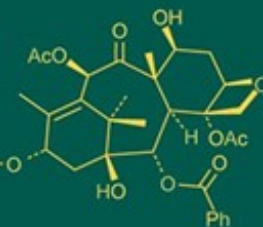
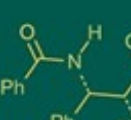
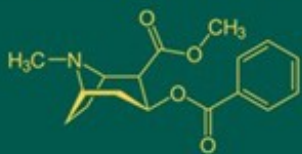


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Addressing climate change effects on aquaculture nutrition: A review of fish feed ingredients and adaptation approaches: a review

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ABSTRACT

The aquaculture industry is experiencing rapid global expansion. It provides a sustainable way to meet this demand by supplementing or even replacing wild-caught fish, which are often overexploited and at risk of depletion. The primary aquaculture operations worldwide largely depend on the surrounding ecosystem and environment functionality, highlighting their susceptibility to climate-related challenges. Hence, it's crucial not to overlook the issues arising from climate change when cultivating aquatic animals. Feed constitutes a substantial input in aquaculture practices. Intensive aquaculture farming and other aquaculture methods depend significantly on feed to ensure the growth and well-being of the cultivated aquatic organisms. Climate change has impacted the production, distribution, and composition of feed ingredients utilized in aquaculture. The quality and quantity of ingredients are also experiencing change due to the effects of climate change. Managing the nutrition of aquaculture will indeed present a formidable and intricate challenge to tackle. This review succinctly discusses various feed ingredients utilized in aquaculture and analyzes the effects of climate change on these components. Furthermore, it explores potential future feed ingredients and dietary immunostimulants that could help to cope with the changing climatic conditions in the aquaculture sector.

Keywords: Climate Change, Aquaculture, Sustainability, Feed Ingredients, Immunostimulants

1 Introduction

In the twenty-first century, the aquaculture and fisheries sectors have acquired significant acknowledgment for their crucial role in enhancing worldwide food security and nutrition. In 2020, the worldwide production of aquatic animals was estimated at 178 million tonnes. Capture fisheries produced 90 million tonnes, making up 51 percent of the total, while aquaculture contributed 88 million tonnes, comprising 49 percent. The average consumption of aquatic animal foods per person increased by approximately 1.4 % per year, rising from 9 kg in 1961 to 20.5 kg in 2019 (FAO, 2022) [1]. Feed is widely regarded as the most crucial input for boosting fish production. It is a matter of significant concern because it constitutes a major recurring expense and also influences the yield and determines the value of farmed fish (Naseem *et al.*, 2021) [2].

Diets, alongside other factors, significantly influence stress tolerance and overall health in fish. Therefore, to ensure optimal growth and resilience against stress and disease, it's imperative to provide fish with diets that fulfill all their nutritional requirements in sufficient quantities (Oliva-Teles 2012) [3]. Climate change is widely recognized as a significant risk to global food security, affecting both the quantity and quality of food available (Kumar *et al.*, 2023) [4]. The anticipated effects of climate change on all fishing endeavors, encompassing both aquaculture and capture fisheries, are forecasted to be severe. These effects comprise elevated water temperatures, heightened water acidity, and the relocation of species from their traditional habitats to new locations (Hall, 2015) [5]. A diverse array of fish species, regions, and aquaculture systems are vulnerable to severe temperature fluctuations induced by climate change, including heat waves and cold snaps. Notably, some of the most impacted areas are among the world's largest aquaculture producers. For instance, Egypt, Vietnam, China, Bangladesh, and certain areas in the Mediterranean such as Italy, Turkey, and Spain are projected to be highly vulnerable to these extreme climatic change (Islam *et al.*, 2022) [6]. The consequences of changing climatic conditions will likely present numerous obstacles to aquaculture endeavors. Contemporary aquaculture operations mainly utilize feed-based production systems, with feed serving as a significant input comprising approximately 30–70% of operational expenses (Naseem *et al.*, 2021; Pailan *et al.*, 2023) [2, 7]. Close to 70% of aquaculture-based fish production depends on feed supply (Tacon *et al.*, 2011) [8].

Large-scale aquaculture operations globally predominantly depend on the surrounding environment and ecosystem functions, making them susceptible to the adverse impacts of climate change. Consequently, the in

fluence of climate change on aquaculture cannot be disregarded (Pailan *et al.*, 2023) [7]. Rising worldwide temperatures certainly impact individual fish by modifying physiological functions, including metabolism, thermal tolerance, reproductive success, growth, food consumption, and the ability to sustain internal homeostasis amidst a fluctuating outside environment (Ficke *et al.*, 2007) [9]. At this crossroads, the aquaculture industry faces the dual pressures of meeting global food demand and addressing the consequences of climate change. The need for sustainable, climate-proof fish feed solutions has never been more critical. Traditional fish feed ingredients, such as fish oil and fishmeal, are becoming increasingly scarce and costly because of overfishing, habitat destruction, and changing ocean conditions (Kumar *et al.*, 2023) [4].

Future fish diets will incorporate a broader array of alternative ingredients to fishmeal compared to the present. Most of these ingredients are more complex than fishmeal, necessitating comprehensive assessment to ascertain their nutrient content and suitable inclusion concentrations within potential diets (Glencross *et al.*, 2007) [10]. In fluctuating climatic conditions, metabolic and physiological responses undergo alterations, necessitating increased energy intake from food. Hence, it's essential to devise a nutritional plan to effectively manage this phenomenon. The quality of feed could also impact the adjustment to climate stressors (Pailan *et al.*, 2023) [7]. Given the evolving climate conditions, sustaining the growth of aquaculture poses significant challenges, particularly concerning the nutritional and feed management of cultivated aquatic species.

Research on the impact of climate change on fish nutrition, especially the feed ingredients is a dynamic field with ongoing studies exploring various aspects of this complex issue. In an earlier review, Rahman *et al.* (2018) made a thorough review discussing the broader consequences of climate change on aquaculture, including implications for feed availability, feed conversion efficiency, and fish growth and health, and explored adaptation and mitigation strategies to strengthen the resilience of aquaculture. However, the necessity of a detailed review highlighting the impacts on fish feed ingredients is still unexplored. Against this backdrop, this review provides insights into the consequences of climate change on the availability of feed components, and feeding options of fish. Further, this review explores innovative and sustainable alternatives that can help secure the future of aquaculture.

2. The impact of climate change on aquaculture

Aquaculture serves as a means to attain long-term viability in the output of aquatic goods. Given the ongoing unsustainable depletion of resources from capture fisheries, the aquaculture industry is increasingly viewed as the sole resolution to fulfil the growing global request for aquatic goods (Maulu *et al.*, 2021; Pailan *et al.*, 2023) [11, 7]. Fisheries and aquaculture pay particular attention to plants and poikilothermic animals because they are highly susceptible to temperature variations in their surrounding environment, which are increasingly influenced by climate change (Kumar *et al.*, 2023) [4]. The primary concern at present revolves around whether the industry is expanding sustainably and rapidly adequate to cope with the projected future need, which is further exacerbated by the swift growth of the human population and the altering climate (Myers *et al.*, 2017; Maulu *et al.*, 2021) [12, 11].

Climate change denotes alterations in the statistical patterns of weather over prolonged periods, usually spanning from decades to millions of years (Yazdi and Shakouri, 2010) [13]. Furthermore, the solubility of oxygen (O₂) in water demonstrates a negative correlation with water temperature (Ficke *et al.*, 2007) [9]. The consequences of climate change on the sustainability of aquaculture have attracted significant attention due to the industry's substantial involvement in world food security, nutrition, and livelihoods (Dabbadie *et al.*, 2019; Maulu *et al.*, 2021) [14, 11]. Climate change exacerbates the complexity and uncertainty of aquaculture systems, potentially leading to a range of unfavourable conditions (Galappaththi *et al.*, 2020) [15]. One significant ramification of climate change is the global limited avail-

ability of fresh water, which adversely impacts aquaculture productivity and intensifies the demand for water resources (Turrall *et al.*, 2011) [16]. The physiology of fish is closely intertwined with temperature, as they have evolved to adapt to specific hydrological conditions and ecological niches. Consequently, their physiology and life cycle will inevitably be influenced by changes brought about by climate change (Ficke *et al.*, 2007) [9].

Anticipated consequences of climate change on aquaculture production are costs, along with additional necessary goods and services for fishers and aquaculture producers (Maulu *et al.*, 2021) [11] likely to manifest through both direct and indirect pathways. Direct effects encompass the influence on the physical and physiological facts of fin-fish and shellfish stocks within culture systems. Indirect effects may arise from alterations in primary and secondary productivity, ecosystem structure, and input supplies, or through impacts on product prices, including fluctuations in fish oil and fishmeal.

3. Significance of fish feed ingredients in aquaculture

Feeds and feed ingredients comprise the vital energy and nutrients required for the development, reproduction, and well-being of aquatic creatures. Imbalances in these nutrients can hinder growth or predispose animals to illnesses. Dietary standards establish the optimal levels of energy, fats, protein, amino acids, minerals, and vitamins necessary for aquatic animal health (Prabu *et al.*, 2017) [17]. Assessing feed ingredients is essential for nutritional research and the progress of feeds for aquaculture species (Glencross *et al.*, 2007) [10]. When assessing ingredients for aquaculture feeds, it's crucial to comprehend several key factors to effectively incorporate a specific ingredient into feed formulation. This encompasses understanding (1) ingredient digestibility, (2) ingredient palatability, and (3) nutrient utilization and potential interference (Glencross *et al.*, 2007) [10].

Prepared diets can be categorized as either complete or supplemental. Complete diets furnish all the required nutrients, including carbohydrates, fats, protein, minerals and vitamins required for the maximum development and well-being of fish (Prabu *et al.*, 2017) [17]. In assessing specific ingredients, the goal of nutritional science ideally should be to acquire insights into the nutritional consequences of utilizing those ingredients. Subsequently, once this understanding is attained, efforts should focus on applying it to the formulation of commercial feeds. While it may be noted that there isn't a singular approach to conducting ingredient evaluations, there are evidently drawbacks and challenges to be mindful of during the assessment procedure (Glencross *et al.*, 2007) [10].

4. Challenges and impacts of climate change on feed ingredients

The global output from aquaculture has consistently risen while capture fishery production has been decreasing. Aquaculture holds significant promise in addressing the growing demand for fish, but one of its key hurdles lies in securing an adequate supply of feed ingredients (Bandara, 2018) [18]. Aquaculture production relies entirely on nutrient provision, similar to agricultural practices on land (Tacon *et al.*, 2008) [19].

4.1 Plant based feed ingredients

Incorporating plant-based components into fish feed is a widespread exercise driven by their greater availability and lower cost in comparison to fish meal (Bandara, 2018) [18]. Plant-derived feed components have emerged essential components of fish feed, providing energy and serving as binders to guarantee pellet durability in water until ingested (Raza *et al.*, 2019) [20]. Acacia, copra meal, lupin seed meal, sunflower meal, safflower meal, soybean meal, peaseed meal, cottonseed meal, leucaena leaf meal, and various dried aquatic plants, including both floating and submerged varieties with high protein content, are also utilized in fish feed production (Hajra *et al.*, 2013) [21]. Moreover, soybean meal (SBM) has been recognized as a feasible alternative plant protein for fishmeal (Singh *et al.*, 2023) [22] (Table 1).

Many potential alternative nutrient sources derived from plants are recognized to contain a diverse array of antinutritional substances with imbalanced amino acid profile and lower protein content (Francis *et al.*, 2001; Bandara, 2018) [24, 18]. Antinutritional factors operate through various mechanisms but can negatively impact feed consumption and digestibility of nutrients in fish species (Bandara, 2018) [18] (Table 2). The majority of *anti-nutrients* present in protein

sources used in fish feed, when incorporated at certain levels, do not cause mortality but rather induce adverse physiological effects, resulting in decreased growth and compromised health conditions. Reduced food conversion efficiency, hypoglycaemia (decreased blood glucose levels), pancreatic hypertrophy, liver damage, and other abnormal tissue changes are commonly noticed (Hajra *et al.*, 2013) [21].

Table 1. Average nutrient composition (%) of common plant based feed ingredients in fish diet (Adapted from Pilly and Kutty, 2005) [23]

Plant Ingredient	Dry Matter	Crude Proteins	Crude Fat	Carbohydrate	Crude Fiber	Crude Ash
Soybean Cake (China)	89.9	40.9	3.51	35.69	4.34	5.46
Rice bran (China)	89.0	13.68	17.9	37.02	6.84	13.56
Groundnut oil Cake (China)	88.55	39.51	3.56	33.36	3.55	8.57
Cottonseed cake (China)	91.3	36.58	4.99	33.41	8.31	8.01
Mustard seed cake (China)	89.8	13.1	1.06	41.66	7.10	15.34
Wheat bran (China)	87.2	11.33	2.64	58.25	8.87	5.51
Barley (Europe)	85	9.0	1.5	4.5	2.6	8.5
Maize (Europe)	87	9.9	4.4	69.2	2.2	1.3

The present utilization of plant-based aquaculture feeds (PBAF) as substitutes for fishmeal heavily depends on a handful of primary crops like soy, maize, and wheat. However, these crops, crucial for direct human consumption, are susceptible to negative impacts from climate change (Hall, 2015) [5]. The cultivation and availability of traditional crops used in aquaculture feed production, including soybean, rapeseed, maize, rice, and wheat bran, are anticipated to undergo significant changes due to climate change.

Consequently, this will have implications for feed production and utilization in fish culture (Raza *et al.*, 2019) [20]. It is recognized that climate change is expected to have detrimental impacts on tropical terrestrial agriculture, and a significant portion of the agricultural waste products utilized in aquafeeds are sourced from tropical regions (De Silva *et al.*, 2009) [25]. The cultivation of soybeans in major producing nations like Brazil has experienced a decline, primarily attributed to environmental concerns (Singh *et al.*, 2023) [22]. Due to climate change, crop production will experience alterations in both quantity and quality (Pailan *et al.*, 2023) [7]. Ultimately, it will have impacts on aquafeeds production.

Table 2. Anti-nutritional factors present in plant based feed ingredients (Francis *et al.*, 2001; Hajra *et al.*, 2013) [24, 21]

Plant based ingredients	Anti-nutritional factors
Soybean meal	Protease inhibitors, lectins, phytohaemagglutinin, phytic acids, saponins, phytoestrogens, antivitamin, allergens, antivitamin
Pea seed meal	Protease inhibitors, lectins, cyanogens, saponins, tannins, antivitamin, phytic acid
Cottonseed meal	Phytic acid, phytoestrogens, gossypol, antivitamin, cyclopropenoic fatty acid
Mustard oilcake	Glucosinolates, tannins
Rapeseed meal	Protease inhibitors, glucosinolates, phytic acid, tannins
Sesame meal	Phytic acid, protease inhibitors
Sunflower oil cake	Protease inhibitors, saponins, arginase inhibitor
Corn/maize	Protease inhibitors, phytic acid, tannins, invertase inhibitor, aflatoxin

4.2 Fish meal

Fish meal is a solid product derived from grinding of fish and fish byproducts, followed by the removal of water and all or some of the oil content (Murthy *et al.*, 2019) [26]. Fish meal serves as a naturally balanced feed component, rich in protein, energy, and minerals such as calcium and phosphorus. Additionally, it contains essential vitamins like choline, biotin, and vitamins B₁₂, A, D, and E, along with micro-nutrients like selenium and iodine. Two primary categories of fish meal exist: one derived from the byproducts of processing various edible fishery products (such as salmon or tuna), and the other obtained from fish specifically caught to produce fish meal (like herring, menhaden, or pollack) (Cho *et al.*, 2011) [27]. Based on the data at hand, approximately 20 million metric tonnes of fish are harvested, constituting 11% of the overall catch, and are allocated for non-food purposes. Out of this, about 16 million metric tonnes, equivalent to 9.03% of the total catch, are specifically utilized for the production of fish oil and fishmeal (FAO, 2022) [1]. The feed manufacturing sector relies significantly on fish meal as a key provider of nutritional protein (Bandara, 2018) [18] (Table 3). Half of the fish meal utilized by the aquaculture industry amounts to 50%, while the fish oil content in aquafeeds make up to approximately 88% (Shamshak *et al.*, 2008) [28].

Table 3. Nutritional profile of fish meal (Adapted from Cho *et al.*, 2011) [27]

Nutrients	Availability
Crude Protein (%)	59 –64.6
Ash (%)	15
Moisture (%)	10
Crude Fats (%)	9.8
Non-Nitrogenous Extract (%)	0.4
Essential Amino Acid, g/100g Crude Protein	
Arginine	5.70
Histidine	2.41
Isoleucine	4.74
Leucine	7.74
Lysine	7.91
Methionine	3.02
Cystein	0.94
Phenylalanine	4.12

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Nutrients	Availability
Tyrosine	3.33
Threonine	4.37
Tryptophan	1.18
Valine	5.43

In spite of these noted advantages, the manufacturing of fish oil and fish meal relies heavily on marine fishery yields and incidental catch.

Global fish meal production data indicate a steady decline on average of 1.7% per year (Tacon *et al.*, 2008) [19]. Fishmeal production is concentrated in specific regions worldwide, leading to increased costs and challenges in sourcing it for many aquaculture-practicing countries (Francis *et al.*, 2001) [24]. The availability of fish meal is not guaranteed year-round (Hajra *et al.*, 2013) [21]. Globally, the majority of fish meal is utilized in feed for terrestrial animals like swine and poultry (Trushenski *et al.*, 2006) [29]. As a result, the growing production of terrestrial animals is leading to competition for fish meal as a valuable feed ingredient.

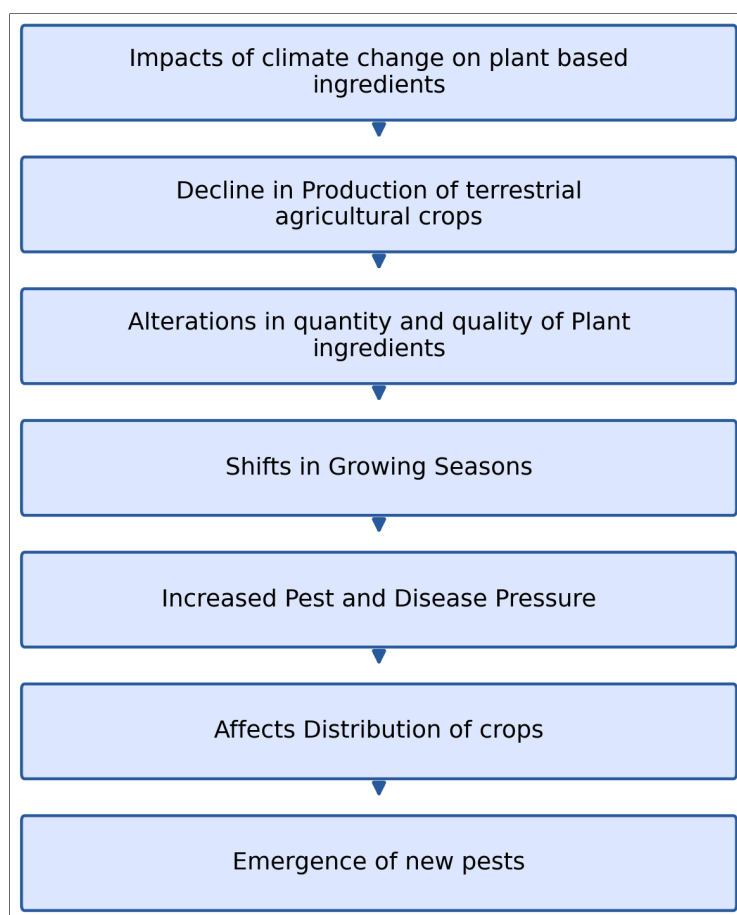


Figure 1. Impacts of climate change on plant based ingredients

Pelagic or forage fish, primarily employed in fishmeal production, exhibit greater sensitivity to climatic events due to their high reliance on inter-annual, environmentally induced variations in recruitment (Jannathulla *et al.*, 2019) [30]. The increased production of fish from intensive aquaculture techniques has heightened the need for fishmeal sourced from small pelagic fishes, emerging as a progressively significant concern (Soliman *et al.*, 2017) [31].

The bycatch from capture fisheries which is the major source of fish meal production were observed to be impacted by climate change (Merino *et al.*, 2010; Lindegren *et al.*, 2013) [33, 32]. Alterations in ocean circulation patterns could potentially adversely affect the dependability of small pelagic stocks utilized in fishmeal production (Soliman *et al.*, 2017; Révész *et al.*, 2019) [31, 34]. Natural fish food organisms, including phytoplankton, zooplankton, crustaceans, and bivalve molluscs, are sensitive to environmental factors. Climate change might have adverse impacts on these organisms, resulting in a decline in aquaculture performance (Reid *et al.*, 2019; Pailan *et al.*, 2023) [35, 7]. Warmer oceans with increased thermal stratification could result in a decrease in phytoplankton species diversity, as some species may have less adaptive capacity to thrive in such conditions (Acevedo-Trejos *et al.*, 2014) [36]. The anticipated global warming is also predicted to reduce the levels of omega-3 fatty acids (FAs) in phytoplankton, which serves as the primary source of omega-3 FAs in

aquatic environments. This potential decrease may carry consequences for the crucial omega-3 FA content in fish feed (Reid *et al.*, 2019) [35]

4.3 Insect meal

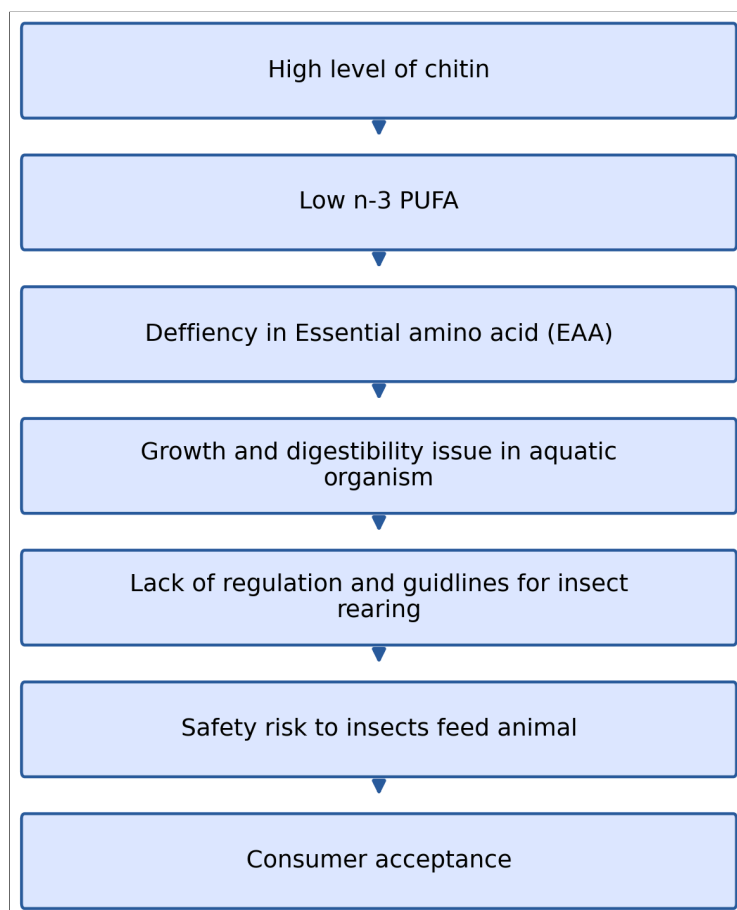
Insect farming is regarded as environmentally friendly because it makes efficient use of limited resources and boasts a low carbon footprint (Singh *et al.*, 2023) [22]. In the past twenty years, studies have been carried out to investigate the impacts of substituting fish meal with insect meals on the growth and health of various aquaculture species (Daniel, 2018) [37]. Feeding fish with insect-based meals has been found to significantly impact their growth performance. The development of aquatic organisms fed with insects varies depending on the developmental stage and species of both the insects and the aquatic organism (Hameed *et al.*, 2022) [38]. Insect meal is abundant in essential amino acids (EAAs) such as lysine and methionine, although slight variations may occur depending on the insect taxon. Insect meal additionally comprises compounds like taurine and hydroxyproline, which are typically lacking in plant-based feed (Henry *et al.*, 2015) [39]. In Europe and various regions worldwide, there's an anticipation that insects will increasingly substitute animal-derived proteins, especially within the fisheries and poultry industries (Singh *et al.*, 2023) [22]. (Table 4).

Table 4. Nutritional profile of insect meal (Adapted from Nogales Mérida *et al.*, 2019; Singh *et al.*, 2023) [40, 22]

Insects <i>Sp.</i>	Moisture (%)	Crude Protein (%)	Crude Fat (%)	Ash (%)
<i>Tenebrio molitor</i>	27.3–57.6	8.3 - 59.81	16.6 – 40.3	1.9–4.5
<i>Hermetia illucens</i>	90.0–92.5	30.7 – 58.8	11.3 – 40.7	14.6–28.4
<i>Musca domestica</i>	88.1–96.1	28.63 - 70.4	7.06 – 25.3	1.1–24
<i>Zophobas morio</i>	35.2–42.1	6.9 – 50.27	38.92 – 41.78	2.4–8.2
<i>Acheta domesticus</i>	22.9–33.2	8.8 – 64.1	7.9 – 24	3.6–13.4

The exoskeleton of insects consists primarily of the polysaccharide chitin. Despite the presence of chitinase enzyme, which can potentially break down chitin, it remains largely indigestible for most fishes. Furthermore, there have been reports of bioaccumulation of pesticides in fish through the consumption of insects (Ogunji *et al.*,

2007) [41]. The limited presence of polyunsaturated fatty acids (PUFA) in land-based insects diminishes their effectiveness as feed for marine fish. The large-scale cultivation of insects for use in aquaculture is still in its nascent stages of evolution (Bandara, 2018) [18].

**Figure 2.** Challenges in insect meal in aquaculture (Singh *et al.*, 2023) [22]

The extent of shifts in precipitation and temperature trends varies globally, which means that insect species inhabiting different environments will also vary in regards to the degree of climate change they encounter and their sensitivity to these changes (Stange *et al.*, 2010) [42]. The rise in climatic variability has led to a decrease in the level of parasitism among caterpillars. This decrease, in turn, might escalate the occurrence and severity of herbivore outbreaks (Sangle *et al.*,

2015) [43]. Climate warming additionally mitigates the risk of winter mortality among insect populations by reducing the incidence of extreme cold temperatures (Ayres *et al.*, 2000) [44]. Climate can also induce indirect effects on a particular insect species through its influence on the physiology of vegetation or natural enemies (Stange *et al.*, 2010) [42].

Table 5. Inclusion of insect-based meals in aquafeeds for different fish fpecies

Fish species	Insect Species	Proportion of Insect-Based Meal (%)	References
<i>Acipenser baerii</i>	<i>Hermetia illucens</i>	0-100	Caimi <i>et al.</i> , 2020
<i>Dicentrarchus labrax</i>	<i>Tenebrio molitor</i>	0-50	Gasco <i>et al.</i> , 2016
<i>Lates calcarifer</i>	<i>Musca domestica</i>	10–30	Lin and Mui, 2017
<i>Clarias gariepinus</i>	<i>Imbrasia belina</i>	4–24	Rapatsa and Moyo, 2019
<i>Sparus aurata</i>	<i>Chironomids</i>	4.5–9	Roncarati <i>et al.</i> , 2019
<i>Clarias gariepinus</i>	<i>Gryllus bimaculatus</i>	30	Taufek <i>et al.</i> , 2016

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4.4 Terrestrial animal by-products

Terrestrial animal by-products such as blood meal, poultry waste, bone meal and meat have been extensively employed as protein sources for numerous fish species. This is attributed to their high protein level and favourable EAA profiles (Tacon 1990).

4.4.1 Poultry by-products

Poultry by-products encompass ground components of poultry by-product meal, comprising necks, legs, underdeveloped eggs, and a small quantity of feathers, which are inherent to processing procedures and unavoidable (Jayathilakan *et al.*, 2012) [45]. One of the most promising substitutes for fishmeal is poultry by-products because of their high protein content, essential fatty acids, vitamins, minerals, palatability, and protein quality (Galkanda-Arachchige *et al.* 2020) [46]. Additionally, Poultry by-products was shown to be a more affordable protein source than FM and easily accessible in huge numbers all year round, particularly in areas that produce poultry, like Asia (Galkanda-Arachchige *et al.* 2020) [46].

4.4.2 Blood meal

Animal blood that is clean and fresh is used to make blood meal. Blood meal normally has quantities of crude protein and crude fat ranging from 80-85% and 0.5%–3%, respectively (NRC, 2011). High levels of histidine and lysine can be found in blood meals. Based on the species and its life stage, different diversity rates pertain to blood meals. However, adding blood meal at a rate of 5–10% could produce the best outcomes (Hertrampf and Piedad-Pascual, 2012). The widespread adoption of blood meal in aquaculture is primarily fueled by its consistent quality and increased digestibility (Nogueira *et al.*, 2012) [47]. Additionally, blood meal has been shown to help prevent cataracts in farmed salmon (*Salmo Salar*) (Breck *et al.*, 2003) [48].

4.4.3 Feather meal

The high protein content and easy availability of feather meal, which is obtained from the slaughter of chicken, make it a good substitute protein source for aquafeeds. Rich in essential amino acids (EAA) in-

cluding cystine, threonine, and arginine, feather meal has a crude protein content of around 800-900 g/kg (Tesfaye *et al.*, 2017) [49]. The protein content of feather meal ranges from 76.40-87.30% (Han *et al.*, 1991) [50]. The diets of rainbow trout (*O. mykiss*) and European seabass (*D. labrax*) (Campos *et al.*, 2017) [51], have been found to benefit from the use of feather meal as a replacement for other protein-rich components (Dalsgaard *et al.*, 2012) [52].

Poultry by-products are not efficiently utilized by fish due to their low digestibility and inadequate EAA profiles. When included at higher rates, feather meal has been observed to negatively affect the growth of several fish species. According to Sulieman *et al.*, (2011) [53] fish do not effectively consume poultry by-products because of their low digestibility and insufficient EAA profiles. In comparison to fish meal, feather meal contains less EAA such as histidine, lysine, methionine, and tryptophan (Klemesrud *et al.*, 2000) [54]. Studies conducted by Hasan *et al.* (1997) [55] have shown that the inclusion of feather meal at higher rates might have an adverse effect on the development of multiple fish species.

Poultry productivity is impacted by climate change because it disrupts the animals' healthy balance. According to Abioja *et al.*, (2021) [56], birds under heat stress frequently show negative symptoms as reduced feed intake, growth rate, feed digestion and efficiency, immunity, welfare, and survivorship. Poultry by-product meals depend on the poultry industry, which may face disruptions in production due to heat stress, disease outbreaks, and feed availability under changing climates. This affects the consistent supply and cost of Poultry by-product for fish feed (Sandström *et al.*, 2022) [57]. The availability of lysine in blood meal was shown to be negatively correlated with heat application (Nogueira *et al.*, 2012) [47]. Blood meal and feather meal are nutrient-rich but may face seasonal or regional production variability worsened by climate stressors on livestock health and productivity (Hasan *et al.*, 2024) [58]. Climate-driven supply chain challenges, including transportation and storage under more extreme weather, can degrade these perishable by-products, affecting their quality for aquafeed use (Campos *et al.*, 2020) [59].

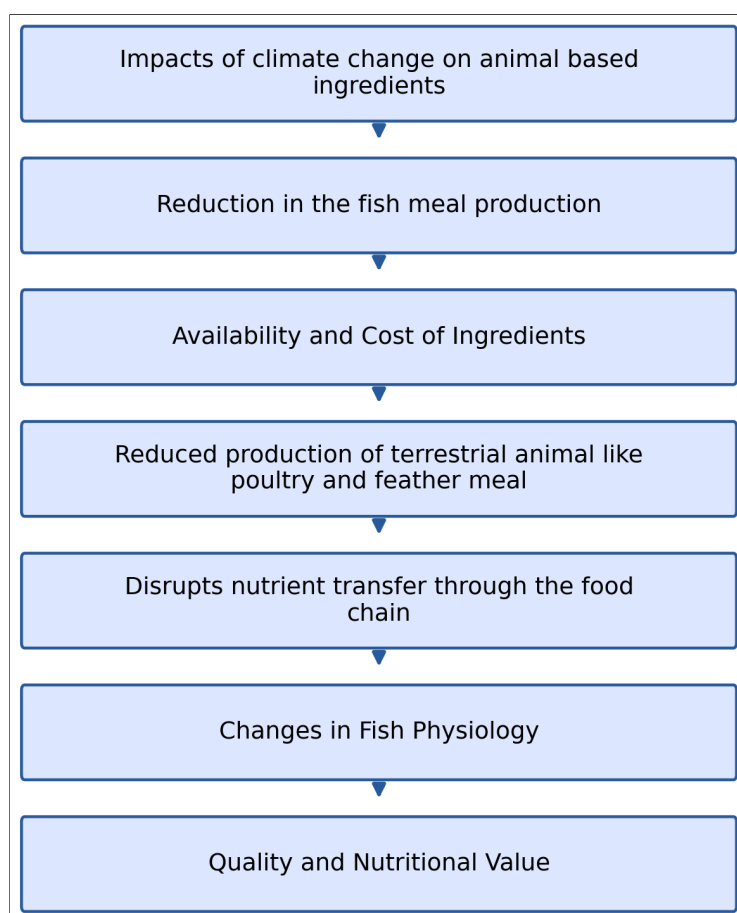


Figure 3. Impacts of climate change on animal based ingredients

Table 6. Utilization of terrestrial animal by-products in aquafeeds for various fish species

Fish species	Terrestrial animal by-products	Proportion of Terrestrial animal by-products in diet (%)	References
<i>Oncorhynchus mykiss</i>	Combined poultry by-product + feather meal	0-54	Steffens, 1994
<i>Psetta maeotica</i>	Poultry by-product meal	0-85	Yigit <i>et al.</i> , 2006
<i>Cromileptes altivelis</i>	Poultry by-product meal	0-7.2	Shapawi <i>et al.</i> , 2007
<i>Litopenaeus vannamei</i>	Poultry by-product meal	0-31.3	Cruz-Suárez <i>et al.</i> , 2007
<i>Oreochromis niloticus</i>	Blood meal	0-25.5	Kirimi <i>et al.</i> , 2016
<i>Oreochromis niloticus</i>	Blood meal	0-100	Kirimi <i>et al.</i> , 2017
<i>Mylopharyngodon piceus</i>	Blood meal	0-21.14	Twahirwa <i>et al.</i> , 2021
<i>Dicentrarchus labrax</i>	Hydrolyzed feather meal	0-12.5	Campos <i>et al.</i> , 2017
<i>Oreochromis niloticus</i>	Feather meal	4-15	Bishop <i>et al.</i> , 1995
<i>Oreochromis niloticus</i> × <i>O. aureus</i>	Feather meal	0-4.6	Poolsawat <i>et al.</i> , 2021
<i>Nibea japonica</i>	Feather meal	1.5-10.4	Wu <i>et al.</i> , 2018

5. Approaches to address challenges in fish nutrition caused by climate change

5.1 Integrated multitrophic aquaculture (IMTA) systems

One method of adapting to climate change is "Integrated Multi-Trophic Aquaculture (IMTA)" (Clements *et al.*, 2017) [60]. As an example of an ecosystem-centered aquaculture technique, it involves the co-culture of food finfish, inorganic extractive species such as seaweeds, and organic extractive species such as shellfishes from various trophic levels in an integrated farm. The goal of this strategy is to create environmentally sustainable, well-balanced systems (Troell *et al.*, 2009; Chopin *et al.*, 2012) [62, 61]. The IMTA system uses natural food sources found in the system to meet around half of the nutritional needs of farmed fish, reducing the quantity of feed utilized in aquaculture operations (Fawole *et al.*, 2023) [63].

In IMTA, shellfish and seaweeds absorb waste particles and nutrients, thereby reducing mineralization and mitigating higher water temperatures (Sreejariya *et al.*, 2011) [64]. This can lead to decreased waste production, alleviate environmental stress, and promote the sustainability of aquaculture practices. In IMTA, seaweeds play a role in cooling water by absorbing pollutants and toxic elements. Additionally, they contribute to carbon sequestration through photosynthesis (Chung *et al.*, 2013) [65]. In coastal open-waters, IMTA may be less susceptible to the effects of floods, sea level rise, and freshwater scarcity caused by drought and rainfall variations. This resilience allows open-water IMTA systems to maintain water quality (Ahmed *et al.*, 2016) [66].

5.2 Improved utilization of ingredients

Dietary fiber and anti-nutrients in the components have an impact on feed intake and digestibility. Increasing feed conversion efficiency and optimizing nutrient usage are important tactics for adjusting to shifting climate conditions. Techniques including solid-state fermentation, adding exogenous enzymes, soaking, and protein extraction can be used to increase the use of plant-based components (Fawole *et al.*, 2023) [63]. The use of *Chaetomium globosum* for leafmeal fermentation led to increased feed efficiency and development in rohu fingerlings (Meshram *et al.*, 2018) [67]. The utilization of nutrients was improved when *Labeo rohita* fingerlings were fed a diet that in-

cluded 0.1% exogenous enzymes (xylanase and cellulase) in leaf meal-based fish feed (Maiti *et al.*, 2019) [68].

5.3 Selecting species through genetic means

Variability in genetics is a primary factor distinguishing plastic responses, such as variations in reproductive timing and growth rates, among families, populations, or within species (Hutchings, 2011) [69]. Extended exposure to stressors induced by climate change can trigger phenotypic alterations, and the adaptability of stress tolerance transforms into acclimation. This process may subsequently give rise to local adjustment or acceptance (Kassahun *et al.*, 2012) [70]. There is evidence indicating that genetic changes in response to temperature fluctuations can be adaptive. According to Healy *et al.*, (2012) [71], killifish can develop a greater tolerance to heat when they are repeatedly exposed to heated temperatures. Fish genetic selection may be based on climate change and utilize traits like heat tolerance, feed conversion efficiency, and thermal sensitivity for growth to provide quantifiable selection responses (Kavanagh *et al.*, 2010) [72].

5.4 Biofloc

Biofloc technology (BFT) is a new and developing approach in fish farming that aims to achieve sustainable aquaculture (Dauda *et al.*, 2018) [73]. According to Sgnaulin *et al.* (2018) [74], BFT is a method for maintaining water quality that requires little to no water exchange. It works by cultivating and regulating heterotrophic bacteria within the culture system. Preserving a balanced carbon-to-nitrogen ratio (C/N) is the cornerstone of biofloc systems, since it facilitates the development of heterotrophic bacteria. According to Dauda *et al.* (2017) [75], these bacteria produce nitrogen gas out of the system and use ammonia for growth. It is a sustainable alternative culture systems, as it efficiently recycles and reuses nutrients within the system (Kumar *et al.*, 2017) [76]. With BFT, operators can boost stocking density for mature stock, all the while reducing waste and conserving water (McCusker *et al.*, 2023) [77]. It has been suggested that dried bioflocs be used in aquafeeds to substitute of fishmeal or soybean meal (Hargreaves, 2013) [78]. In summary, BFT maintains water quality by utilizing ammonia to produce microbial proteins, which serve as food for the cultured fish. This results in increased efficiency in feed utilization, decreased food conversion ratio, and reduced feeding costs in sustainable eco-friendly aquaculture.

5.6 Dietary immunostimulants against challenged climatic conditions

In response to climate change, it is imperative to embrace novel strategies to address emerging challenges. Such strategies may encompass the utilization of locally available, nutritionally balanced feed ingredients (Tacon *et al.*, 2011) [8]. Using alternative climate-resilient crops with desirable nutritional properties is another potential strategy (Hall, 2015) [5]. An effective strategy to mitigate problems caused by climate change involves the utilization of immunocuticals, antioxidants, and anti-stress compounds (Fawole *et al.*, 2023) [63]. Under changing climatic conditions, dietary immunostimulants could offer protective effects in fish (Wang *et al.*, 2017) [79].

The health of African catfish, *Clarius gariepinus*, appears to benefit most when fed fishmeal or soy-meal at varying temperatures, exhibiting optimal results amid thermal stress conditions (Al-Deghayem, 2019) [80]. The addition of dietary supplements such as grape seed extract, known for its antioxidant properties, and sea lettuce *Ulva lactuca*, enhanced the survival rate of *Haliotis laevis* under high-temperature conditions (Lange *et al.*, 2014) [81]. Adjusting the mineral ratio of Mg to Ca in the diet could enhance the ability to cope with acidification in the *Paracentrotus lividus* (Asnaghi *et al.*, 2014) [82]. Feeding *Lates calcarifer* with Stearidonic and γ -linolenic acid has demonstrated an improvement in low-temperature tolerance (Alhazzaa *et al.*, 2013) [83]. To adapt to rising temperatures in mirror carp *C. carpio*, an adaptive strategy involved increasing the dietary protein level, which led to elevated immune response, antioxidant enzymes, and gene expression of heat shock proteins (Huang *et al.*, 2015) [84]. The stress induced by low temperatures in seabass can be alleviated by an antioxidant product derived from honeybees, known as propolis (Šegvić-Bubić *et al.* 2013) [85]. Nutritional bioenergetic models have been created for various aquaculture species, including *Oncorhynchus mykiss* (Hua *et al.*, 2009) [86], *Oreochromis niloticus* (Chowdhury *et al.*, 2013) [87], and *Lates calcarifer* (Glencross *et al.*, 2012) [88]. These models are designed to calculate the ideal digestible protein and energy requirements under varying temperature conditions.

O. niloticus exhibited enhanced performance when exposed to cold temperatures and fed fish oil (Corrêa *et al.*, 2017) [89], also White but-

ton mushroom is recommended to cope with heat stress (Dawood *et al.*, 2020) [90]. A correlation was discovered between the presence of 0.5% Tryptophan and the suppression of stress induced by temperature fluctuations in *O. mykiss* (Hoseini *et al.*, 2020) [91]. Supplementing diets with riboflavin at 5 mg/kg and se- nanoparticles at 0.5 mg/kg could potentially provide protection to *Pangasianodon hypophthalmus* against thermal stress (Kumar *et al.*, 2019) [92]. A foundational diet containing 150–200 mg/kg of carotenoids has been observed to boost immune responses to disease and confer resistance to high-temperature stress in Yellow catfish (*Pelteobagrus fulvidraco*) (Liu *et al.*, 2019) [93].

5.7 Case studies of climate-proof fish feed

Numerous case studies have reported the utilization of insect meals to convert organic waste into protein, demonstrating a lower environmental footprint compared to traditional feed ingredients. As an example, Ynsect, a France based company, specializes in mealworm farming for the aquaculture feed production (Thévenot *et al.*, 2018) [94]. Protix in the Netherlands specializes in the large-scale production of Black Soldier Fly larvae (Xu *et al.*, 2020) [95]. BioMar in Denmark focuses on the development of plant-based feed formulations aimed at increasing the evident nutrient digestibility of soybean meal in fish feed (Dalsgaard *et al.*, 2012) [52]. Marketable solutions for decreasing food waste are provided by insect-based bioconversion; these solutions are energy and space-efficient, ecologically benign, offer genuine market and commercial opportunities, and produce feed conversion ratios higher than those of conventional livestock (Li *et al.*, 2013; Van Huis *et al.*, 2017) [96, 97]. The ISBR (Integrated Sequential Biorefinery) diversification plan has been put into practice during the last ten years by the University of New Brunswick's Canadian IMTA Network (CIMTAN) in cooperation with Cooke Aquaculture Inc., an industrial partner in Atlantic Canada. And they start integrating salmon, mussels, and seaweed farming system (Chopin, 2015) [98]. Cultivation technologies and harvesting methods, along with breeding practices, can be enhanced to improve the cost-efficiency of biofilters, particularly in the emerging European seaweed cultivation industry (Holdt *et al.*, 2014) [99].

Table 7. Dietary immunostimulants against challenged climatic condition (Islam *et al.*, 2022) [6]

Species Name	Ingredients	Effect	Reference
African catfish, <i>Clarias gariepinus</i>	Fishmeal or soy-meal	Show tolerance against temperature	Al-Deghayem, 2019
Greenlip abalone, <i>Haliotis laevis</i>	Grape seed extract & sea lettuce <i>Ulva lactuca</i>	Enhanced survival rate under high-temperature conditions	Lange <i>et al.</i> , 2014
Purple sea urchin, <i>Paracentrotus lividus</i>	Mg & Ca	Enhances ability to cope with acidification	Asnaghi <i>et al.</i> , 2014
Barramundi, <i>Lates calcarifer</i>	Stearidonic and γ -linolenic acid	Improvement in low-temperature tolerance	Alhazzaa <i>et al.</i> , 2013
Mirror carp, <i>Cyprinus carpio</i> ,	Increasing the dietary protein level	Adaptation to rising temperatures with elevated immune response, antioxidant enzymes, and heat shock proteins (HSP).	Huang <i>et al.</i> , 2021
Barramundi <i>L. calcarifer</i>	Propolis - an antioxidant product derived from honeybees	Reduces stress with lower temperature	Šegvić Bubić <i>et al.</i> , 2013
Nile tilapia, <i>Oreochromis niloticus</i>	Fish oil	Enhanced performance at cold temperatures	Corrêa <i>et al.</i> , 2017
Nile tilapia, <i>O. niloticus</i>	White button mushroom	Cope with heat stress	Dawood <i>et al.</i> , 2020
Nile tilapia, <i>O. niloticus</i>	Dietary fatty acids (fish, linseed, sunflower, olive, and coconut oils)	Improves performance	Corrêa <i>et al.</i> , 2017
<i>Pangasianodon hypophthalmus</i>	Riboflavin @ 5 mg/kg & selenium-nanoparticles @ 0.5 mg/kg	Protection against thermal stress	Kumar <i>et al.</i> , 2019

(continued on next page)

Species Name	Ingredients	Effect	Reference
Yellow catfish, <i>Pelteobagrus fulvidraco</i>	150–200 mg/kg of carotenoids	Boost immune responses to disease and confer resistance to high-temperature	Liu <i>et al.</i> , 2019
Pufferfish, <i>Takifugu obscurus</i>	Astaxanthin	Improve resistance against high temperature stress	(Cheng <i>et al.</i> 2018)
Gilthead seabream, <i>Sparus aurata</i>	Additional Vit C, E, non-essential amino acids	Winter feed diet shows positive effects during thermal stress	Schrama <i>et al.</i> , 2017
Rainbow trout, <i>Oncorhynchus mykiss</i>	0.5% Tryptophan	Suppress of stress induced by temperature	Hoseini <i>et al.</i> , 2020



Figure 4. Approaches to address challenges in fish nutrition caused by climate change

Conclusion

Aquaculture plays a vital role in human nutrition and the global food supply, particularly for impoverished populations. The effects of climate change, including global warming, are increasingly evident worldwide, accompanied by shifts in climate patterns. As a consequence, extreme weather occurrences like floods, droughts, heavy rainfall, increasing water temperatures, and ecological shifts have become more frequent. The effects of climate change may vary depending on the geographical location. Poikilothermic animals like fish are particularly susceptible to temperature fluctuations. Understanding how aquaculture adapts to climate change is vital. The impact of climate change on aquaculture could pose significant difficulties and harm. Administering the nutrition and feeding of aquaculture animals is expected to be a challenging endeavor. Developing countries may find it challenging to meet their food demands due to the effects of climate change on fisheries and aquaculture, while developed countries may suffer financial losses. Conventional feed ingredients may not be as suitable for withstanding altered climate conditions and facilitating faster fish growth, such as increased temperatures. Numerous researchers have investigated non-conventional feed ingredients that can assist fish in coping with the stress induced by changed climate conditions. Many of them have good impacts on growth and survival of fishes.

Author contributions

C. Judith Betsy: Conceptualization, Critical analysis, review editing. **Gavhane Shrinath Vajjanath:** Conceptualization, Compilation, Formal analysis, Writing – review & editing. **Ilansekaran Kaviyarasi:** Compilation, review editing. **Soibam Khogen Singh:** Review editing. **Sourabh Debbarma:** Review editing. **Saiprasad Bhusare:** Review editing.

Data availability

Non applicable

Conflicts of interest

The authors report no conflicts of interest in this work.

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