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The Role of Digital Technologies in Supporting Climate Change Adaptation in Fisheries and Aquaculture

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Abstract The Indeed, future climate change needs calls for action since its effects are seen. The impacts of climate change seen over the years may include rising mean temperatures, sea level rise, explosive intensification of cyclones, irregular precipitation patterns, soil and beach erosion and the exponential increase in extreme weather conditions. One of the main focuses that has retained international attention is unequivocally the food crisis. Fisheries and aquaculture have long been the source of food for many nations across the world where the impacts of climate change compelled resilient measures. Evidence has been seen in regions such as Bangladesh and Africa where climate change has highly affected fisheries and aquaculture. One of the exacerbations of climate change would be the rising temperatures. It has also been observed that temperature has a direct impact on the physiological development of fish and shellfish. This report demonstrated the paramount of studies available to address climate change and the role of digital technology as an adaptation strategy. Results were further classified into 4 distinct areas such as Internet of Things (IoT)-Artificial Intelligence (AI)-Blockchain, Genetics, Geographical Information Systems and Digital technology-business models. Research permitted the discovery of several tools and technologies adapted to increase production amidst coercive climatic conditions. It has been noted that this sector was very keen to adopt new digital technologies to improve production. It followed that genetically strengthened fish species could adapt to areas where the impacts of climate change are very harsh and survival rates for species are very low. Research has been done on innovative digital technologies, but are seemingly under review, where fish cages or aqua pods could provide additional support for fish production. Digital technologies enhance aquaculture operations by providing real-time water quality and fish health monitoring, increasing efficiency, enhancing decision-making, detecting diseases early and promoting sustainability. They streamline processes, reduce labour costs, and optimize resource use, ultimately leading to better fish health and reduced antibiotic use. Nevertheless, challenges in aquaculture adaptation strategies, include data management, cybersecurity, cost, accessibility, skills training, and regulatory framework adaptation. These challenges can compromise data and operations, limit access to digital technologies, and require skill training for aquaculture operators. Addressing these challenges is crucial for realizing their benefits. It has been concluded through this study that aquaculture and fisheries industries have very promising futures. The digital technologies involved in improving production are no less to evolve further. The use of machinery and tools is next to step into another hi-tech age where industry 5.0 is cited as the coming future. Connecting the transregional, national and international innovations are key successes to the fisheries and aquaculture sector.
Keywords Climate change; Digital technologies; Fishery; Aquaculture; Adaptation; Mitigation

1 Introduction

From the Sixth Assessment Report of the International Panel on Climate Change (IPCC, 2021), it was highlighted that the effects of rising temperatures that followed from the acceleration of global warming would be irreversible. Alongside issues about climate change, there is also the issue of food security. The Food and Agricultural Organization (F.A.O., 2022) has brought its inputs and has aided global climate debates on fisheries and aquaculture. Advances from global climate debates have recognized the need for greater and accelerated initiatives for fisheries and aquaculture to mitigate the effects of climate change and adapt to them. According to the United Nations 2014, more than 3 billion people worldwide rely on seafood as a major source of nutrition and a significant source of income.

Changes in climate and extreme weather events, like in many other areas of agriculture and food production, are having a considerable impact on the aquaculture and fisheries industries (Barange et al., 2018). Siddique et al.

(2022) reported that Bangladesh's aquaculture industry was an example to showcase the sensitiveness of climate change whether inland or coastal towards fishery production. Coral reefs and mangrove forests, two of the most biodiverse ecosystems on Earth, can be found in this region. Climate change is altering the distribution and abundance of fish stocks, affecting the livelihoods of millions of people who depend on fisheries and aquaculture. Cyclones, hurricanes and other storms cause severe damage in southern Bangladesh. Flooding, saline intrusion into soil, waterlogging and erosion have all been exacerbated by increased rainfall. Furthermore, inland aquaculture costs are rising because of severe floods induced by increased rainfall and severe weather events. Equally, rising sea surface temperature is posing a climate-related hazard to coastal fisheries in Africa, as emphasized by Dismukes (2022). Climate change is exacerbating existing environmental and socio-economic challenges in this region. Changes in ocean temperatures and chemistry are impacting fisheries, while increased flooding and erosion are affecting aquaculture operations. Monnereau and Oxenford (2017) argued that increasing temperatures are destroying coastal habitats, changing the types of fish species accessible for fisheries and increasing the likelihood of storms affecting coastal towns. Alongside, rising sea levels, storm frequency and ocean acidification threaten the existence of tropical islands, threatening their crucial economies and livelihoods for many communities.

Aquaculture irrevocably also includes the production of shellfish, crabs and seaweeds, which are valuable sources of human nourishment as well as molecular components for the pharmaceutical sector. According to the study's projection of current carbon emission rates, worldwide salmon production will decline by 3% by 2050 and by 14% by 2090, as studied by Holmyard (2021). The expected effects are mostly brought about by the direct effects of ocean warming on farmed species and the indirect effects of shifting forage fish stocks needed to make fishmeal and fish oil for aquafeed. The distribution of fish stocks and the structure of ecosystems would be greatly impacted by changing ocean currents and warming waters, according to the same study. Temperature variations in both the water and the air, particularly in marine environments, and other changes in oceanographic conditions, such as currents, wind speed, and waves, are indicators of how climate change affects aquaculture (Maulu et al., 2021). Extreme weather patterns which are occurring more frequently and with more ferocity have substantial implications, whether they result in storms that cause property damage or flood freshwater crops. Different physiological effects and pressures will have an impact on a fish's or shellfish's growth and development, which may make them more vulnerable to illnesses and infections. The emergence of novel illnesses and parasite infections worries veterinarians as well. The planned and ongoing development effort concerns for selective breeding of more robust strains, for higher temperature and disease tolerance, is anticipated.

Norway, Myanmar, Bangladesh, the Netherlands, and China would be the nations most impacted by the worst-case scenario as has been projected (Holmyard, 2021). Alternatively, bivalve-producing regions might experience fewer changes since the effects of climate change on species like mussels, oysters, and clams are probably less severe. The construction of an optimal living environment and fish species reproduction depends on water temperature. This is why it ranks first on the list of most determining elements. During a specific period, a fish population may be tolerant of temperature variations in the region where it is spread. Important physiological processes like feeding, respiration, osmoregulation, growth, and reproduction are controlled by temperature (Ninawe et al., 2018). The world's changing climate, overfishing, and deteriorating water quality are threats to tropical coral reefs. Coral communities with high levels of genetic variation are probably the key factors in evolutionary adaptations to climate change.

As described by Mustafa et al. (2021), the spectrum of activities that make up aquaculture of aquatic species, such as fish, molluscs, crustaceans, and aquatic plants, has been expanding with various levels of interventions. Through innovative ideas, farmers, scientists, customers, and businesspeople have influenced the various types of aquaculture systems. The rate of change that aquaculture will need to make to fulfil demand will be influenced by innovations and new technology.

To meet the constantly expanding demand for farmed seafood, aquaculture firms need to strive for profit from the newest innovative technology where there is still a dearth of knowledge. The aquaculture sector is preparing itself to employ the latest intelligent types of machinery that can carry out tasks that traditionally would require human judgment. Consequently, digital technologies are having positive impacts on fisheries and aquaculture. The recent shift is emphasized towards digital technology which is known as Industry 5.0; where artificial intelligence, machine learning, robotics, and the human intellect are combined to advance into human-centric solutions (Rowan, 2023). Connecting transregional, national, and international digital innovation hubs is sought to help the fisheries and aquaculture sector reduce significant risks like climate change, global pandemics, and conflicts that could endanger fish and seafood production.

Hence this study aimed at applying digital technologies in supporting climate change adaptation in fisheries. This gives an overview of the impact of climate change in this sector worldwide. Besides, this research will help to fill in the gaps in the literature on the impacts of climate change on the fisheries and aquaculture sectors. The focus would be to analyze new technologies adapted and adopted to fill the gaps that surfaced upon research of literature gaps.

2 Literature Review

2.1 Challenges of food in climate change

The current state of the environment is largely attributed to the worldwide phenomenon known as climate change (Siddique et al., 2022). Consequently, as pointed out by Maulu et al. (2021), climate change is viewed as a major challenge to the quality and quantity of agriculture and a risk to global food production. Aquatic ecosystems are more vulnerable to environmental change than terrestrial ones, and fish physiology is more influenced by climatic conditions than that of terrestrial animals. Because of this, the aquaculture sector is continually feeling the negative consequences of climate change. As depicted by Yazdi and Shakouri (2010), aquatic ecosystem health is essential for fisheries and aquaculture, yet these facts are frequently overlooked and devalued despite their major contributions to food security and livelihoods. Likewise, Siddique et al. (2022) denoted that since people are generally growing more concerned about the nutritional benefits of their food choices, there is an increasing demand for fish, especially as its health benefits continue to gain recognition.

The productivity of capture fisheries has not increased in the previous 20 years, but aquaculture production must rise to meet the increasing demand for fisheries products from a larger and wealthier population (Boyd et al., 2022). Aquatic animal farming has been practised for more than 2,000 years, but it wasn't until the twentieth century that it started to make a difference in the amount of meat produced worldwide. F.A.O. (2022) estimates that 17% of all animal-sourced protein for human consumption comes from aquaculture and fisheries combined.

Mustafa et al. (2021) reported that global aquaculture expanded by 7.5%~9.2% yearly since 1970 to approximately 115 million tons by 2018. Approximately 424 aquatic species (Yazdi and Shakouri, 2010) are currently raised for food on a global scale, providing nutrition: global trend from 20.5 kg~21.5 kg of fish consumed per capita (Mustafa et al., 2021), food security, and livelihoods for millions of people while also helping to reduce poverty.

Palardy (2022) described the fact that seafood has a comparable low carbon footprint to a land-bred farming animal. Boyd et al. (2022) reported in their study that aquaculture is responsible for producing nearly 0.49% of global greenhouse gas emissions.

The top five aquaculture producers are China, India, Indonesia, Vietnam, and Bangladesh, as denoted by Galappaththi et al. (2020). Small-scale farmers in developing countries account for the majority rest of the world's aquaculture production. Climate change effects enhance the complexity and unpredictability of aquaculture systems, which can lead to several undesirable situations. It has been noted nevertheless that the whole aquaculture production system is a complex one experiencing quick changes and technological innovation is a key response to mitigate the effects of climate.

2.2 Drivers of climate change

According to the definition provided by the World Meteorological Organisation, climate is the average variability of significant amounts of different atmospheric variables over a period ranging from months to thousands of years. Long-term weather patterns are described by a place's climate. Though it is challenging to connect specific weather events to climate change, the increase in global temperature has been projected to induce more general effects, such as glacial retreat, shrinkage of the Arctic, and global sea level rise. Glaciers are rapidly changing all over the world, which undoubtedly affects how ocean currents flow and move plankton, which is the primary food source for aquatic life.

Ninawe et al. (2018) expressed the fact that global warming is jeopardizing the seasonal plankton blooms, causing a decrease in fish consuming these organic materials, thereby increasing the water sulfide content. Likewise, a surge in carbon dioxide level due to climate change would reduce the sea water's pH level, acidifying the seawater, and consequently adversely impacting crustaceans. According to Koenigstein et al. (2016), many fish stocks will be affected by the effects of climate change, which include ocean acidification, oxygen depletion, and other long-term and regional environmental changes like salinity, nutrient redistribution or eutrophication, as well as pollution.

Feeding, breathing, osmoregulation, growth, and reproduction are all significant physiological processes that are controlled by temperature (Ninawe et al., 2018). The foundation of an optimal living environment and fish species reproduction criteria depend largely on water temperature. It is assumed that a fish population can strive to live under certain conditions within temperature variations in a specific area for a determined time otherwise there is a migration that would occur.

According to the study conducted by Ninawe et al. (2018), for a region experiencing climatic temperature changes, a fish population would pursue the following characteristic behaviours: moving from the southern area to the northern area of an ovulation region, changes in ovulation areas, likelihood migration for northern latitudes and elongation of fish growth period throughout the year.

Ninawe et al. (2018) described the impacts of fisheries observed in India in their study. It was noted that the variety of fish, its distribution, its abundance, and its phenology of fish may be impacted by water warming. Fisheries will suffer greatly from storms, floods, and drought. Due to their fundamental living metabolism and the availability of food organisms, many fish species have a restricted range of optimum temperatures. Therefore, the distribution of these organisms and life processes could be impacted by just a minimal 10 °C shift in seawater. The changing distribution of fish species, recruitment, and their abundance during shorter periods, such as a few years, may be brought on by rising temperatures (Koenigstein et al., 2016).

2.3 Climate change in the aquaculture sector

Troell et al. (2017) redefined aquaculture as a counterpart of traditional agriculture producing food from aquatic environments as a main growing medium. Similarly, aquaculture includes farming of aquatic organisms including fish, crustaceans, plants and molluscs, with the intended purpose of the rearing process to improve the traditional stock and feeds and give protection from predators. Holmyard (2021) announced that though it is expected that aquaculture is going to increase production by 2050 reaching its target of 74 million metric tons, the actual trending estimated global warming scenarios would drop production by 16%, posing an unprecedented threat. The focus in the world is that aquaculture is currently able to substantiate access to good protein, minerals and healthy omega-3 fatty acids, allowing a healthier and wealthier food supply (Galappaththi et al., 2020).

Scenarios described by Holmyard (2021) still showcase alarming impacts of climate change such as a reduction of forage-fish supplies to be used as fishmeal or oils in aquafeeds, shifting of ocean currents regimes and warming of waters altering the ecosystem altogether. It is no longer viable to replace fish forages with wild-caught fish thus alternative plant-based sources need to be adopted such as soy or corn, nevertheless. These plants are themselves being severely affected by climate change and extensive usage.

Another effect of climate change is the pressure being placed on the conditions fish are farmed. F.A.O. (2022) described that climate stressors such as temperature increases in air and seawater changes in precipitation and hydrometeor intensity such as cyclones and eventually oxygen levels in sea or freshwater are causing magnitudes of problems in sustaining a proper farming principle. Yazdi and Shakouri (2010) depicted some direct stressors that affect the physiology and behaviour of fish species whether in their growth (Siddique et al., 2022), their reproductive cycle, the mortality or life expectancy and their distribution across the ocean.

Constant seawater temperature changes are provoking the shifting of fish farms away from the seashore, making these farms susceptible to shark attacks, susceptible to oceanographic current shifts and animal stress. Barange et al. (2018) reported that other indirect drivers of climate change affecting aquaculture are disease spread, toxic algae proliferation and eutrophication of fish species. Shelton (2014) described that sea-level rise, storm surges and flooding may positively and negatively impact aquaculture. In circumstances of inland aquaculture, water scarcity, overland heat and salinization are effects of climate change.

Climate change impacts on aquaculture affect communities and livelihoods. The human population may bear losses and damages to their livelihood assets which creates a certain stress (Shelton, 2014). Higher temperature, disease spread and toxicity in fish production subsequently affect the health of humans. Relocation of fish from area to area creates competition among fish producers to strive for more resistant species to breed. There is also the susceptibility to cross-contamination and product market losses.

2.4 Climate change in the fisheries sector

According to the Food and Agricultural Organization (F.A.O., 2014), the term fishery is said to be an activity involving the harvest or capture of either farmed or wild fish from a body of water. Alternatively, it can be defined as a unit comprising a group of people chosen by a higher authority to perform duties requiring breeding and harvesting some specific type of fish into a water source based inland or at sea.

According to a report published by F.A.O. (2022), seawater fishery resources are expected to continuously decrease due to overfishing along traditional fish stock along latitudes from 65.8% in 2017 to 64.6% in 2019. There is an important threat that projects inland fisheries face an increase in fishing to satisfy the demand for fish meat globally.

Ninawe et al. (2018) explained in their research that alongside physiological changes within fish metabolism, imbalances in the growth cycle of phytoplankton and changes in the ocean chemistry, the fishing community are compelled to move further north to have a proper fish catch, that also fishing into deeper sea depth.

The Marine Stewardship Council of 2023 published in its report that fishing stock is expected to decrease by up to 6% by 2050 in tropical areas and a slight rise in fish species in higher latitudes. Monnereau and Oxenford (2017) described in their study, the different effects of climate change on fisheries in SIDS where apart from direct physical impacts, there was also the association of socio-economic impacts. It is argued that small to medium-scale fisheries would have difficulty adapting to traditional fishing cycles and techniques, creating a financial limitation.

It has been noted that small-scale artisanal fishing using fish traps is frequently affected by adverse windy and severe weather. As pointed out by Monnereau and Oxenford (2017), small-scale fishing communities especially those from SIDS, are generally the population living on coastal land near seashores risking regularly for fishing. The reduction of incomes greatly impacts the livelihood of those people which affect deeply the social cohesion of that community.

Mohammed and Uraguchi (2013) depicted that Sub-Saharan African countries are dependent on fisheries and climate change still exerts physical-social-economical stresses endangering their food consumption and living. It has been noticed that some fish species are on the border of extinction which reduces local food production and consumption, thereafter, migration of species towards favourable environments reduces catches lastly since most of the production is of export quality, reduction in catches reduces income exacerbating pressure on food security.

2.5 Digital tools as climate change adaptation

Dahl (2020) advocated that climate change is compelling countries to change their mindset and invest massively to address sustainable measures involving aquaculture and fishery. Climate change has become the uttermost priority around the world which likewise engages in making provision for food security and protecting vulnerabilities of this specific type of food production.

Mustafa et al. (2021) emphasized the fact that even though aquaculture can improve food sufficiency around the world, the need for science and technology is inevitable. Digital technologies have the potential to support adaptation strategies in fisheries and aquaculture, but they are not a panacea for addressing climate change impacts. Limitations include data quality and availability, infrastructure and connectivity, cost and accessibility, specialized skills and training, and cybersecurity concerns. The digitalization of such an industry would enable sustainable production of food while adopting safer technologies, improving the workforce and capturing larger value chains. This analysis aligns with the research of Zhang and Gui (2023), who described that China had to counteract overfishing and pollution by adopting a database network that uses detection sensor technologies and data mining techniques, encompassing machine learning and digital neural networks to geo-localize and sustainably fish at sea.

Digital technologies may not fully address the complexities of climate change impacts on fisheries and aquaculture, as they may not fully capture the social, cultural, and economic contexts in which these industries operate. Oversimplification of complex issues can lead to inadequate or ineffective solutions. Overreliance on technology may distract from other critical adaptation strategies, such as policy changes, community engagement and ecosystem-based approaches. The fisheries sector as described by Girard and Du Payrat (2017), are massively using innovative technologies. Collaborative-friendly devices include mobile radio-telephonic devices, geo-positioning services and telemetry accessibility to locate and translocate fishing areas are successful examples of such technologies.

Dismukes (2022) emphasized that the use of digital technologies involving machine learning, smartphones, open-source data, remote sensing, satellite recognition, and video production, all have the potential of creating a wide area of possibilities to collect, communicate, analyze and distribute climate-related information. Balasundram et al. (2023) pointed out some climate change adaptation strategies for building resiliency for a smart seafood industry. The use of specialized equipment that could provide precision nutrition for farmed fish is one strategy to reduce anthropogenic greenhouse gas emissions. To address some limitations and inadequacies, it is essential to integrate digital technologies with other approaches, develop context-specific solutions, ensure equitable access and benefits, and foster international cooperation and knowledge sharing. By acknowledging and addressing these limitations, it is possible to develop more effective and sustainable adaptation strategies that support the resilience of fisheries and aquaculture in the face of climate change.

Nowadays, climate change adaption strategy involves equipping boats with digital tools with the aim of reducing losses in the seafood sector. This evolution enables proper management of resources and reverses the threat of overfishing while allowing fishermen to improve their profitability together helping the sea organism and marine lives. Rowan (2023) went some miles further in describing the use of digital tools in disrupting traditional farming systems and proposing solutions in sectors which could choose alternatives for fish forages, recycling of aquaculture systems, DNA editing for robust breeds, novel marketing strategies, disease mitigation and monitoring systems and cybersecurity.

3 Systematic Literature Review

3.1 Data collection

There are several studies and research performed by authors describing the use of technology and digitalisation in the field of aquaculture and fisheries. But the studies were more pronounced and in-depth in one field only such as computerization, which could not show the application of the tool in that context. To fully analyse those research and studies, the systematic review approach is adopted to get a full grasp of available techniques used in this field.

For a systematic review process performed in this study, the PRISMA framework (Selcuk, 2019) for data analysis was used as a research and analysis tool. The analysis of data comprised of searching and collecting secondary data from around literature to perform an in-depth analysis. The search engine 'Google Scholar' was used while setting the following parameters; 10 years of data from 2013 till 2023 and 'review articles' type. Given that this web search engine is a powerful academic metasearch tool (Hoseth, 2011), handy, free of charge and easily accessible, a plethora of articles and publications were obtained to compose a meta-scientific database.

The systematic literature review can be conveniently subdivided into eight main steps as part of this methodology. Initially, the research statement is formulated which denotes the main topic to focus the research, followed by the creation and validation of a review protocol such as the PRISMA framework (Rethlefsen et al., 2021) to take into consideration what kind of related journal articles need to be reviewed and used in this study. After that, the critical part consists of determining inclusion and exclusion criteria, which would decide what kind of information is needed or not (Koym, 2022). Then, the literature search is performed using one or many search engines, search tools and/or search databases.

The following search query was used as refined keywords: 1: 'digital technologies' AND 'climate change adaptation' AND 'fisheries and aquaculture', 2: 'digital technologies' AND 'fisheries and aquaculture', 3: 'climate change' AND 'fisheries and aquaculture', 4: 'fisheries and aquaculture' AND 'digital technologies'.

Data reliability refers to the duplication of study results using equal measuring instruments while data validity is the measurement of whether there is sufficient evidence or theory for the search topic (Chetwynd, 2022). A benchmark was set on the meta-scientific data obtained and was initially tabulated on an Excel sheet for an initial analysis while eliminating duplicate records. The inclusion criteria must be able to categorize research, be reliably interpreted, and reduce the volume of literature to a level that is manageable for the review. Even though not all methodological criteria must be used for screening, studies may be excluded (exclusion criteria) if they fail to meet any of them (Xiao and Watson, 2019). The final step is getting the collection of studies ready for extraction of related data and performing a synthesis as quality assessment, which acts as a refined sieve to polish the whole-text articles. The criteria's reasonableness and defiance ability are the most crucial factors at this stage.

The collection of studies (Table 1) was viewed and analyzed within the inclusion criteria which need to treat all related issues about technological advancement of the fisheries and aquaculture sector. Other criteria could be the different tools used in the research. The exclusion criteria therefore treat all related issues about technology without addressing the climate change subject. Thus, after careful analysis and proofreading, the total number of research papers used in this study was reduced to 32. The following table drafts the titles of those papers, alongside their authors and the year in which they were published (Table 2).

Table 1 First count of research papers obtained

Search Number	1	2	3	4
Number of papers	17	30	28	16

Figure 1 demonstrates the number of years there has been interest for researchers to work in that field of study. There have been numerous studies published in year 2017 and 2020. The years 2021 and 2023 had the same number of research publications. It is expected that research will continue while the graph displays a linear projection curve which has a positive coefficient.

Figure 2 describes the different types of papers available from the 'Google Scholar' meta-database. It is visible that there had been an interest in published journal articles rather than review articles. Nevertheless, only 5 conference papers were found compared to 12 and 15 review and article papers respectively.

Figure 3 shows the different types of data used by researchers the main component of the data used is the theoretical component with 13 researchers, followed by review data with 10 researchers and finally, 9 researchers used quantitative data.

Table 2 Research papers used for this study

Title	Years	Authors
Advances in geographic information systems and remote sensing for fisheries and aquaculture	2013	Meaden and Manj arrez
Remote fish aquaculture monitoring system based on wireless transmission technology	2014	Sung, Chen and Wang
Advanced application of geospatial technology for fisheries perspective in the Tarai region of the Himalayan state of Uttarakhand	2015	Ingole et al.
Automated Monitoring System for the Fish Farm Aquaculture Environment	2015	Chen, Sung and Lin
Coping styles in farmed fish: consequences for aquaculture	2015	Castanheira et al.
Application of machine vision systems in aquaculture with emphasis on fish: state-of-the-art and key issues	2016	Saberioon et al.
A proposed fish counting algorithm, using digital image processing techniques	2017	Aliyu et al.
Advances of genotyping-by-sequencing in fisheries and aquaculture	2017	Li and Wang
Applications of next-generation sequencing in fisheries research: a review	2017	Kumar and Kocour
Intelligent feeding control methods in aquaculture with an emphasis on fish: a review	2017a	Zhou et al.
Near-infrared imaging to quantify the feeding behaviour of fish in aquaculture	2017b	Zhou et al.
IoT-based automated fish farm aquaculture monitoring system	2018	Saha, Rajib and Kabir
Near-infrared computer vision and neuro-fuzzy model-based feeding decision system for fish in aquaculture	2018	Zhou et al.
How emerging data technologies can increase trust and transparency in fisheries	2019	Probst
Innovations and digital transformation of the Russian fishery complex	2019	Kharin, Kuzin and Mnatsakanyan
A secure fish farm platform based on blockchain for agriculture data integrity	2020	Hang, Ullah and Kim
Automatic recognition methods of fish feeding behaviour in aquaculture: a review	2020	Li et al.
Genomes of major fishes in world fisheries and aquaculture: status, application and perspective	2020	Lu and Luo
Intelligent monitoring and control technologies of open sea cage culture: a review	2020	Wei, Wei and An
Prospects and opportunities for the introduction of digital technologies into the aquaculture governance system	2020	Gorbunova et al.
Technological applications and adaptations in aquaculture for progress towards sustainable development and seafood security	2020	Mustafa et al.
Application of machine learning in intelligent fish aquaculture: a review	2021	Zhao et al.
Aquaculture in Brazil: past, present and future	2021	Valenti et al.
Computer vision models in intelligent aquaculture with emphasis on fish detection and behavior analysis: a review	2020	Yang et al.
Digitalization in the context of solving ecosystem problems in the fishing industry	2021	Mnatsakanyan and Kharin
An overview of disruptive technologies for aquaculture	2022	Yue and Shen
AI and IoT-based collaborative business ecosystem: a case in Chinese fish farming industry	2023	Yang et al.
Digital transformation on aquaculture in indonesia through efishery	2023	Zainudin et al.
The application and research of new digital technology in marine aquaculture	2023	Zhang and Gui
The role of digital technologies in supporting and improving fishery and aquaculture across the supply chain-Quo Vadis	2023	Rowan

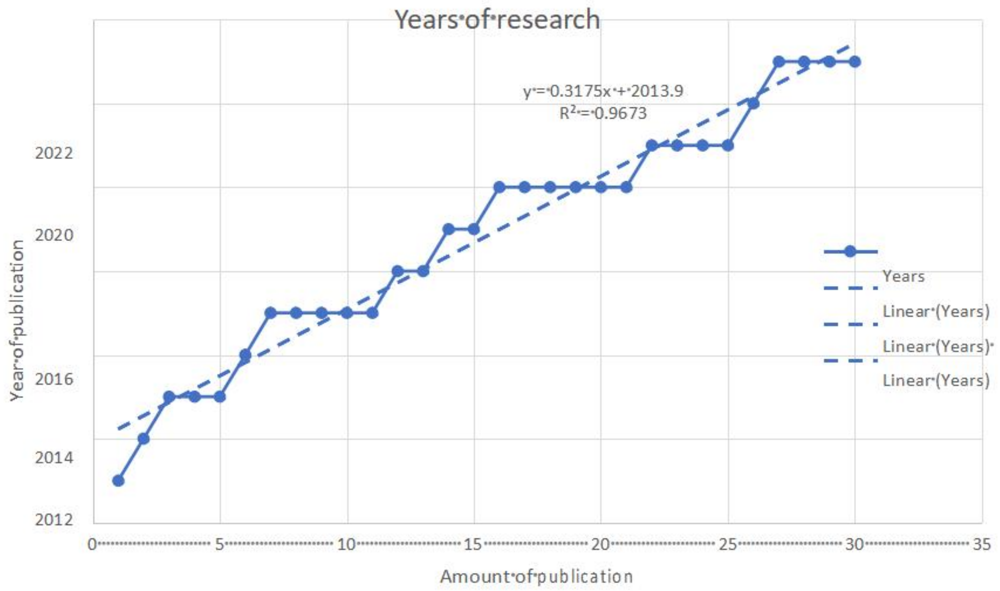

Figure 1 Number of years research was performed

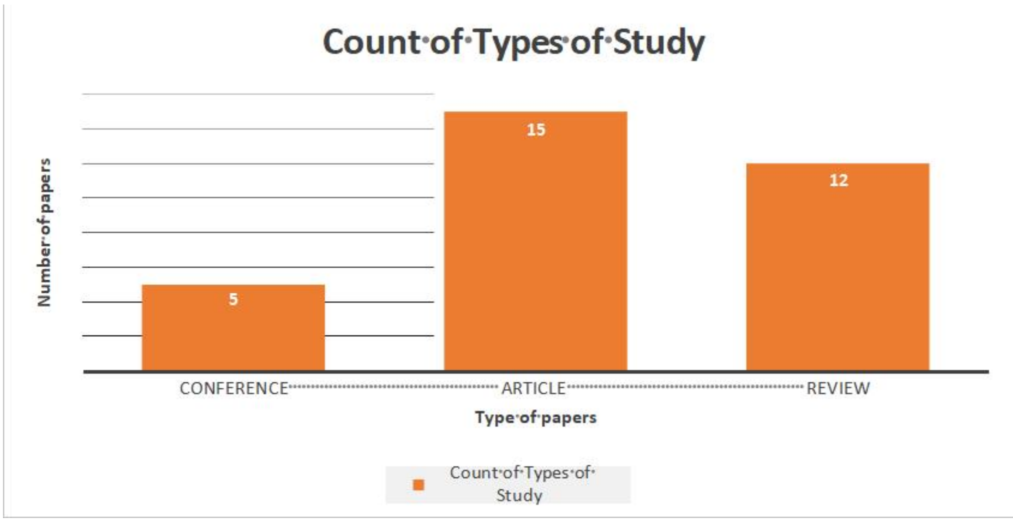

Figure 2 Types of study performed by researchers

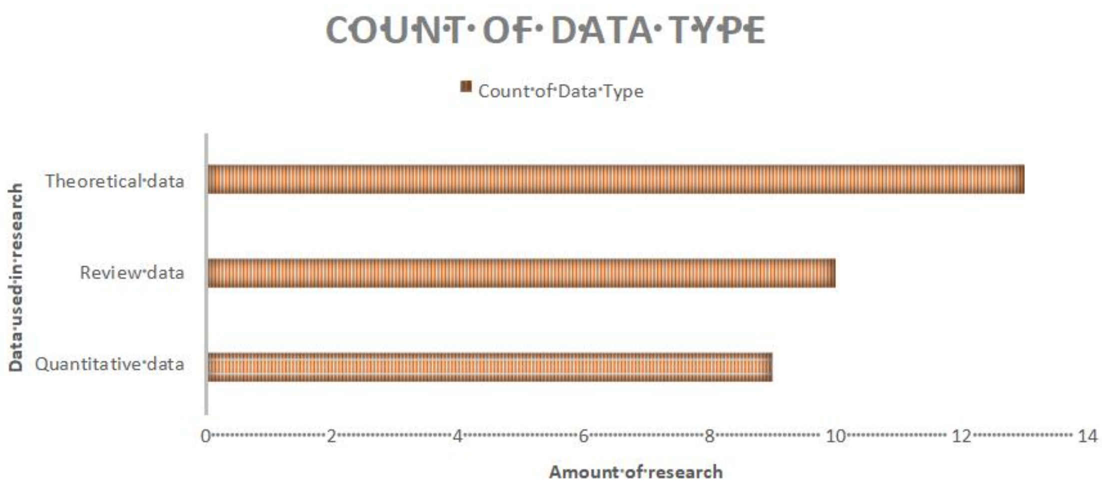

Figure 3 Type of data used by researchers

Figure 4 shows the number of research done per different categories that addressed the issue of climate change and fisheries/aquaculture. Most of the researchers focused on sensors and genetics as a means of climate mitigation and as a digital technological tool for adaptation.

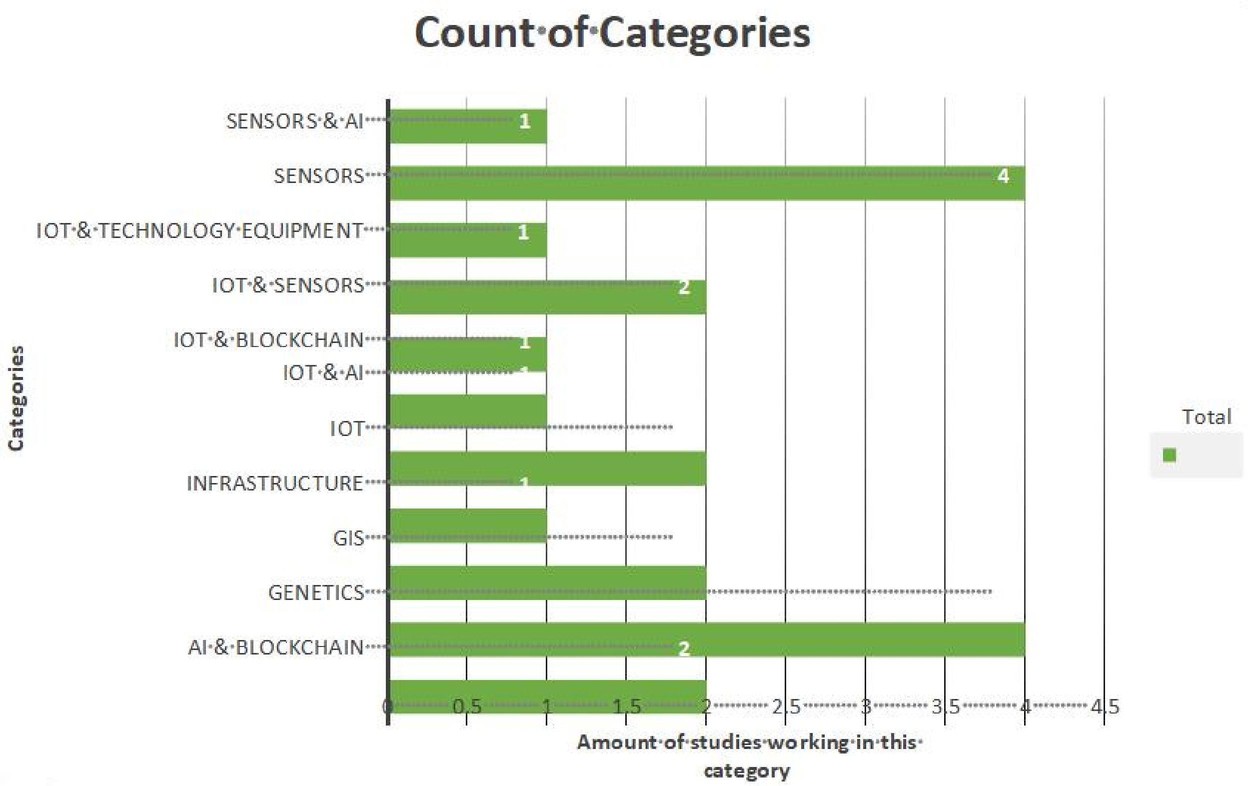

Figure 4 Categories addressed by researchers

4 Analysis and Discussion

4.1 Internet of things artificial intelligence and blockchain

In their study, Zhang and Gui (2023) described novel digital approaches in the seafood industry, including the intensive use of intelligent aquaculture equipment that could monitor remotely the freshwater quality from inland aquafarms, provide automatic feeds in inland aquafarms (Li et al., 2020), automatically clean the processing facility and automatically fish after adequate growth cycle, all based on technology using telemetry systems, satellite remote sensing, acoustic sensors, and IoT sensors used to monitor ocean health, fish populations, illegal fishing activities, fish behaviour, migrations, noise pollution and water quality amongst others. Nevertheless, the fishery technological sector has not been able to improve substantially as it requires quite a financial investment.

Zhang and Gui (2023) also proposed some novel technologies that could be used in the coming years to develop and improve marine aquaculture, as confirmed by Wang et al. (2021). There are some technologies which are mainly being used such as IoT (Internet of Things), big data and cloud computing, the blockchain (Hang et al., 2020) artificial intelligence, data analysis and sharing and finally data encryption, prediction and decision making, (Zhou et al., 2017b). Probst (2019) focused on the use of blockchain, data mining and artificial intelligence that could be problematic for local fishermen. The fishermen might perceive the use of those technologies as a possibility for authorities and large companies to deplete their ocean resources. Furthermore, the author added that the technical equipment needed to maintain blockchains in real time is very costly. The volume of information via satellite systems is very different than on land stations and the cost is very high.

According to Cordis (2021) and Kok et al. (2021), with the use of acoustic eco-pulsing technology, fish products could be tracked and farmed where those species find their host forage. The report further stated that this technology, known as fish finder, would be mostly used for commercial rather than recreational fishing, in the context of climate change adaptation to aquaculture and fisheries. A 3-D environment is created to analyze mass fishes swimming along different directions and would use sensors to have a good head count.

Rowan (2023) noted that alongside the development of these digital tools (Gorbunova, 2020), this could be simultaneously synchronized to provide a real-time analysis (Saberioon et al., 2016), and while using machine learning and artificial intelligence, it could easily manage large amounts of data. Machine learning algorithms could predict fish populations, identify fishing patterns, and detect anomalies in ocean data (Er-Rousse and Qafas, 2024). Data visualization tools could help visualize complex data, identify trends, and inform decision-making. Predictive modelling may forecast fish migrations and optimize fishing operations. Rowan (2023) described that aquaculture production in Central Luzon and Calabarzon in the Philippines had increased consistently, indicating successful operations. However, some locations experienced production variations, requiring targeted interventions. Machine learning techniques, such as Linear Regression, Support Vector Machine, and Multi-Layer Perceptron, could improve forecasting accuracy, aiding in long-term fisheries management. Likewise, Saha et al. (2018) focused on the aspect of the Internet of Things which could be used to monitor the inland aquaculture system at a low cost. The IoT would involve capturing images (Sung et al., 2014.) and performing processing to control heaters, aeration facilities, actuators or feeding systems through the physiological component of the breeds. Since this is a very cheap and easily understandable technology, the farmers and fish breeders may have sufficient control over their production.

A fish farm in Norway adopted IoT sensors to monitor water quality, track fish growth, and detect disease outbreaks. The sensors provided real-time data, enabling the farm to optimize feeding, reduce waste, and improve fish welfare (Zhang and Gui, 2023). As a result, the farm increased its production by 20% and reduced its environmental impact by 15%.

Technological breakthroughs have been noticed in the use of submersible aquatic farming cages such as Aquapods (Connolly, 2018), vertical aquaponics and genetics modifications. Likewise, Wei et al. (2020) described the fact that using open-sea close cages could be a possible solution to maintain a mode of marine aquaculture. The use of different sensors such as water quality sensors, intelligent monitoring sensors (Ibrahin et al., 2017) and automatic level sensors have been described by the author as devices that could be used in the open sea cage aquaculture system. Nevertheless, the author again noticed that there had been problems with the wirings which could not transmit the required information effectively. Due to failed data conveyance, there had been less glitch in real-time monitoring of the water quality. The use of machine vision, camera sensors and sonar technologies failed to provide adequate information due to an unknown seabed environment and the limitations of the vision sensors (Zhou et al., 2018). Another digital challenge depicted by Rowan (2023) is the use of blockchain in the fishery sector where a safe model of the fish business model can be mapped reducing frauds and improving traceability of the farmed fish to fork while avoiding wastages and disease proliferation. Mobile apps and online platforms could facilitate real-time communication among fishermen, fisheries managers and researchers. Virtual reality could enhance training and education. Autonomous underwater vehicles would monitor ocean health, fish populations and pollution.

Zhao et al. (2021) reviewed the use of machine learning for the aquaculture system, as compared to the traditional machine system, the development of deep learning and neural network systems have a high scope in breeding intelligently (Yang et al., 2020) concerning the climate differences. The machine learning system would add the component of data processing, information manipulation, real-time monitoring and decision-making process to facilitate the production of fisheries products. Nevertheless, the high complexity of this system together with difficulty in conjugation climate modelling, geographical mapping and biological control, proved that this system is not reliable for maintaining climate-smart production.

Connolly (2018), described extensively the use of sensors that could be used to regulate the physiological environment of farmed fish through the regulation of water pH level, monitoring salinity of water, control of oxygen and carbon dioxide levels, and handling turbidity and pollutants. The author also emphasized that through e-fishery, the sensors can detect and control the hunger level of fish and distribute feed subsequently (Zhou et al., 2017a). Robotics could automate fish farming operations, monitor water quality, and detect disease outbreaks. Automated fishing may be geared towards optimizing operations, reducing bycatch, and improving fish welfare.

Santos (2023) reported that a floating solar technology developed by industrials could help in aquaculture projects but there has been a dearth of research on this topic such that no relevant scientific articles have been found treating this subject. This technology was established to use floating solar panels on top of farmed cages to create electrical energy required for the level of temperature of the water and for powering the fish farms.

4.2 Genetics

Kumar and Kocour (2017) denoted the use of genetic bottleneck to modify the DNA sequence (Lu and Luo, 2020) of consumable fish species that would be revolutionary and sustain the different climatic constraints. The studies demonstrated that in Next- Generation Sequencing, there had been a large opening of information about genomic sequencing as described by Li and Wang (2017) including the genes variation, mutations and physiological effects of the organisms. Nevertheless, the NGS required large processing power and would be very costly. But there would need to be high hope that a vast variety of species be studied using this NGS method.

According to Robledo et al. (2018), their study successfully demonstrated the efficiency and effectiveness of technology in combating the Amoebic Gill Disease through the genetic manipulation of traits potentially contributing to disease resistance. The genetic architecture would enable the original genetic sequencing to develop traits for host resistance.

4.3 Geographical information system

According to Ingole et al. (2015), the use of a GIS system could help to track and keep control of the culture of land-based fisheries while enhancing economic returns. Using this system would be a great way to control the different effects of extreme weather events susceptible to causing damage to fisheries and aquaculture. Aguilar-Manjarrez (2013) proposed that using GIS and remote sensing would lead to a sustainable fisheries and aquaculture industry. It is important to have a marine spatial planning protocol that would help extract the information while empowering policy-making to act accordingly about the changing climate.

Meaden (2019) demonstrated the use of GeoCrust 2.0, a GIS developed by the University of Algarve, which is used in Portuguese fisheries to store, analyze, and display data from Vessel Monitoring Systems (VMS). The data is grouped into 0.2 by 0.2 nautical mile gridded cells, with trawling frequency and depth varying from zero to over 115. The data is divided into seven zones, with the proportion of different catch species and catch rate per hour displayed. Likewise, the author showed that The Gulf state of Oman relies heavily on fisheries for employment, income, and food due to limited resources. Most of the catch occurs in coastal shelf waters in the southeast, primarily due to Somalia's upwelling. GIS maps show the seasonal spatial evolution of catches, highlighting the importance of sustainable fishing practices.

4.4 Usage of digital technologies and business models

According to Bachtiar et al. (2022), aquaculture maintenance and management require monitoring and forecasting water quality, with pH, dissolved oxygen, and temperature being key parameters. IoT can support this maintenance by monitoring pond water quality remotely. This device monitors temperature, oxygen content, pH, and turbidity levels, allowing fish farmers to monitor their production remotely. Real-time measurements of these parameters, which affect shrimp growth, can be accessed from smartphones or tablets, reducing the need for in-person monitoring.

Zainudin et al. (2023) demonstrated the e-fishery which connotates the use of digital platforms to provide a safe fishery that could be bred sustainably and be a sustainable contribution to food security. This model business could help farmers and fishermen to promote their catch while engaging in safe fishing practices. Kharin et al. (2019) likewise denoted that digital technologies could help the long travel of merchandise to retailers through a sustainable practice concerning the society of the future.

Rowan (2023) described the use of an integrated multitrophic aquaculture system developed by the Irish peatlands relying upon the micro-algae, bacteria and duckweed to manage the wetlands. With the use of Next-Generation sequencing, artificial intelligence and machine learning, this peatland could be converted into an aquaculture-prone area to sustainably breed certain types of fish adapted to such areas. This peatland had been earmarked to be suitable for deploying other digital technologies such as drones and robots aided with satellite systems to control the production of fisheries, meanwhile having real-time control of the production.

5 Conclusion

It can be concluded that this study showcased that there is literature and interest among researchers to continue reviewing papers and describe the positive effects of digital technologies on the management and production of fisheries and aquaculture.

The results from this study gave a large variation of digital components used throughout the world which have been successfully implemented. However, some disadvantages have been given that digital technologies could not resolve when applied to the industry of fisheries and aquaculture. This study addresses the safe practice of different digital and technological components which could be adapted to have sustainable food production.

Finally, it can be said that the use of digital technologies should work alongside fisheries and aquaculture production as a view to mitigate its effects. The use of machinery and tools can help to alleviate the effects of fish farming.

Conflict of Interest Disclosure

The author affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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