aquatic resources, leading to heightened pollutant concentrations and severe impacts on aquaculture as observed in some parts of India (Dubey et al., 2017). Additionally, in Ireland, in 2018, one of the warmest and driest periods recorded, there was a >50% increase in algal growth rates due to heat waves and drought conditions impacting aquaculture wastewater quality (O'Neill & Rowan, 2021). Whereas, in Furnas Reservoir, Brasil, drought conditions were associated with increased concentrations of bacterial fatty acids, suggesting organic matter subsidies from fish farming (Boëchat et al., 2020). In Ghana, small-scale aquaculture revenue decreased by 53.4% due to drought and other climatic factors, with fish supply reduced by 25% as a result (Asiedu et al., 2018). In the Sundarban delta, reports mentioned a 0.019°C annual rise in air temperature and a 0.05°C/year increase in surface water temperature, increased salinity levels particularly in the Western and Eastern sectors, a rise in severe cyclonic storms by 26% over 120 years, sea level rise at 12 mm/year during 2002-2009, and significant impacts on aquaculture productivity and water quality (Chand et al., 2012b). Concurrently, elevated water temperatures and reduced dissolved oxygen levels exacerbate the stress on aquatic life, affecting species like carp and tilapia in Bangladesh (Ahmed & Diana, 2016). Specifically, climate change has led to significant environmental shifts in Bangladesh, including a 1.4 °C rise in mean temperature by 2050, intensified rainfall patterns with a mean annual increase of 5.52 mm from 1958-2007, and a sea level rise of 15.9-17.2 mm annually (Rahman et al., 2021). In this instance, tilapia farming has been identified as a viable adaptation strategy in Bangladesh due to the species' tolerance to a wide range of water conditions, including low water quality, varying salinity levels up to 25 ppt, and temperature fluctuations up to 34 °C, allowing for resilient production in freshwater, brackish, and saltwater environments. Adaptation strategies such as polyculture, monoculture, integrated farming, and seasonal waterbody utilisation for tilapia were cited as mitigation for climate-induced challenges.

Flooding introduces additional risks by diluting water quality and facilitating the escape and spread of non-native species and pathogens, as seen during the 2015/2016 El Niño in southern Brazil, where about 1.14 million fish escaped into the Paranapanema River (Casimiro et al., 2018). Furthermore, non-native species such as *Oreochromis niloticus* and *Coptodon rendalli,* which accounted for 96% of the escaped fish, risked genetic contamination of native populations and facilitated the spread of pathogens and parasites across uncontained waters (Casimiro et al., 2018). Floods pose complex challenges by both diluting marine environments and increasing salinity in freshwater systems. These changes can harm the health of various species and result in substantial fish mortality, as observed in India's Sundarban region (Chand et al., 2012a). The oscillation between these extremes—drought and flood—demands robust and flexible management strategies to maintain and enhance the resilience of freshwater aquaculture. Given these significant challenges, the aquaculture industry has to continuously adapt and plan for more resilient infrastructures. Adaptation may require substantial investments in infrastructure redesign and technological enhancements, which adds financial strain to this capital-intensive industry (Reid et al., 2019).

Sea level rise

As sea levels continue to rise, coastal aquaculture regions are increasingly at risk of inundation, which not only reduces available land but also leads to increased salinity in surrounding water bodies. Such changes in salinity can severely impact aquatic species, especially those that struggle with even slight changes in salt levels (Dasgupta et al., 2017). For instance, in the Nile Delta, rising sea levels are projected to result in the inundation of 54.35 to 59.92% of current fish farm areas under different climate scenarios (Soliman, 2023). Furthermore, the influx of saltwater into freshwater ecosystems disrupts these habitats, resulting in biodiversity loss and the displacement of species. These shifts present significant challenges for managing and sustaining freshwater-dependent aquaculture systems, putting the survival of many coastal ecosystems and species at risk, particularly those that cannot adapt to higher salinity (Nicholls, 2011). Global warming intensifies these issues by altering precipitation patterns and increasing evaporation rates, further raising salinity levels in coastal and estuarine waters. The effects of increased temperature can especially be seen in shrimp ponds where evaporation during the culture period can significantly raise water salinity (Yang et al., 2019). Furthermore, in Bangladesh, proximity to shrimp ponds has significantly raised soil salinity by 0.14%, diminishing paddy farming yields and profitability for every metre closer to the ponds (Morshed et al., 2020). These environmental changes impose socioeconomic impacts on aquaculture communities, compelling them to adopt costly adaptations such as relocating farms or transitioning to salt-tolerant species. In Bangladesh, increased soil salinity has driven many to diversify into aquaculture or migrate internally (Chen & Mueller, 2018). The intersection of elevated temperatures and higher salinity levels can diminish the survival and growth rates of aquaculture species, showing the need for strategic planning and investment in adaptive measures to sustain aquaculture under evolving climatic conditions (Fernandes et al., 2021; Chen & Mueller, 2018). Similarly, an 8-week trial demonstrated that different types of shrimp feed processing (extruded vs. steamed pellets) and protein sources (soya/pea vs. fish meal) affect the survival and nutritional outcomes of *Litopenaeus vannamei* in varying salinity conditions, and this highlights the critical role of tailored feed strategies under environmental stress (Moss et al., 2024).

Coastal upwelling and hypoxia

Coastal upwelling is crucial for supplying nutrients that support primary productivity, as well as the growth of shellfish and juvenile fish in coastal areas. This phenomenon, driven by seasonal wind patterns, brings nutrient-rich deep water to the surface, enriching surface waters with nitrogen and boosting primary production (Buck et al., 2014). However, studies indicate that climate change is intensifying these upwelling events, altering currents and upwelling patterns, thus increasing ocean acidity and the frequency of hypoxic conditions, leading to ecological and economic consequences (Bakun et al., 2015). For instance, the increased ocean acidity from upwelling high CO_2 seawater has severely impacted shellfish populations, exemplified by a 75% reduction in Pacific oyster larvae production at Whiskey Creek Shellfish Hatchery, threatening the $270 million West Coast oyster industry (Whitefield et al., 2021). Furthermore, severe hypoxia in the California Current System, linked to abnormal subarctic water flows, has caused mass die-offs of fish and invertebrates, significantly disrupting ecosystems and economic viability (Grantham et al., 2004). Changes in upwelling intensity also disrupt nutrient cycles, affecting food particle densities necessary for fish larvae and leading to broader ecological impacts, such as shifts in benthic community structures and increases in harmful algal blooms (Kelly, 2001). Ultimately these changes at the coast can also result in seasonal hypoxia, in combination with rising sea surface temperature and increased rainfall (Barange et al., 2018), resulting in mass mortalities and reduced growth for coastal finfish aquaculture (Barange et al., 2018). Notably, species like the Chilean scallop (*Argopecten purpuratus*) have evolved physiological strategies to adapt to these variable conditions, optimising metabolic performance under hypoxia and maintaining calcification despite the acidic conditions (Ramajo et al., 2019). For shellfish aquaculture, upwelling of high CO_2 seawater can result in acidification and mass mortalities of mussel and oysters, impacting economic viability of aquaculture operations (Chan et al., 2019; Barton et al., 2015), this will be discussed in more detail under ocean acidification impacts.

Ocean acidification

Ocean acidification, driven by escalated atmospheric CO_2 levels, reduces seawater pH and carbonate ion concentrations, and critically impairs the ability of calcifying organisms such as shellfish and corals to form and maintain their calcium carbonate structures (Byrne and Fitzer, 2019; Fitzer et al., 2016). In addition, reduction in carbonate saturation states inhibit shell formation and reduce growth and survival in many marine calcifying organisms (Doney et al., 2009). Studies warn that higher CO_2 could reduce calcification rates by up to 25% for important species such as mussels and Pacific oysters by 2100 if emissions stay high, with potential economic losses in Asian mollusk farming ranging from \$16.08 billion to \$498.28 billion (Narita et al, 2012; Yu, 2019; Gazeau et al., 2007). Species-specific responses to ocean acidification suggest that some species are more vulnerable than others (Leung et al., 2022; Byrne and Fitzer, 2019). The integration of precision aquaculture practices could mitigate some of these impacts by enabling more controlled, responsive farming techniques that adjust to changing environmental conditions and optimise the resilience and productivity of vulnerable species. Empirical studies have shown variable impacts across different life stages, with generally more severe effects noted for reproduction and during the early developmental stages, impairing their capacity to grow effectively (Leung et al., 2022). For shellfish aquaculture coastal acidification, due to upwelling of high CO_2 seawater and sulphate soil acidification, has been shown to reduce larval development and settlement in oysters, *Magallana gigas* and *Saccrostea glomerata*, an essential life stage for aquaculture resulting in mass mortalities and reduced growth (Barton et al., 2015; Fitzer et al., 2019). Calcification is energetically costly and in combination with other environmental parameters such as increased temperature and food supply, calcification rates can be maintained, as seen in mussels, oysters and scallops (Leung et al., 2022; Lee et al., 2021; Melzner et al., 2011). Increasing temperature has the potential to alleviate shell growth in combination with ocean acidification, resulting in thicker, harder shells in crustaceans, gastropods and molluscs (Byrne and Fitzer, 2019). However, rising seawater temperatures combined with acidification significantly increase the bioavailability and toxicity of heavy metals in marine aquaculture. For example, under elevated temperatures (+4°C) and increased CO_2 levels (pCO_2 at 1100 μatm), mercury accumulation in the liver of *Argyrosomus regius* significantly increased, while elevated CO_2 alone decreased mercury levels (Sampaio et al., 2018). Additionally, combined lower pH (7.4) and higher temperatures (25°C) in Mediterranean mussels led to increased cadmium toxicity, enhancing metallothioneins and oxidative damage (Nardi et al., 2017). In smooth scallops, reduced pH and higher pCO_2 levels also increased cadmium toxicity, reducing antioxidant activity in the gills (Nardi et al., 2018). Despite these challenges, some species show signs of potential resilience or adaptation, suggesting that while the overall impact is negative, there could be some hope for certain species to withstand the changes (Leung et al., 2022). Under acidified conditions (pH 7.5), *Haliotis midae* showed up-regulation of oxidative stress and cytoskeletal proteins, this indicates a metabolic shift to more energy-efficient ATP generation mechanisms (Carroll & Coyne, 2021). Additionally, ocean acidification has been linked to an increase in oxidative damage indicators (MDA) in coral reef fishes (Mitchell et al., 2023).

Several studies have demonstrated that the behavioural and physiological responses to climate change-related stressors may impact fish resilience to other stressors (Servili et al., 2022). For instance, *Acanthopagrus schlegelii* exposed to projected ocean acidification scenarios (pH 7.80 and 7.40) exhibited decreased growth rates, feed efficiency, and protein efficiency ratios, along with multiple atrophies in the microvilli of the small intestine, reducing nutrient absorption (Tegomo et al., 2021). Juvenile *Dicentrarchus labrax* subjected to acidified conditions (pH 7.8 and 7.5) for 11 months showed a slower return to basal cortisol and glucose levels post-stress (Servili et al., 2022), while short-term exposure (pH 7.9 to 7.5 for 7 days) in *Lates calcarifer* did not affect growth or behaviour but caused significant gene expression changes related to ion homeostasis and neural regulation (Wang et al., 2021). Chronic high acidification (pH 7.5) in *Dicentrarchus labrax* larvae led to faster mineralisation and reduced skeletal deformities without significant changes in survival or growth (Crespel et al., 2017). Additionally, high pCO_2 conditions (end-of-century CO_2 levels) increased somatic and otolith growth rates in *Symphodus ocellatus*, with slower-growing individuals displaying larger otoliths relative to body length under ambient pCO_2 conditions (Di Franco et al., 2019). Ocean acidification, therefore, impacts fish aquaculture and marine fish physiology by altering growth, reproduction, stress response, and nutrient absorption. This shows the need for adaptation strategies to mitigate its adverse effects on marine ecosystems and the aquaculture industry.

Aquaculture resilience and adaptation

To combat some of these climate change challenges, aquaculture is turning to genetic and genomic advancements, selective breeding (Fitzer et al., 2019), and innovative techniques like Integrated Multi-Trophic Aquaculture (IMTA), and hatchery environmental treatment (Barton et al., 2015) which optimises resource use and stabilises environments against climate variability (Oyinlola et al., 2020). Advances in genomics have shown potential to enhance stress tolerance in marine species by up to 30% (Kole et al., 2015; Cushman & Bohnert, 2000). Moreover, the integration of remote sensing and GIS tools in climate-smart aquaculture strategies is enhancing resilience to climate change (Alleway et al., 2022). Therefore, to ensure a sustainable future, aquaculture must evolve to use emerging scientific insights and technological developments to address acidification and temperature variability.

Scientometric analysis

In this study, the scientometric analysis aims to quantify the scope and impact of research in aquaculture and climate change. This analysis uses a dataset extracted from leading scientific databases including Web of Science (Core Collection - WOSCC) utilising advanced data mining techniques to ensure comprehensive coverage of relevant publications. The inclusion criteria for these publications were defined by a combination of keywords and Boolean operators, to encapsulate the multifaceted interactions between aquaculture practices and climatic variables. Keywords of aquaculture is “aquacultur*” OR “aqua-cultur*” OR “aqua* farm*” OR “mariculture” OR “aquatic polyculture” OR “sea farm*” OR “freshwater farm*” OR “freshwater culture” OR “fish farm*” OR “shellfish farm*” OR “crustacea* farm” OR “mollusc farm” OR “mussel farm*” OR “oyster farm*” OR “shrimp* farm*” OR “prawn farm*” OR “lobser farm” OR “crab farm” OR “sea cage*” OR “net pen*” OR “pen culture” OR “fish pond*” OR “seaweed farm*” OR “macroalgal farm*” OR “aquatic production” and climate change related keywords is “climat* chang*” OR “global warm*” OR “greenhouse effect*” OR “greenhouse gas*” OR “weather pattern*” OR “weather* variab*” OR “weather* extrem*” OR "extreme weather event" OR “extreme* climat*” OR “sea level ris*” OR “sea level change” OR “heat wave” OR “heatwav*” OR “temperature ris*” OR “temperature effect*” OR “warm* ocean” OR “sea surface* temperat*” OR “ocean acidific*” OR “hurrican*” OR “el nino” OR “el-nino” OR “la nina” OR “la-nina” OR “drought*” OR “flood*” OR “heavy precipitation” OR “heavy rainfall” OR “CO2 concentration*” OR “melt* of the glacier*” OR “melt* ice*” OR “sea ice” OR “hypoxia” OR “season* change*” OR “season* variat*” OR “atmosph* pollut*” OR “permafrost” OR "burning of fossil fuel" OR “tropical storm*” OR “storm event*” OR “chang* weather* pattern*” and their numerous derivatives were deployed to filter and retrieve pertinent scholarly articles only. The keywords selection is based on the previous Systematic Map Protocol and published by Azra et al. (2022) and Noor et al. (2021). Additionally, our analysis leans heavily on the CiteSpace algorithm's capability to extract and cluster related data for the present review such as keywords, co-citation, etc. (Chen, 2017; Chen, 2022).

Following data acquisition, the preprocessing stage involved a deduplication process, normalisation of author names and affiliations, and standardisation of terminology to homogenise the dataset for subsequent analysis. This refined data then underwent a detailed bibliometric analysis, where techniques such as co-citation and co-authorship network analysis were applied. These methods are instrumental in unveiling the collaborative networks and intellectual structures that underpin the field, identifying both central and peripheral actors within the research community. These methods are supported by the advanced version of CiteSpace software (6.3.R2, 64 bit) (Chen and Song, 2019). Further, to dissect the thematic structure of the literature, advanced text mining techniques were utilised. These techniques facilitated the extraction and visualisation of prevalent themes and sub-themes within the research field, providing granular insight into the dominant research trajectories as well as emerging frontiers. Each identified theme was quantitatively assessed based on its citation impact and temporal growth, offering a measure of its scientific relevance and evolution over time.

In parallel, network analysis algorithms were deployed to construct and analyse citation networks, enabling the identification of seminal works and influential researchers whose contributions have significantly shaped the field (Chen, 2017; Chen, 2022). Metrics (i.e., measurement(s) of quantitative assessment) such as betweenness centrality, eigenvector centrality, and PageRank were calculated to determine the influence and connectivity of individual articles and authors within the network. The integration of these diverse scientometric tools and techniques culminates in a multidimensional analysis that not only maps the current landscape of aquaculture and climate change research but also highlights pivotal gaps and discrepancies in the literature. This comprehensive overview is instrumental in guiding future research efforts, policy-making, and strategic funding allocations towards areas that promise maximum impact and sustainability in the face of global climatic changes.

Insights from scientometric mapping: trends and gaps

Evolution of the literature

The descriptive results and scientometric analysis are now presented in various analysed charts and figures. Figure 1 indicated the evolution of 47 years of the literature on research about aquaculture and climate change. Between 1977 and 2023, 4,785 articles were published focusing on aquaculture and climate change. During the development phase from 1977 to 2011, there was a limited number of publications. A gradual increase in numbers of publications was observed during the growing phase from 2012 to 2018 whereby 1,330 were published over the course of 6 years. In following years from 2019 to 2023, there was a significant increase in the number of publications with 2022 having the highest number of published articles—a 398% increase compared to ten years prior (2012). Based on data generated from 2019 to 2023, it is predicted that the number of publications will continue to soar by as much as 1,000 articles with the citation expected to reach nearly 38,000 in 2030. Furthermore, from the 4,785 articles identified, 103,180 references were generated. Based on the data downloaded from the WOSCC database, on average, there are 22 citations for each article published about aquaculture and climate change.

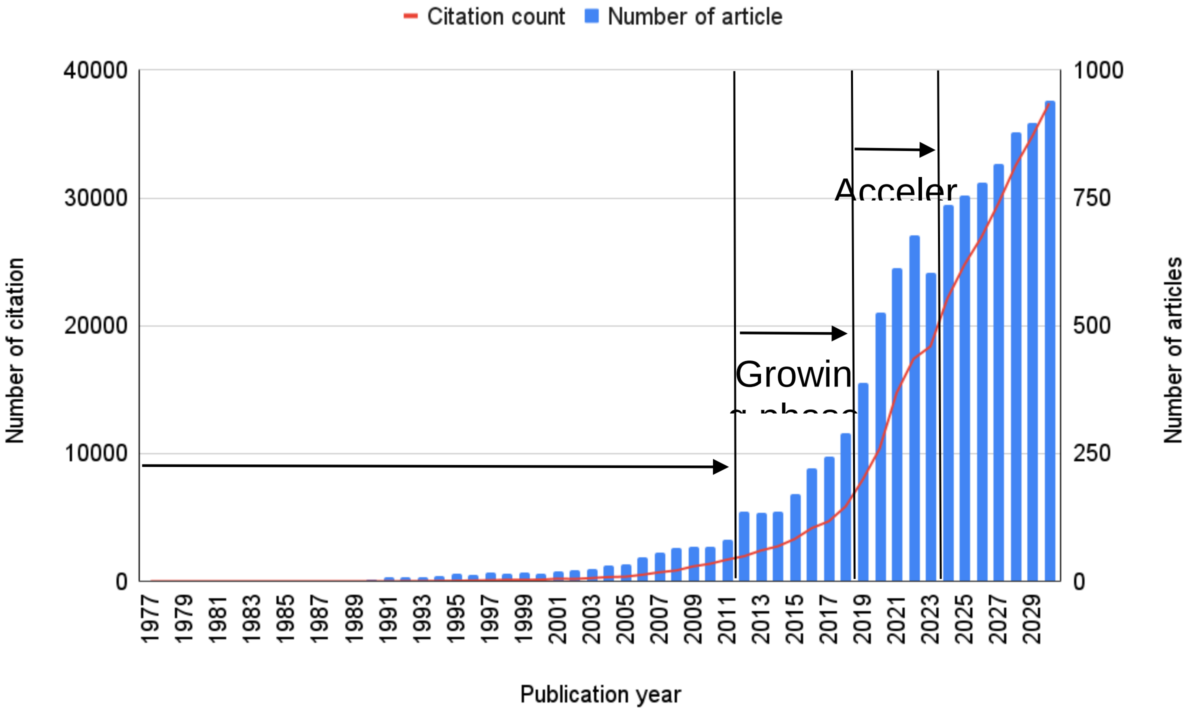


Figure 1. The evolution of total number and citation count for studies related towards aquaculture and climate change based on the web of science core collections database from 1977 until 2023 (*Calculation of the forecasting is according to the data generated during the accelerate phase)

Collaborative research between countries

Based on the results generated from the WOSCC database, a total of 73% of countries (143 countries per 195 total states or countries) have conducted research on aquaculture and climate change. China, the United States of America (USA), Australia, Canada, England, Spain, France, Norway, and Germany are the leading countries in research on aquaculture and climate change (Figure 2). In terms of publication volume, the top three countries are

China, the USA, and Australia with a total of 2,192 records. Based on the scientometric analysis, there is also a strong collaboration between the American continent and European countries, but a lack of network of collaboration found in and within African countries and continents.

Institutional analysis

Through institutional analysis, the Chinese Academy of Science (China) ranked first in terms of publication with 241 publications, starting in 2001, followed by Ocean University of China (China) and University of Chinese Academy of Science (China). The ranking of top most influential (highly cited and referred) organisations in aquaculture and climate change research are as follows: the Institute of Marine Research (Norway), the Chinese Academy of Science (China), the French National Institute for Ocean Science and Technology (France) and Plymouth Marine Laboratory (U.K.) (Figure 3).

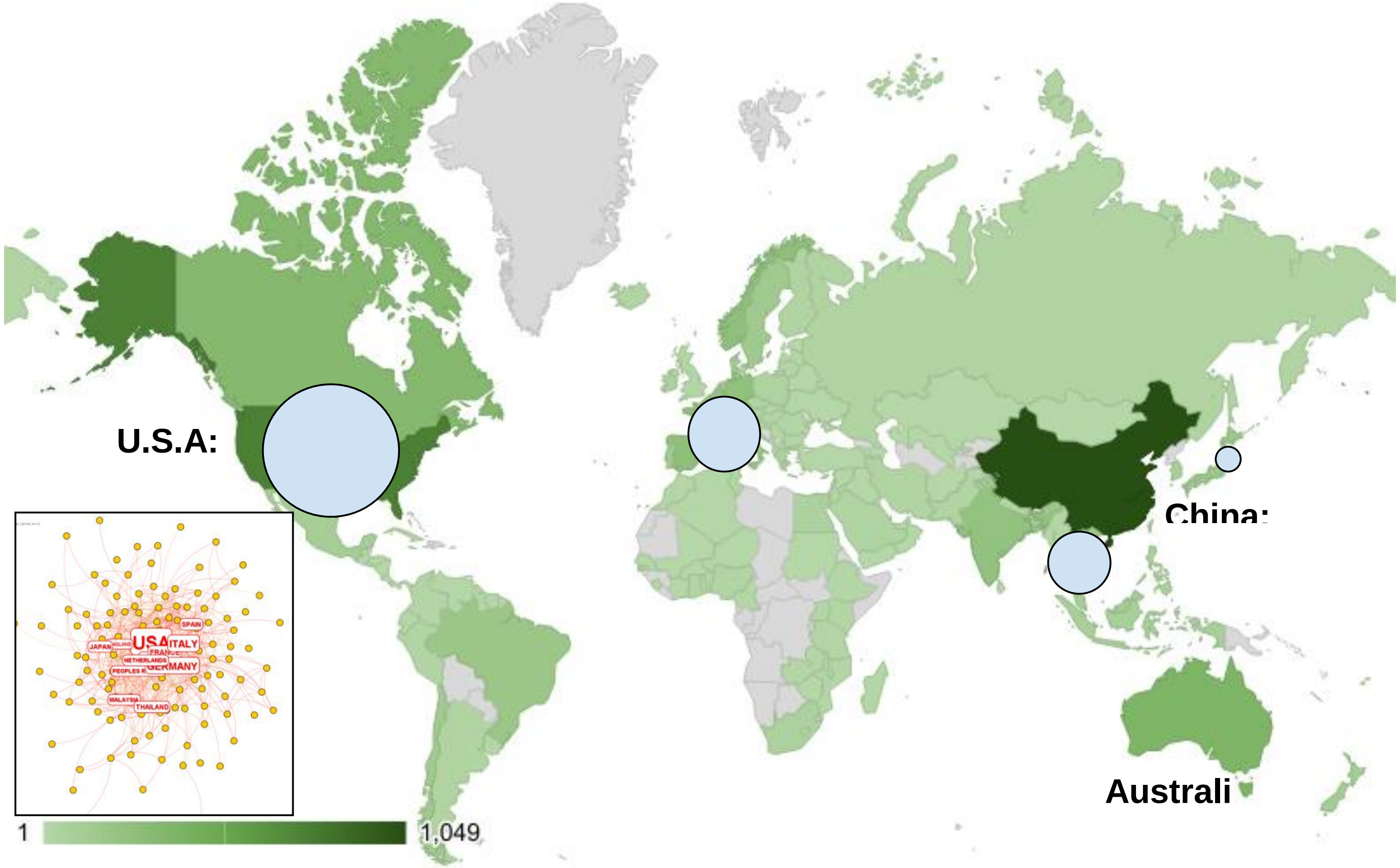


Figure 2. Nations publishing the most research on aquaculture under changing climate with most influential countries has been circle's marked, bigger circle shows higher influential collaboration countries (based on the small box within the figure, generated through centrality score at CiteSpace software)

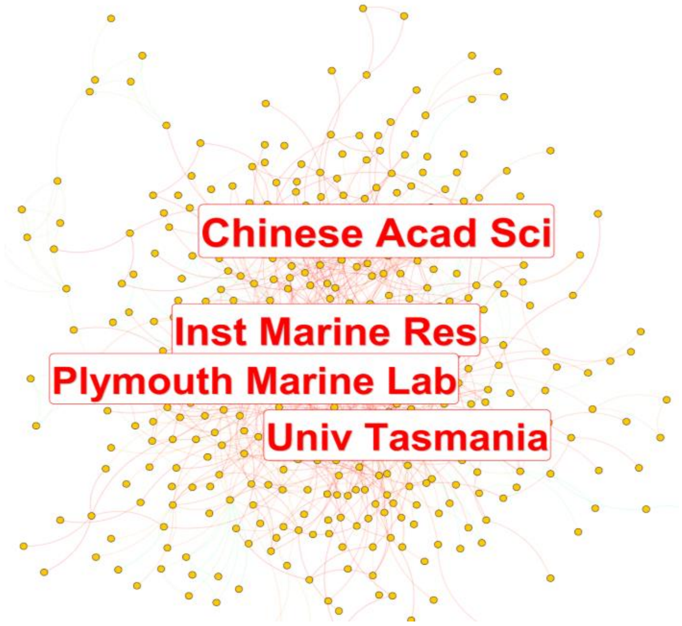


Figure 3. Top institution with higher centrality score in the field of aquaculture and climate change based on the downloaded metabase of Web of Science Core Collection

Document analysis

Table 1 presents the top five documents based on the descriptive dataset from Web of Science Core Collection search activities and scientometric analysis using the advanced version of CiteSpace. The articles are categorised into four groups: (i) highly cited references (co-citation analysis), (ii) most influential documents (highest centrality scores), (iii) most referred articles (highest degree values), and (iv) top five articles receiving direct citations according to the Web of Science search string.

Document burstness

Table 2 displays the top 10 document bursts related to aquaculture and climate change, as identified from metadata generated using the advanced version of the CiteSpace software on the Web of Science Core Collection database.

Table 1. Top 5 co-cited papers in terms of (i) highly counted citation in the reference section (co-citation), (ii) most influential documents (higher centrality score) and (iii) most referred articles (higher degree value) with additional information on (iv) top 5 articles that received direct citation based on the Web of Science search string

Reference (Type of article) - Count/Score/Value/ Citation number	Year	Journal / Sources (Highest Quartile WOS - 2022)	Regions	Climate change elements	Aquaculture activities
(i) Highly cited references or "co-citation" (based on the higher record count)					
FAO, Food and Agriculture Organization(Report) - 178	2022b	SOFIA Flagship Report (N/A)	Global	General	General
IPCC, Intergovernmental Panel on Climate Change (Report) - 61	2022	IPCC 6th Assessment Report (N/A)	Global	General	General
Yuan et al. (Letter) - 56	2019	Nature Climate Change (Q1)	China	Greenhouse gases emission	Conversion of paddy fields to aquaculture, Freshwater aquaculture
Breitburg et al. (Review) - 56	2018	Science (Q1)	Global	Global warming driven by greenhouse gas emissions, deoxygenation in open ocean	Aquaculture pen / Marine aquaculture

Naylor et al. (Review) - 52	2021	Nature (Q1)	Global	Most elements of climate change	General aquaculture
(ii) Most influential documents (based on the higher centrality score)*					
Handisyde et al. (Review) - 0.08	2017	Fish & Fisheries (Q1)	Selected countries	General climate	General aquaculture
Wade et al. (Original Research Article) - 0.05	2019	Journal of Thermal Biology (Q1)	Australia	Heatwave	Cage-farmed Atlantic salmon
FAO (Report) - 0.04	2014	SOFIA Flagship Report (N/A)	Case studies globally	Various elements, such as ocean acidification	General
Ayer & Tyedmers (Original Research Article) - 0.04	2009	Journal of Cleaner Production (Q1)	Canada	Net-pen salmon farming	Global warming, ocean acidification
Pelletier & Tyedmers (Original Research Article) - 0.04	2007	Aquaculture (Q1)	Canada	Salmon aquaculture	General
(iii) Most referred articles (based on the higher degree value)*					
Ahmed & Diana (Original Research Article)	2015a	Ocean & Coastal Management (Q1)	Bangladesh	Tiger shrimp aquaculture	Elements of climate variables

Barton et al. (Original Research Article)	2015	Oceanography (Q2)	U.S.A	Pacific oyster	Various elements, focused on ocean acidification
(iv) Article that received direct citation of article based on the Web of Science search string (Based on citation number)					
Orth et al. (Review) - 2,208	2006	Bioscience (Q1)	Global	Seagrass related culture	Extreme climatological events
Alongi (Review) - 1,194	2002	Environmental Conservation (Q2)	Global	Not related to aquaculture (Mangrove)	General
Croxall et al. (Review) - 818	2012	Bird Conservation International (Q2)	Global	Not related to aquaculture (Seabird)	Sea level rise
Brander (Review) - 615	2007	Proceedings of the National Academy of Sciences of the U.S.A (Q1)	Global	Aquaculture in general	Climate variability
Gazeau et al. (Original Research Article) - 547	2007	Geophysical Research Letters (Q1)	Netherlands	Mussel & Oyster	Carbon dioxide (CO_2)

*For most influential articles, the highest centrality score paper is the same from a highly cited document, the IPCC 2022, and replaced with the top six (No. 6) articles in the chronological order. Additionally, same also goes to the most referred article based on the centrality score (i.e., IPCC 2022).

Table 2 Top 15 document burstness generated by the CiteSpace software through the data downloaded at Web of Science Core Collection database from 1977 until 2023

References (Article Type)	Year	Strength value	Begin	End	Regions / Countries	Aquaculture Activities	Climate Change Elements	Summary
Food and Agriculture Organization (Report)	2020	43.01	2022	2023	Global	Aquatic plants & marine animals	General, mostly climate variability & seasonal changes	Sustainable development of aquatic resources, align with Sustainable Development Goals
Kroeker et al. (Original Research Article)	2013	12.81	2015	2018	Global	General, mostly marine life	Ocean acidification	Survival, calcification, growth, development & abundance reduce towards ocean acidification
Troell et al. (Perspective)	2014	11.8	2015	2019	Global	Marine aquaculture	General	Diversity in aquaculture system contributes towards the stability of world food system, especially the rising demand of food protein in the

								face of climate change
Richards & Friess (Original Research Article)	2016	11.03	2018	2021	Southeast Asia	Aquaculture major pressure on mangrove	Deforestation	Palm oil and aquaculture operation impacted the mangrove forest lost in Southeast Asia
Béné et al. (Review)	2015	10.57	2017	2020	N/A	General aquaculture production	General climatic change	Fisheries and aquaculture production deserves more attention compared to other forms of animal production
Béné et al. (Original Research Article)	2016	9.96	2018	2021	N/A	General aquaculture production	Climate induce change	Climate change as major driver in food protein, however insufficiently documented and poorly understood
Ekstrom et al. (Perspective)	2015	9.61	2016	2020	North American continent	Shellfish mollusc aquaculture and fisheries	Ocean acidification	Acidification caused by main drivers of the carbon dioxide is a threat of coastal species especially the mollusc aquaculture and fisheries
Barton et al. (Original Research Article)	2012	9.60	2014	2017	U.S.A	Pacific oyster	Ocean acidification	Carbonate chemistry impacted commercially important hatchery-based oyster production
Duarte et al. (Perspective)	2017	9.38	2021	2023	Global	Seaweed aquaculture	General climate change elements, focused on ocean	Seaweed aquaculture contribute towards ecosystem services and function adaptation benefit

							acidification	
Hamilton and Casey (Original Research Article)	2016	9.24	2018	2021	Global	Not directly related to aquaculture (Mangrove)	Deforestation	Continuous reduction rate for mangrove forest, especially at Southeast Asia regions
Gentry et al. (Original Research Article)	2017	9.21	2019	2023	Global	Marine aquaculture (mostly bivalve)	Sea surface temperature	Potential of marine aquaculture in increasing seafood production
Yang et al. (Original Research Article)	2015	9.12	2018	2020	China	Shrimp aquaculture	Greenhouse gas	Shrimp aquaculture as well as microalgae production could potentially contribute significantly towards greenhouse gases fluxes
Herbeck et al. (Original Research Article)	2013	9.01	2016	2018	China	Shrimp and fish aquaculture	Tropical monsoon, Agriculture runoff, Anthropogenic changes	Aquaculture ponds produce effluents, impacted the lagoon and reef ecosystem, harmful to seagrass and coral health
Allison et al. (Original Research Article)	2009	8.82	2012	2014	Least develop & small island	Focused on fisheries sector	Anthropogenic global warming	Vulnerability and adaptation strategies of selected countries towards impacts of climate change towards fisheries

					countries			
Barton et al.	2015	8.8	2017	2020	U.S.A	Pacific oyster	Ocean acidification	Acidification caused by the carbon dioxide impacted the bivalve aquaculture especially in U.S.A

*Unknown sources from the reference burstness was avoided to reduce confusion of the literature.

Keyword analysis

Based on the data generated from the WOSCC database, the most frequently used keywords in *“Title”*, *“Abstract”*, and *“Keywords"* with their citation counts is “Climate change”, “growth” and “aquaculture” with 793, 558, and 520 counts respectively, followed by “fish”, “temperature”, “impacts” and “ocean acidification”. Meanwhile, for the most influential keywords, the top listed with a centrality score above 0.05 is “fish”, “growth”, “aquaculture”, “temperature”, “Atlantic salmon”, “bay” and “seasonal variation”.

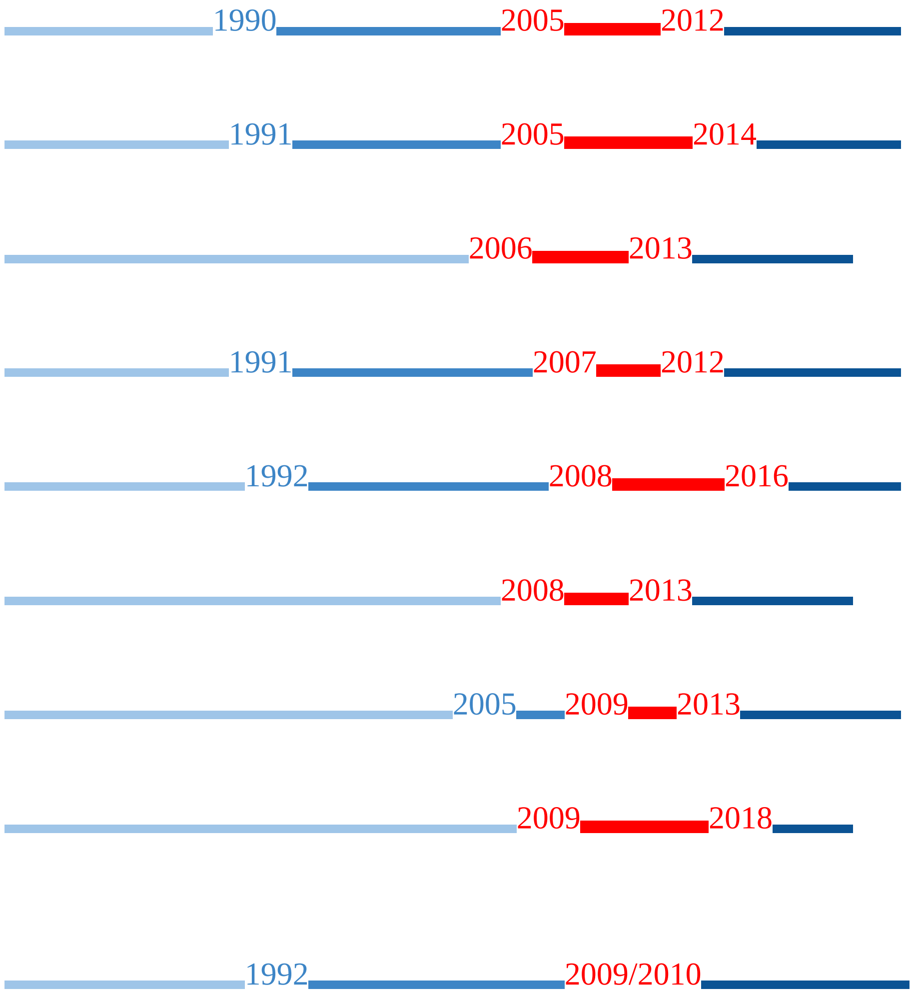
Keywords burstness

Table 3 displays the top 25 keywords based on citation bursts. The red line indicates the burst period while the blue line indicates the timeline (from 1977 to 2023). The burst analysis of keywords reveals that “seasonal-changes”, “biochemical composition” and “culture” are the top-ranked keywords with a strength of 13.95, 9.66 and 9.05 respectively.

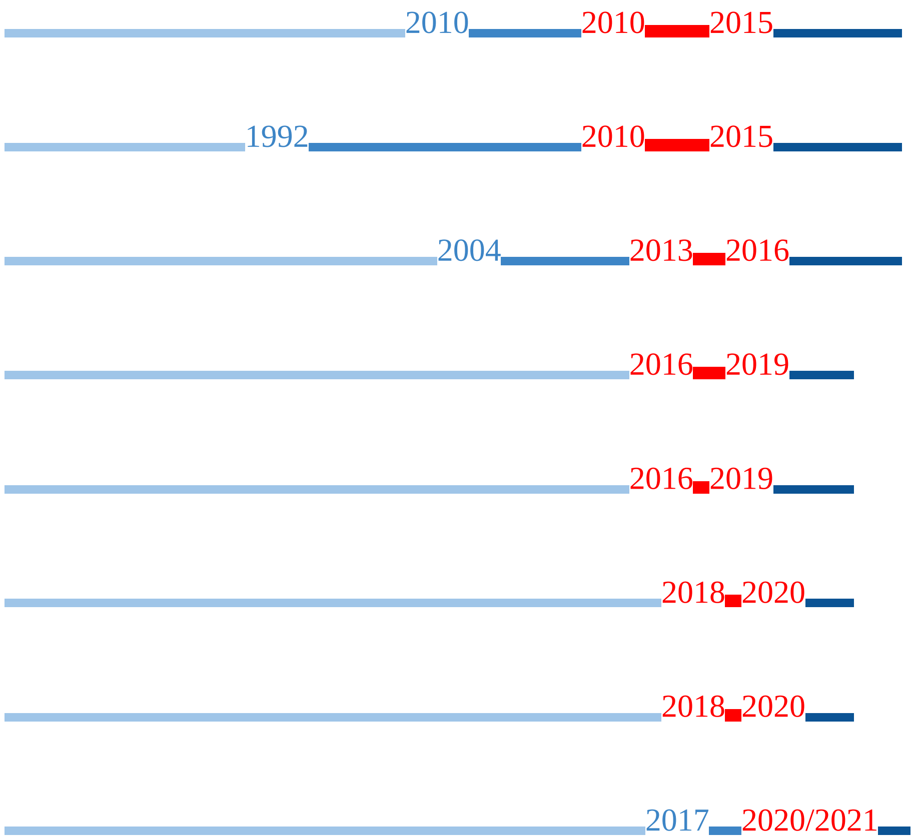
Table 3. Top 25 keywords burstness or also known as “sudden attracted keywords” in the research about aquaculture and climate change, sorting by the time of burstness

Keywords	Year	Strength	Begin	End	Period from established until the end (Years)	1977-2023
Seasonal changes	1997	13.95	1997	2014	18	1977 1997 2014 2023
Coast	1998	5.62	1998	2016	19	1998 2016
Biochemical composition	1999	9.55	1999	2018	20	1999 2018
Mytilus edulis	2003	8.49	2003	2010	8	2003 2010
Condition index	2003	6.49	2003	2013	11	2003 2013
Suspended culture	2003	6.27	2003	2011	9	2003 2011
Crassostrea gigas	1999	7.74	2004	2012	14	1977 1999 2004 2012 2023
Culture	1999	9.05	2005	201	17	1999 2005 2015

				5	
Populations	1990	5.98	2005	2012	23
Hypoxia	1991	5.32	2005	2014	24
Environmental impact	2006	8.23	2006	2013	8
Atlantic salmon	1991	7.78	2007	2012	22
Seasonal variation	1992	7.66	2008	2016	24
Water quality	2008	6.46	2008	2013	6
Ecology	2005	6.21	2009	2013	9
Trout *Oncorhynchus mykiss*	2009	5.62	2009	2018	10
Fish	1992	5.6	2009	2010	19



Management	2002	5.84	2010	2015	14
Rainbow trout	1992	5.67	2010	2015	23
Sediments	2004	5.50	2013	2016	13
Nitrous oxide	2016	5.41	2016	2019	4
Oxygen consumption	2016	5.34	2016	2018	3
Deforestation	2018	6.42	2018	2020	3
Freshwater fish	2018	5.52	2018	2020	3
Reproduction	2017	5.55	2020	2021	2



Research cluster based on references (co-citation)

Figure 4 displays a total of 14 major research clusters generated by the visualisation software, based on studies related to aquaculture and climate change conducted between 1977 and 2023.

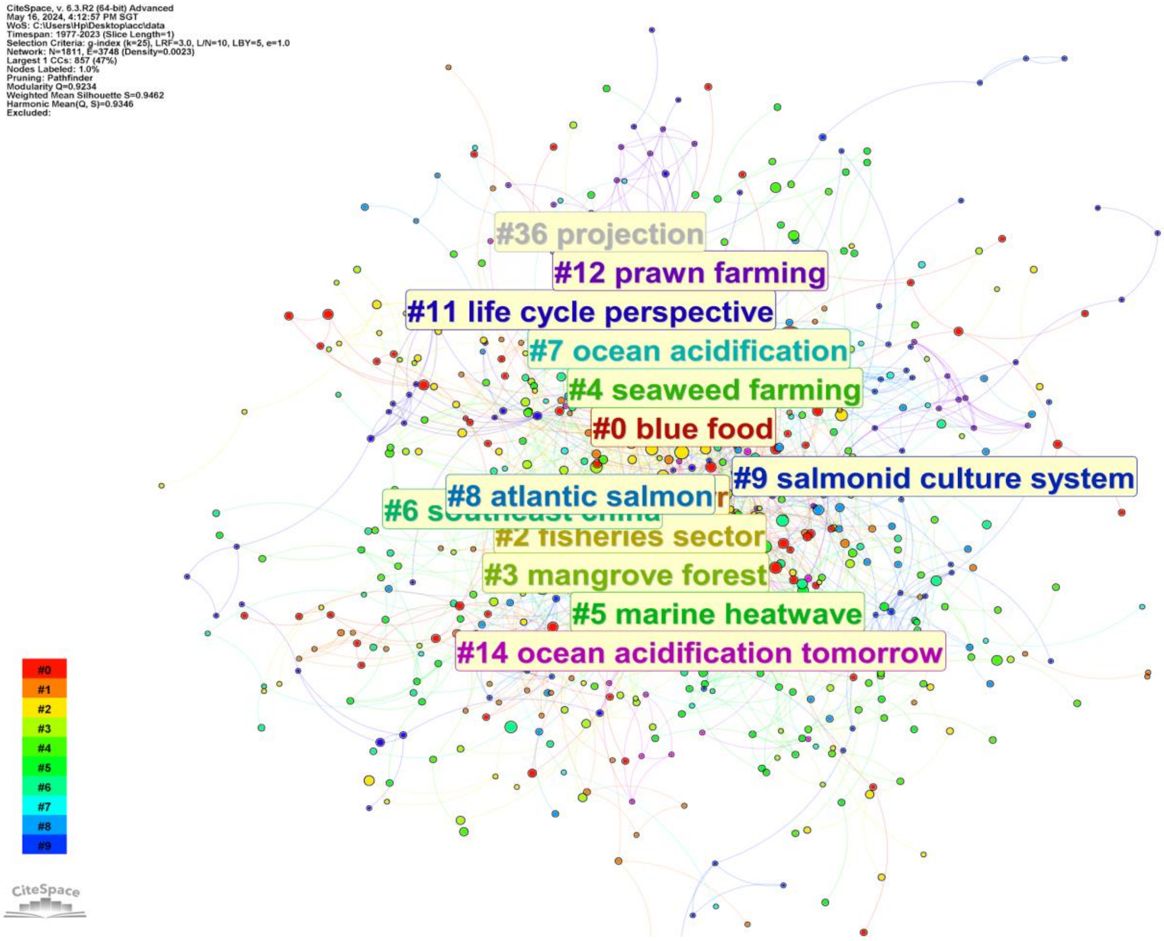


Figure 4. 14 major research cluster in the field of aquaculture and climate change

14 major clusters were generated from this scientometric analysis as shown in Figure 4. The biggest cluster (#0) has a size of 95 members and a silhouette value of 0.939. It is labelled as *"environmental performance"* by LSI, *"blue food"* by LLR, and *"rearing cycle"* by MI. The average year for this cluster is 2018 while the most cited article is by Jones et al. (2022). This article investigated the sources of greenhouse gas emissions and explored the possibility of reduction in emissions, while also assessing the capacity of carbon sequestration from seaweed, bivalve, and fed finfish aquaculture (mariculture) sector. Potential pathways to reduce greenhouse gas, carbon storage, and sequestration were highlighted in this article.

The second cluster (#1) has a size of 93 members and a silhouette value of 0.925. LSI labelled it as is labelled as *"arctic charr"* by both LSI and LLR, *"trophic level"* by MI. The average year for this cluster is 2009 while the major citing article is by Samuel-Fitwi et al. (2013), which utilises life cycle assessment (LCA) methodology to predict the environmental impacts of trout feed feed production from different protein sources. The results of the LCA indicated that plant protein-based feeds were the best option as they had minimal environmental impacts compared to other protein sources.

The third cluster (#2) has a size of 88 members and a silhouette value of 0.903. It is labelled as *“ocean acidification”* by LSI, *“fisheries sector”* by LLR, and *“Greek aquaculture”* by MI. The average year for this cluster is 2014 and the top cited article in this cluster is by Lemasson et al. (2019). An experiment was conducted whereby commercially important oysters *Magallana gigas* and *Ostrea edulis* were subjected to ocean acidification and ocean warming scenarios for a period of 12 weeks. The results indicated that ocean acidification and ocean warming affects the nutritional content of both species of oysters, with *M. gigas* being more vulnerable towards climate change.

The fourth cluster (#3) has a size of 77 members and a silhouette value of 0.914. It is labelled as *“mangrove forest”* by both LSI and LLR, and *“rearing cycle”* by MI. The average year for this cluster is 2015 and the most cited article in this cluster is Jones et al. (2022) as mentioned in cluster (#0).

The fifth cluster (#4) consists of 73 members with a silhouette value of 0.943. It is labelled as *“seaweed farming”* by both LSI and LLR, and *“formation-related carbon flow”* by MI. The average year for this cluster is 2019 while Fujita et al. (2023) is the most cited article whereby they utilised a system mapping process and literature review to characterise the risks and benefits of interventions with seaweed systems. Based on the results, conserving and restoring natural seaweed beds and increasing seaweed farm productivity and resilience are the best mitigation strategies as these are low-risk and provide social, economical, and ecological benefits as well. Other interventions require more data to be accessed.

The sixth cluster (#5) has a size of 70 members with a silhouette value of 0.955. It is labelled as *“European seabass”* by LSI, *“marine heatwave”* by LLR, and *“anti-oxidative responses”* by MI. The average year for this cluster is 2018 and the top cited article is by Islam et al. (2020). This article investigated the combined effects of extreme ambient temperature and hyposaline water on the growth performance, metabolic and molecular stress responses of European seabass, *Dicentrarchus labrax*. The results indicated European seabass copes under the combination of extreme temperature (33°C) and salinities of 12 PSU and 6 PSU. European seabass subjected to salinities of 32 PSU and 2 PSU showed lower growth performance, and higher antioxidant activities.

The seventh cluster is (#6) has a size of 63 members along with a silhouette value of 0.96. It is labelled as *“Southeast China”* by both LSI and LLR, and *“using floating chamber*” by MI. The average year for cluster (#6) is 2017 and the most cited article is by Yang et al. (2019). Yang et al. investigated the spatiotemporal variations of CH_4 water concentration and flux in shrimp ponds with different supply of organic matter and aeration in Southeast China. No significant differences were found among the different shrimp ponds but significant spatiotemporal differences in CH_4 concentration and flux were found within the ponds. This indicates that mitigation of CH_4 emission is possible by improving aeration and feeding practices.

The eighth cluster is (#7) has a size of 60 members and a silhouette value of 0.947. It is labelled as *“ocean acidification”* by both LSI and LLR, and *“rearing cycle”* by MI. The average year for this cluster is 2012 and the major citing article is by Cunningham et al. (2015). This study investigated the effects of elevated pCO_2 under different temperatures on the growth, shell production, and metabolism of juvenile abalone, *Haliotis iris.* The findings suggested that reduced pH in seawater driven by CO_2 negatively impacts the growth, shell production and metabolism of juvenile abalone.

The ninth cluster is (#8) has a size of 60 members along with a silhouette value of 0.981. It is labelled as *"altantic salmon"* by both LSI and LLR, and *"farmed Rohu labeo rohita"* by MI. The average year for this cluster is 2018 and the most cited article is by Beemelmanns et al., 2021. The study looked into the combined effects of moderate hypoxia and incremental temperature increase affects the stress- and immune-related transcriptional responses of Altantic salmon, *Salmo salar*. This study successfully identified 27 stress-related and 15 immune-related changes in transcriptional responses.

The tenth cluster is (#9) has a size of 59 members with a silhouette value of 0.992. It is labelled as *"life cycle assessment"* by LSI, *"salmonid culture system"* by LLR, and *"marine organic-enriched system"* by MI. The average year for this cluster is 2006 and the major cited article is Ayer and Tyedmers, 2009. This article quantifies and compares the impacts of salmonid culture systems in Canada by using life cycle assessment (LCA). The four salmonid culture systems included marine net-pen system, marine floating bag system, land-based saltwater flow-through system, and land-based freshwater recirculating system. The marine floating bag system is ranked as the most eco-friendly system as it requires less feed inputs, lower energy demand and availability of hydroelectric. However, the increase in material and energy demand may cause environmental impacts.

The eleventh cluster is (#11) consists of 45 members along with a silhouette value of 0.988. It is labelled as *"life cycle assessment"* by both LSI and LLR, and *"production system"* by MI. The average year is 2011 and the most cited article is by Aubin et al. (2015). This article investigated the environmental performance of brackish water polyculture of black tiger prawn, mud crabs, tilapia, and milkfish by using life cycle assessment (LCA). The results showed that milkfish have the highest impact in terms of energy-based allocation while black tiger prawn and mud crabs have the highest impact in terms of economic allocation.

The twelfth cluster is (#12) has a size of 38 members and a silhouette value of 0.942. It is labelled as *"Northern Thailand"* by LSI, *"prawn farming"* by LLR, and *"freshwater fish fry"* by MI. The average year for this cluster is 2011 and the major cited article is by Ahmed and Diana, (2015b). This study conducted a field research which used questionnaires interviews, focus group discussions, key informant interviews, and analytical hierarchy process to investigate the impacts of climate change on prawn farming in Bangladesh. Salinity, coastal flooding, cyclones, sea-level rise, water temperature, drought, and rainfall have profound effects on prawn farming. Translocation of prawn culture can be a solution to mitigate the impacts of climate change towards prawn farming. Likewise, many adaptive strategies could be employed, including tailored nutritional strategies to mitigate environmental fluctuations, and compensate for consequent changes in feeding behaviour and osmoregulatory pressures (Moss et al., 2024).

The thirteenth cluster is (#14) has a size of 27 members with a silhouette value of 0.969. It is labelled as *"ocean acidification tomorrow"* by both LSI and LLR, and *"developmental delay"* by MI. The average year for this cluster is 2009 and the top cited article is Cooley et al., 2011. In this study, the implication of ocean acidification towards mollusc was investigated by relating worldwide mollusc harvest data with a climate-ocean model. It is forecasted that 10-50 years after 2010, the mollusc harvest levels can no longer be guaranteed. Hence, it is recommended that countries with high nutritional and economic dependence on mollusc, low adaptability, rapidly increasing population and near to transition decades to implement strategies to maintain mollusc harvest.

The fourteenth cluster (#36) has a size of 9 members and a silhouette value of 0.998. It is labelled as *"coastal ecosystem"* by LSI, *"projection"* by LLR, and *"atlantic salmon"* by MI. The average year for this cluster is 2010 while the most cited article is by Gilbert et al., (2014). This article identified the relationship between the commercialisation of Haber-Bosch (HB) process and the occurrence of harmful algal blooms (HAB). The commercialisation of the HB process intensified the use of nitrogen (N) fertiliser worldwide. However, runoffs, leaching, and denitrification of nitrogen fertiliser lead to eutrophication which presents ideal conditions for harmful algal blooms. Suggested actions to control harmful algal blooms were to quantify the source and fluxes of nitrogen in order to improve nitrogen control.

General discussion

Descriptive analysis

The analysis of 47 years of research on aquaculture and climate change highlights a marked increase in publication activity over time, reflecting the growing recognition of the sector's vulnerability to climate change. Initially, from 1977 to 2011, research activity was limited, but a significant surge occurred from 2012 onwards, particularly between 2019 and 2023. This increase shows the escalating urgency to understand and address climate change impacts on aquaculture (IPCC, 2022; Barange et al., 2018). Notably, China, the USA, and Australia are the leading contributors, indicating their significant roles in advancing aquaculture research (Figure 2). The collaborative network analysis reveals strong intercontinental collaborations, particularly between North American and European countries, although there remains a notable gap in intra-African research collaborations (Maulu et al., 2021). This trend is indicative of the increasing global recognition of the critical need to develop resilient aquaculture practices in the face of climate change. These findings align with previous studies that emphasise the importance of international cooperation and knowledge exchange in addressing global environmental challenges (Ma et al., 2023). The explosion in research publications and citations on aquaculture and its interaction with climate-related changes could advance the Sustainable Development Goals by supporting healthier, more sustainable and equitable food systems, especially in regions vulnerable to climate impacts and food insecurity. Aquaculture is particularly susceptible to environmental challenges exacerbated by human activity, and climate change intensifies these threats, potentially undermining efforts to combat hunger and malnutrition in at-risk areas.

Rising temperatures

In aquaculture research, the critical intersection of rising temperatures with fish physiology and disease management emerges as a dominant theme, reflecting a shift necessitated by climate-induced changes. As our scientometric analysis indicates, keywords such as "growth," "temperature," and "aquaculture" remain central, which show the focus on adaptive strategies to mitigate the impacts of thermal stress (García Molinos et al., 2016). The evidence suggests that Atlantic salmon, frequently the focus of research, suffers dramatically under rising temperatures, which have increased oceanic warmth by approximately 0.13°C per decade, compounding stress and escalating mortality rates by 1.47-8.33% in oysters and 2.18-5.37% in fish due to viral infections (Combe et al., 2023; Pathirana et al., 2022). This aligns with broader trends that also highlight increased prevalence of harmful algal blooms and pathogenic microbes under warmer conditions (Ma et al., 2021). The vulnerability of aquaculture species to thermal stress is further illustrated through physiological studies on species like pikeperch and lenok. Pikeperch exposed to elevated temperatures showed significant histopathological changes and upregulation of stress-responsive proteins, suggesting a robust yet possibly overwhelmed stress response (Chen et al., 2020). Similarly, lenok fish displayed drastic shifts in metabolism under thermal stress, and this might emphasise the need for enhanced understanding and management of energy allocation under varying temperatures (Liu et al., 2019). These physiological insights are important for developing advanced management strategies. For instance, the European seabass has demonstrated better resilience under adjusted salinity conditions during heatwaves, suggesting that environmental manipulation can be a potent tool for mitigating thermal stress (Islam et al., 2020). Moreover, genetic and epigenetic research in species like the ridgetail white prawn show the potential of breeding and nutritional strategies to enhance thermal tolerance, further supported by successful dietary interventions in striped catfish which boosted immune responses and growth performance under heat stress (Mahmoud et al., 2023; Shi et al., 2020). Based on these insights, it becomes clear that the future of aquaculture under climate change hinges on a multi-disciplinary approach that integrates physiological, genetic, and environmental strategies to promote resilience. Our scientometric analysis not only corroborates these findings but also emphasises the escalating research focus on thermal tolerance and stress mitigation. This comprehensive view informs the need for a global strategy that not only addresses immediate thermal stress but also anticipates future challenges through proactive research and policy adaptations. Therefore, the consistent increase in temperature-related research and the severity of thermal impacts call for a shift towards thermal resilience breeding programs. These programs would aim to systematically breed and manage aquaculture species not only for immediate productivity but also for long-term resilience to temperature extremes, a concept that combines traditional breeding techniques with modern genetic insights to safeguard the future of aquaculture in a warming world.

Extreme weather events

Recent studies highlight the acute sensitivity of aquaculture systems to extreme weather events, evidenced by significant economic losses in regions such as coastal Andhra Pradesh, India, and Mozambique. For instance, cyclones and floods have led to economic devastations in shrimp aquaculture in India, with losses ranging from 50% to 100%, while Mozambique experienced similar devastation due to cyclones Idai and Kenneth in 2019 (Muralidhar et al., 2021; Muhala et al., 2021). These events not only cause direct infrastructure damage but also lead to long-term disruptions in production cycles and economic stability, emphasising the urgency for enhanced resilience strategies within the sector. This scientometric analysis further reinforces the global relevance of these challenges, showing that climate change is increasing the frequency and intensity of such extreme weather events. This growing body of evidence necessitates robust and adaptive management strategies to safeguard aquaculture operations. Prominent among these strategies are improved vaccination protocols, selective breeding for resilience, and adaptive nutrition strategies, which are crucial for mitigating impacts of severe and unpredictable weather (Turchini & Nie, 2020). Moreover, examples from Kenyan smallholder farmers and UK agriculture demonstrate localised adaptation measures, including water management and soil health improvement, highlighting a trend towards integrating resilience strategies at both local and global scales (Kalele et al., 2021; Wheeler & Lobley, 2021). The focus on extreme weather impacts within the scientometric analysis illustrates a critical need for a systematic approach to climate resilience in aquaculture. This includes not only infrastructural adaptations but also policy interventions that facilitate sustainable practices and enhance the sector's overall resilience. Such policies should encourage the adoption of advanced technological solutions and promote international cooperation to manage and mitigate the risks associated with extreme weather conditions effectively. Therefore, the integration of comprehensive risk assessment models should become a standard practice within the aquaculture sector. These models would not only forecast the impacts of extreme weather events but also guide the development of tailored adaptation strategies that enhance the resilience of aquaculture systems worldwide, thus safeguarding food security in the face of increasing climate variability.

Hypoxia

Hypoxia emerges as a profound threat to aquaculture, particularly in nutrient-rich coastal regions where it leads to significant ecological and economic impacts. Studies indicate that hypoxic conditions, often compounded by elevated temperatures and nutrient loading from agricultural runoff, catalyse mass die-offs of aquaculture species such as fish and invertebrates, thereby disrupting marine ecosystems and their economic viability (Barange et al., 2018; Grantham et al., 2004). Our scientometric analysis has identified "hypoxia" as a recurrent keyword in influential articles over the past two decades, and this highlights its critical importance and persistent presence in aquaculture and climate change research. This reflects a growing recognition of hypoxia's impact on aquatic environments, evidenced by the detrimental effects on species like Atlantic salmon, where increased temperatures and hypoxia synergistically reduce feed intake and growth (Gamperl et al., 2020). Furthermore, deforestation, another keyword highlighted by our analysis, exacerbates these hypoxic conditions by increasing nutrient and sediment runoff into aquatic systems, which heightens oxygen consumption and disrupts the habitat of freshwater species. The associated rise in nitrous oxide levels can further impair reproductive success, indicating a complex interplay of environmental stressors that affect aquatic life (Scavia et al., 2019). Mitigation strategies, such as improving water circulation, reducing nutrient loads, and utilising oyster aquaculture to naturally ameliorate hypoxia by reducing sediment oxygen consumption, have been suggested. For instance, oyster farming over an area of 10 to 200 km^2 could reduce hypoxic volume significantly, demonstrating a tangible approach to combat this issue (Yu & Gan, 2021). Recent research promotes the need for comprehensive management approaches to mitigate hypoxia. These include maintaining optimal oxygen levels to support the health of species such as pikeperch, whose immune response deteriorates under chronic hypoxia (Schäfer et al., 2021). Additionally, environmental hypoxia impacts on rainbow trout demonstrate the broader physiological challenges faced by aquaculture under such conditions, including growth retardation and calcium dyshomeostasis (Hou et al., 2019). These findings, corroborated by our scientometric analysis, emphasise the urgency of integrating adaptive management strategies that address not only hypoxia but also the contributing factors like deforestation and nutrient runoff. Therefore, moving forward, there is a pressing need for an integrated environmental management framework in aquaculture. This would strategically combine hypoxia mitigation with broader environmental management practices, including reforestation and advanced nutrient management. Such a framework would not only tackle the direct impacts of hypoxia on aquaculture productivity but also address the root causes of environmental degradation that exacerbate this condition, ensuring a sustainable future for aquaculture in the face of escalating climate challenges.

Ocean acidification

Ocean acidification, another issue highlighted in our scientometric analysis, emerges as a critical threat to aquaculture, particularly affecting marine calcifiers like shellfish and corals. This phenomenon, driven by increased atmospheric CO_2 levels, results in lower seawater pH and reduced carbonate ion concentrations, which are crucial for the calcification processes of marine organisms. The analysis highlights its prominence within various research clusters, particularly noting its impact on species such as oysters (*Magallana gigas* and *Ostrea edulis*) and abalones (*Haliotis iris*), which face significant challenges in shell formation and overall survival (Fitzer et al., 2019; Barton et al., 2015). Research anticipates that by 2100, ocean acidification could reduce calcification rates by up to 25%, leading to substantial economic repercussions, with potential losses ranging from $16.08 billion to $498.28 billion in Asian mollusk farming (Yu, 2019; Narita et al., 2012). This substantial economic impact reflects the broader ecological disruptions that acidification can cause, affecting everything from spat settlement to the survival rates of juvenile and adult stages of key aquaculture species. Further, our analysis reveals that additional aquaculture species like clams and cockles also show potential vulnerability to changing ocean chemistries, and this emphasises the need for comprehensive mitigation strategies (Leung et al., 2022; Byrne and Fitzer, 2019). Current research supports adaptive strategies such as selective breeding for acidification-resistant traits and environmental treatments within hatcheries to enhance resilience to acidification. For instance, selectively-bred oyster families have shown the ability to alter their biomineralization pathways, which could serve as a critical adaptation mechanism in the face of ongoing acidification (Fitzer et al., 2019). Moreover, the use of precision aquaculture practices, including real-time monitoring and automated control systems, is advocated to optimise environmental conditions and mitigate the impacts of acidification on susceptible species (Fujii et al., 2021). Molecular and biochemical responses to acidification also highlight potential resilience pathways for marine organisms. For example, despite the disruptive effects on shell structure, mussels have exhibited molecular compensatory responses that may mitigate adverse impacts, suggesting an inherent potential for resilience that could be leveraged through targeted research and technology (Zhao et al., 2019). Therefore, past findings along with this scientometric analysis suggest that an adaptive biomineralization initiative in aquaculture would be beneficial and it would focus on enhancing the resilience of marine calcifiers to ocean acidification through advanced genetic and biotechnological interventions aimed at optimising biomineralization processes under acidified conditions. This would not only help sustain aquaculture production in the face of acidification but also contribute to broader efforts to maintain marine biodiversity and ecosystem functionality.

Scientometric view

The scientometric analysis of aquaculture and climate change research reveals a dynamic and globally diverse academic landscape, wherein approximately 70% of the leading institutions publishing in this field are based in China. This indicates China's significant contribution and influence in aquaculture research, particularly in the context of climate change challenges such as global warming, extreme weather events, and coastal acidification (IPCC, 2022; Barange et al., 2018). Meanwhile, institutions from Europe, Australia, and Canada, despite representing a smaller proportion of the total, are recognised for their high centrality scores, and this shows their pivotal roles in pioneering research and setting international standards in the field. This comprehensive mapping identifies 14 major research clusters that encompass a wide range of topics from environmental performance to seaweed farming and ocean acidification, reflecting the diverse challenges and innovative responses within the sector. Notably, key studies by Jones et al. (2022) and Lemasson et al. (2019) highlight critical issues such as greenhouse gas emissions and the impacts of ocean acidification on marine calcifiers, pointing towards a need for integrated and sustainable aquaculture practices that address both environmental impact and productivity. Further evidence from the analysis shows the effectiveness of IMTA systems and Recirculating Aquaculture Systems (RAS) in enhancing environmental sustainability. IMTA, for instance, utilises the synergistic capabilities of macroalgae and shellfish to reduce waste and improve water quality, demonstrating significant benefits in nutrient cycling and carbon sequestration (Angel et al., 2019; Bennett et al., 2023). Similarly, RAS are highlighted for their potential to reduce habitat destruction and water pollution, although they face challenges related to energy consumption and greenhouse gas emissions (Ahmed & Turchini, 2021; Bergman et al., 2020). The scientometric findings and current literature collectively show the need for advancing aquaculture practices to meet global sustainability goals. They reveal a sector at the frontier of addressing climate change impacts through technological innovation and sustainable practices such as carbon sequestration in seaweed farming and optimised feed utilisation in RAS. Therefore, the convergence of scientometric insights with ongoing research suggests the adoption of diverse aquaculture practices to optimise resource use and minimise environmental impacts but also embed resilience and adaptability at the core of aquaculture systems to address the multifaceted challenges posed by climate change. This would require research and technology to promote pathways for sustainable growth and environmental stewardship in aquaculture globally, ensuring that it contributes effectively to food security and ecological balance.

Co-citation analysis

The present study included a co-citation analysis of the article's references, examining various metrics such as centrality score and degree value (Table 1). Notably, the scientometric analysis highlighted a comprehensive report slated for publication in 2022 by the IPCC Working Group II. This group is focused on drafting the 6th Assessment Report, which delves into the current understanding of climate change impacts and associated risks across various sectors and regions. The anticipated high citation rate of this report stems from several factors: (i) its thorough, interdisciplinary analysis crafted by experts like Hans-Otto Portner, a co-chair and Professor of climatologist, (ii) its emphasis on adaptation strategies previously underexplored, and (iii) its policy-relevant recommendations aligned with frameworks like the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement. Interestingly, the study found that most of the central documents are "original research articles," in contrast to the highly cited works, which are predominantly reports and review articles. This distinction likely arises because review articles, which synthesise multiple studies, serve as a crucial resource across various scientific communities and are often used as primary references in new research projects (Miranda and Garcia-Carpintero, 2018).

Burstness analysis

The document burstness analysis revealed that the most impactful literature comes from the Food and Agriculture Organisation’s flagship report, The State of World Fisheries and Aquaculture (SOFIA, FAO, 2020). This report garnered significant attention between 2022 and 2023, as various authors and scientists emphasised its relevance to achieving the Sustainable Development Goals (SDG 2030). The analysis also highlighted that two key climate change factors, ocean acidification and deforestation, are frequently associated with aquaculture in the existing literature. Additionally, the analysis identified Southeast Asia as a critical region for aquaculture research, likely because it accounts for approximately 22% of global aquaculture production. Notably, the most influential documents within this body of research pertain to "Life Cycle Assessment" studies, which show their importance in understanding the environmental impacts of aquaculture.

Cluster analysis

Research cluster #0, labelled "blue food," represents the largest thematic group in the study of aquaculture and climate change. "Blue" foods are crucial for global food protein supplies and food security, supporting the livelihoods, cultures, and economies of over 3.2 billion people (Cao et al., 2023). This analysis identified a total of 14 distinct research themes, including blue food, arctic charr, fisheries sector, mangrove forest, seaweed farming, marine heatwaves, Southeast China, ocean acidification, Atlantic salmon, salmonid culture systems, life cycle perspectives, prawn farming, future projections of ocean acidification, and climate projections. Notably, the "seaweed farming" cluster, tagged as Cluster ID #4, along with the "Atlantic salmon" theme, identified as Cluster ID #8, highlight that these aquaculture activities are significantly affected by climate change. Additionally, Cluster ID #36, focusing on projections, shows the critical need for future-oriented climate change research related to aquaculture activities.

Conclusion and recommendations

This scientometric review, based on an analysis of 4,785 articles and 224,895 cited references, presents a detailed synthesis of the current scope and depth of research on aquaculture in the context of climate change. Using the Dual Map Overlay in CiteSpace software, this study identifies the interdisciplinary connections across "Ecology, Earth, Marine," "Environmental, Toxicology, Nutrition," "Veterinary, Animal Science," and "Plant, Ecology, Zoology, Geology, Geophysics." This breadth highlights the diverse nature of aquaculture research, encompassing a range of disciplines necessary to address the multifaceted challenges posed by climate change. Table 4 summarises the findings of this scientometric analysis.

Ocean acidification and its impact on the cultivation of bivalves and seaweed emerged as a significant research focus, reflecting growing concerns over its effects on marine calcifiers crucial to aquaculture productivity. Similarly, the keyword 'warming' dominates, aligning with its critical role in influencing research trajectories within the field. The persistent emphasis on 'seasonal variations' – noted for nearly 24 years of consistent focus – underscores the importance of understanding temporal environmental patterns on aquaculture activities.

Despite China's dominance in publishing, our analysis reveals a more collaborative research network in North America and Europe, highlighting the potential for increased cooperative efforts in regions like Southeast Asia and Africa. These areas, currently underrepresented, could benefit significantly from enhanced funding and collaborative research to develop resilient and sustainable aquaculture systems capable of adapting to climate change impacts.

Our findings show the need for further investigation into the impacts of deforestation and land-use changes on aquaculture, particularly how altered water flows and increased sedimentation contribute to broader ecosystem changes like hypoxia and nutrient pollution. Research should also explore adaptive strategies that integrate climate resilience into aquaculture practices, such as selective breeding for traits conducive to survival under altered environmental conditions and the development of Integrated Multi-Trophic Aquaculture (IMTA) systems to optimise resource efficiency and ecological balance.

Moreover, the research clusters identified through scientometric analysis emphasise the need to expand on innovative approaches like genetic engineering and biotechnological advancements to enhance the stress tolerance of aquaculture species. This would address critical gaps in current research and lead to practical applications that mitigate the adverse effects of climate factors like ocean acidification and warming. Therefore, this extensive review calls for a strategic shift towards more holistic, integrated research approaches that encompass ecological, technological, and socio-economic dimensions. Ensuring the sustainability and expansion of aquaculture in the face of escalating climate challenges will require robust, evidence-based strategies and international collaboration, highlighting the essential role of aquaculture in global food security in an era of environmental uncertainty.

Table 4. Insights for enhancing aquaculture resilience to climate change

Category	Insights and Recommendations	Key Evidence/Source
Research Needs	1. **Impact of Deforestation:** Explore how deforestation impacts aquatic environments, especially on water quality, sedimentation, and resultant hypoxia.	Persistent focus on "deforestation" in scientometric results; identified as a bursting keyword indicating increasing research focus.
	2. **Ocean Acidification Mitigation:** Develop targeted methodologies to mitigate effects of acidification on marine calcifiers, focusing on physiological and molecular resilience.	Studies on "ocean acidification" underline the urgent need for mitigation strategies, particularly affecting shellfish calcification (Scientometric clusters on marine ecology).
	3. **Climate-Resilient Species Development:** Accelerate genetic and biotechnological research to develop species resilient to extreme climatic variables.	Emphasis on "warming" resilience as driven by the recurring presence of this keyword in climate-related research impacting aquaculture (Scientometric analysis).
Current Trends	1. **Integrated Multi-Trophic Aquaculture (IMTA):** Promote IMTA to improve sustainability through enhanced nutrient cycling and waste reduction.	IMTA identified a significant trend within "environmental performance" research clusters (Scientometric analysis).
	2. **Precision Aquaculture Advances:** Apply advanced technologies for real-time monitoring and automated controls to optimise aquaculture conditions.	Growing references to "precision aquaculture" and "real-time monitoring" indicate a shift towards high-tech solutions in aquaculture (Scientometric mapping).

	3. **Adaptation to Extreme Weather Events:** Develop strategies and infrastructure improvements to protect aquaculture from increasing extreme weather threats.	Frequent references to "extreme weather events" in environmental impact and resilience clusters (Scientometric analysis).
Future Prospects	1. **Strengthen Global Research Collaborations:** Facilitate enhanced international partnerships, especially involving underrepresented regions like Southeast Asia, Africa, and SIDS.	Discrepancies in global research output and collaboration highlight the need for increased international partnership (Scientometric insights).
	2. **Development of Resilient Systems:** Develop aquaculture systems integrating traditional and scientific innovations to respond effectively to climatic stressors.	Focus on resilience in research clusters emphasises the need for systems adaptable to climatic variability (Analysis of key trends and clusters).
Recommendations	1. **Enhanced Sustainable Management Practices:** Implement sustainable practices significantly reducing environmental impact, focusing on adaptive feeding strategies and optimised nutrient management.	Support from the literature on improved management practices aimed at minimising environmental impacts (Scientometric results and reviews).
	2. **Promotion of Genetic and Environmental Adaptations:** Encourage selective breeding and environmental adjustments in hatcheries to foster species resilience to environmental stressors.	Evidence from selective breeding and environmental control studies highlights their effectiveness in enhancing species resilience (Scientometric clusters).

	3. **Global Cooperation and Policy Innovation:** Advocate for enhanced international cooperation and cohesive policy frameworks supporting sustainable aquaculture practices globally.	Calls for international policy alignment and cooperative efforts to address climate impacts on aquaculture (Scientometric insights).

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