Asian Journal of Fisheries and Aquatic Research

Volume 26, Issue 2, Page 20-36, 2024; Article no.AJFAR.112353
ISSN: 2582-3760

Climate Change Impacts on Aquaculture Systems in Key Producing Nations: Assessing Vulnerability and Proposing a Novel Adaptation Measure

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

Article Information

DOI: 10.9734/AJFAR/2024/v26i2733

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/112353

Original Research Article

Received: 27/11/2023
Accepted: 01/02/2024
Published: 07/02/2024

ABSTRACT

Climate change poses a significant threat to the aquaculture industry, impacting both the productivity and sustainability of this vital sector. This study focuses on the vulnerability of the top aquaculture producing nations to climate change and explores potential novel adaptation strategy. The vulnerability assessment considered various factors, including the exposure of aquaculture systems to climate change, Productivity of the industry, climate change initiators and the GDP of each nation surveyed. The study identifies the United Kingdom (UK) aquaculture as the most vulnerable and at risk of climate change impacts followed by the United States of America (USA) and Nigeria's aquaculture. In terms of continents, Europe, Oceania, and Africa are identified as the most vulnerable regions, while America and Asia are considered the least vulnerable. The UK, with its extensive aquaculture operations and geographical exposure to climate change risks, faces significant challenges in adapting to changing conditions especially with the exit from European Union (Brexit). The USA, another major aquaculture producer, also faces vulnerability due to its diverse range of climatic conditions and coastal aquaculture operations. Nigeria, a prominent aquaculture producer in Africa, is highly vulnerable to climate change due to its dependence on

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freshwater aquaculture systems leading to low water usage in aquaculture despite vast marine water resource. Strict measures including novel adaptation measure such as the NanoSolar technique must be put in place in these countries in other to ensure that aquaculture production doesn't decline and also to ensure that global food security is not put under pressure with the growing world population size.

Keywords: Aquaculture; producing; productivity; global food security, climate change.

1. INTRODUCTION

Fish is an important source of protein and omega-3 polyunsaturated fatty acids [1]. These fishes can easily be obtained via captured or cultured fisheries. However with the the continued indiscriminate harvests in capture fisheries, the aquaculture sector is seen as the major solution to meeting the rising demand for fish globally [2,3]. According to FAO [3], aquaculture's contribution to global fish production has continued to rise, reaching 82.1 million tonnes (46%) out of the estimated 179 million tonnes of global production. Aquaculture is an important source of food and livelihood for many people globally, and its importance is expected to continue growing for years to come [4]. Global aquaculture production has been steadily increasing over the past few years [5].

However, this rapidly expanding industry is not immune to the impacts of climate change. Climate change poses significant threats to aquaculture systems worldwide, affecting water quality, species composition, disease prevalence, and overall productivity [6]. Climate change is expected to have a much greater effect on global aquaculture production [7,6]. Rising temperatures, changes in precipitation patterns, and ocean acidification are all expected to have a negative effect on aquaculture production [7]. Warmer temperatures can lead to increased disease outbreaks, while changes in precipitation patterns leads to water shortages and increased salinity levels [8,9], having a significant impact on aquaculture production, which is considered a risk to the world food production metrics [10,11], especially the dietary protein intake [12]. Thus, the aims of the study is to determine the vulnerability and risk of some top aquaculture producing countries from major continents to climate change using a new method.

2. MATERIALS AND METHODS

2.1 Study Area

The study area (Table 1) is spatially segregated based on continent, with the major producing country [13] on each continent.

Studies about climate vulnerability with respect to aquaculture have focused on rainfall and temperature [14], including water use in aquaculture, and a study on the assessment of vulnerability has also been conducted in some of the study area.

2.2 Climate Change Vulnerability Index

The CCVI is determined using three indices (equation 1), which include the climate change initiator measured using CO_2 emitted, exposure to climate change, which includes major environmental parameters like temperature and precipitation, and productivity measured from aquaculture production from each nation with the quantity of water used in aquaculture calculated using the formula (equation. 2) below:

$$\text{Vulnerability}(V) = (I+E)_n - (P)_n \ldots \quad \text{equation 1}$$

$$A_{WU} = (F_Q.\ 45m^3)_n \ldots\ldots \quad \ldots.\ \text{equation 2}$$

Assuming 45 m^3 is needed to produce 1kg of fish [15].

45m^3/kg according to Verdegem et al. [16] is basically the water requirement for extensive aquaculture. This value was however picked over intensive aquaculture system water use of 2.7m3/kg because it gives room to accommodate various aquaculture system in different countries because of its large value (45m^3/kg)

V= Vulnerability
I= Climate change initiator
E = Exposure to climate change
P= Productivity
A_{WU}= Aquaculture water use
F_Q= Fish quantity

Climate change vulnerability were measured using the above metrics because climate change major cause is through human anthropogenic activities bar the natural cause which might be not frequent such as volcanic eruption, orbit change and tectonic shifts. However Climate change records today are showing signs of global warming due to the release of greenhouse gases. Thus, for this study CO_2 is the major greenhouse gas considered as the climate change initiator(I). This initiator causes changes in climatic parameters that affects aquaculture production. In aquaculture, these basic climatic parameters are temperature and precipitation. Thus, to temperature and precipitation changes affects majority of other water quality parameters such as dissolved oxygen (DO), pH, turbidity. Also, this change leads to flooding and droughts which wreak havoc in the aquaculture industries such as fish escapement, destruction of aquaculture facilities and lack of water for aquaculture production respectively.

The I and E values are added and normalized, then the normalized aquaculture production values for each country are the subtracted to determine how vulnerable the aquaculture venture can be for each country and the continent.

The climate change initiator, exposure, and productivity indices (Table 2) values (1991–2022) are all normalised using the formula (equation 3).

Normalisation value = (initial value-minimum value) ÷ (maximum value-min value) …... equ.3

Each country's exposure, climate change initiator, and productivity normalised values are summed to give the exposure, climate change initiator, and productivity values for each continent. Likewise, the vulnerability level determined using Equation 1 is summed up based on the aquaculture-producing countries from each continent to give the vulnerability level by continent.

The following parameters (Table 2) are collated and analysed to determine the vulnerability level of each country and continent.

The parameters describing climate exposure, initiator, and productivity were selected based on the perceived notion and critical thinking that the initiator (greenhouse gases) is the major determinant of how hot the world is and has great influence on the amount or quantity of precipitation the earth receives. The final parameters selected for the assessment of climate change vulnerability in this study are listed in Table 3. The CCV were calculated by selecting two important variables for climate exposure, two proxy variables for productivity, and one proxy variable for the climate change initiator.

Climate change risk were determined using the equation below:

CCI = Vulnerability(V)n – Gross domestic products (GDP)n………..Equation 4

CCI = Climate Change Risk, n = Normalized values

CCI were determine using this formula because a risk is a likely threat that exploits how vulnerable an aquaculture system can be. Thus, the major buffer or asset against climate change vulnerability used in this study is the GDP (1991-2021) of each aquaculture country sampled based on fact that without a high or good GDP, the probability that a country would be able to adapt to climate change is likely low. A high GDP assists the government in providing the needed cushion (funding, facilities) for the aquaculture industries to adapt to climate and increase their fish production.

Climate indicators focus on greenhouse gas (GHG) emissions due to the fact GHG gases are the main cause of global warming and climate change [7]. By assessing the levels of GHG emissions, we can understand the extent of human activities contributing to climate change and the potential impacts on aquaculture production. This indicator helps identify countries that might be more vulnerable due to their own emissions or the emissions they are exposed to.

Table 1. Major aquaculture countries surveyed

Asia	Africa	America	Europe	Oceania
China	Egypt	Chile	Norway	Australia
India	Nigeria	North America	UK	New Zealand
Vietnam				Fiji
Bangladesh				
Indonesia				

Table 2. List of parameters that describe climate exposure, sensitivity, and climate change initiator (1991–2021) (World Development Indicator 2023) [17]

Exposure	Productivity	Climate change Initiator
1. Temperature	1. Fish Production	2. Worldwide governance indicator (WGI)- $C0_2$ Emission
3. Precipitation	2. Aquaculture water use(calculated-equation 2)	

Table 3. Final parameters selected for the assessment of climate change vulnerability in this study

Category	Sub-categories	Parameters
Exposure	Temperature Rainfall	Average monthly temperature Average monthly rainfall
Productivity	Fish production	Annually aquaculture production(tonnes) $Fish_{quantity}.45m^3$
	Water Use in Aquaculture	
Initiator	Worldwide governance indicator	CO_2 emissions (% per capita)

Exposure variables consider temperature and precipitation because temperature and precipitation are critical climate variables that directly affect aquaculture productivity [18,19]. Rising temperatures can lead to the loss of suitable habitats for fish, reduced oxygen levels, increased disease prevalence, and altered reproductive cycles. Changes in precipitation patterns can impact water availability and quality. Assessing exposure to these changes allows for a better understanding of the potential vulnerabilities of aquaculture producing countries.

Productivity measures focus on fish production and aquaculture water use. Assessing fish production and aquaculture water use helps evaluate the vulnerability of aquaculture systems to climate change. Changes in temperature, precipitation, or water quality can directly impact the productivity and sustainability of aquaculture operations. By considering these measures, we can identify countries that heavily rely on aquaculture for food security and economic growth, and therefore, have a higher vulnerability to climate change.

By combining climate indicators, exposure variables, and productivity measures, the methodology achieves a more comprehensive understanding of vulnerability. Climate indicators provide insights into global climate trends, exposure variables analyze the local context, and productivity measures assess the on-the-ground consequences. This holistic approach enables more accurate vulnerability assessments and facilitates targeted adaptation and mitigation strategies. The selected methodology aligns with the policy relevance of assessing vulnerability to climate change in aquaculture producing countries. Governments and international organizations can use these indicators and measures to identify vulnerable countries and prioritize resources for building resilience, implementing adaptive strategies, and supporting sustainable aquaculture practices.

3. RESULTS

3.1 Aquaculture Water Use by Countries

Chile Aquaculture consumed $650,000*1.33m^3$, with USA, UK, Norway, Nigeria, and Egypt Aquaculture consuming 20 million, 10 million, 75 million, 12 million, and 70 million$*1.33m^3$, respectively. Bangladesh, China, Indonesia, Fiji, and Australia consumed a water value of (118 million, 3.28 billion, 657 million, 2 billion, and 5 million) * 1.33 m^3, respectively. (Fig. 1).

3.2 Climate Change Indices

The least productive (in terms of water use and quantity of fish produced) countries are China, Indonesia, India, Bangladesh, Chile, Australia, New Zealand, and Vietnam, at a normalised value of 0.00. (Table 4). Fiji has the highest sensitivity rate at 0.19, followed by the United States, Norway, the United Kingdom, Egypt, and Nigeria at 0.023, 0.02, 0.007, and 0.001, respectively.

However, continental Africa is the most exposed to climate change at 0.115, followed by America and Oceania at 0.055 and 0.059, respectively, while the least exposed continents are Asia and Europe at normalized values of 0.049 and 0.048, respectively (Fig. 4). Africa is has the highest percentage of exposure to climate change (35%), followed by Oceania (17%), with Asia and Europe (15%).

Nigeria has a climate change initiator value of 0.92, with Egypt having a value of 0.64, Indonesia, India, Bangladesh, China, Vietnam, the USA, and Chile having 0.36, 0.12, 0.02, 0.08, and 0.93, respectively. Others, such as Chile, Australia, New Zealand, Fiji, Norway, and the UK, have 0.45, 0.72, 0.78, 0.36, and 0.72, respectively, as their initiator values (Fig. 5).

However, continentally, Oceania countries top the list for the major cause of climate change with respect to aquaculture production, followed by Europe, Africa, America, and Asia. Oceania has an initiator value of 1.86; Europe, America, Asia, and Africa have 1.72, 1.38, 0.73, and 1.54, respectively (Table 6).

Vulnerability indices for various top aquaculture-producing countries are found below. Nigeria, Egypt, and China have a vulnerability value of 0.92, 0.74, and 0.16, respectively. Indonesia, India, and Bangladesh the United Kingdom has a value of 0.37, 0.13, 0.12, and 1.12, respectively (Fig. 4). Others include Norway, the United States, Chile, Australia, New Zealand, Fiji, and Vietnam, with values of 0.73, 0.94, 0.47, 0.84, 0.82, 0.16, and 0.09, respectively (Fig. 6).

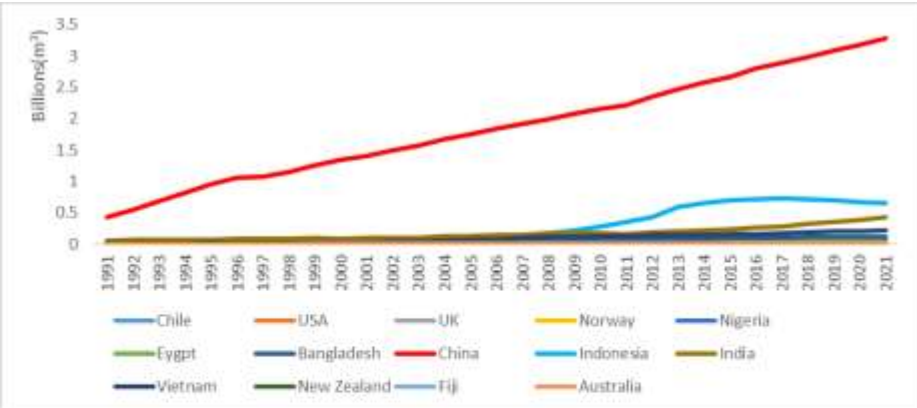

Fig. 1. Aquaculture Water Use (1991–2021). Values should be multiplied by 1.33 cubic metres to get the actual volume of water used in aquaculture in m^3. [20]

*Africa has a water use of 1 billion * 1.33 m^3, with Europe making use of 1.3 billion * 1.33 m^3, Asia Aquaculture consuming 75 billion * 1.33 m^3, Oceania 132 million * 1.33 m^3, and America at 1.6 million * 1.33 m^3 (Fig.2).*

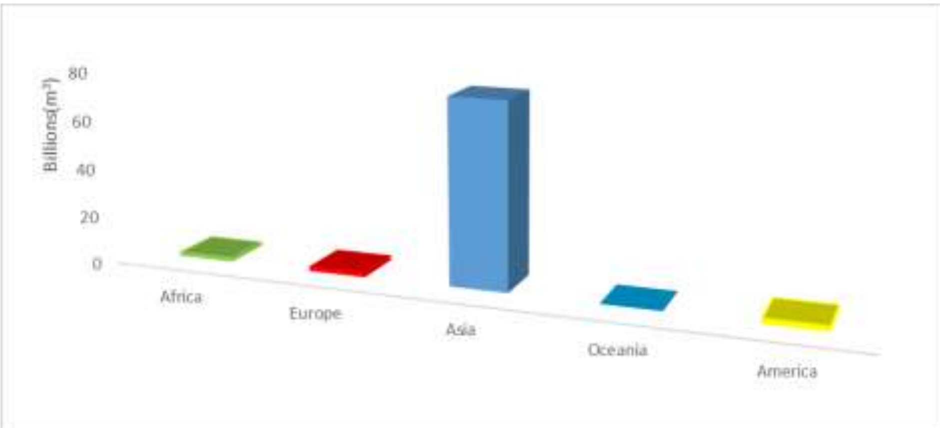

Fig. 2. Aquaculture Water Use (1991–2021)*1.33m^3 [20]

Table 4. Normalised productivity (1991–2021) [20]

S/N	Country	Production
1	Nigeria	0.001
2	Egypt	0.006
3	China	0
4	Indonesia	0
5	India	0
6	Bangladesh	0
7	UK	0.009
8	Norway	0.019
9	United States	0.023
10	Chile	0
11	Australia	0
12	New Zealand	0
13	Fiji	0.199
14	Vietnam	0

Oceania and Europe have a sensitivity of 0.198 and 0.029, while America and Africa have a climate change sensitivity value of 0.023 and 0.008 (Table 5).

Table 5. Normalised Production Value by Continent (1991–2021) [20]

S/N	Country	Production
1	Africa	0.008
2	America	0.023
3	Asia	0
4	Europe	0.029
5.	Oceania	0.198

Egypt has the highest exposure rate at 0.11, followed by the United States, the United Kingdom, and Norway at 0.034, 0.024, and 0.023, respectively. The least exposed countries are Bangladesh, Vietnam, and Fiji, at a normalised value of 0.003, 0.006, and 0.004, respectively (Fig. 3).

Table 6. Climate change initiator (1991-2021) (Data Source: World Development Indicator 2023)

S/N	Country	Initiator
1	Africa	1.54
2	America	1.38
3	Asia	0.73
4	Europe	1.72
5.	Oceania	1.86

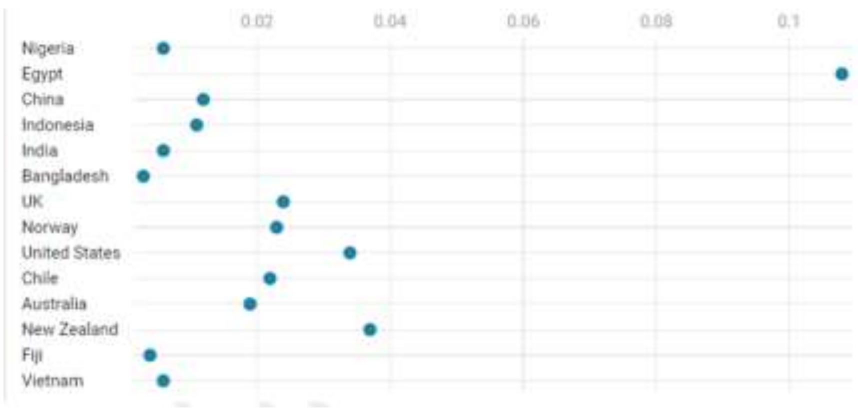

Fig. 3. Climate Change Exposure by Top Aquaculture Producing Countries (1991–2021) [17]

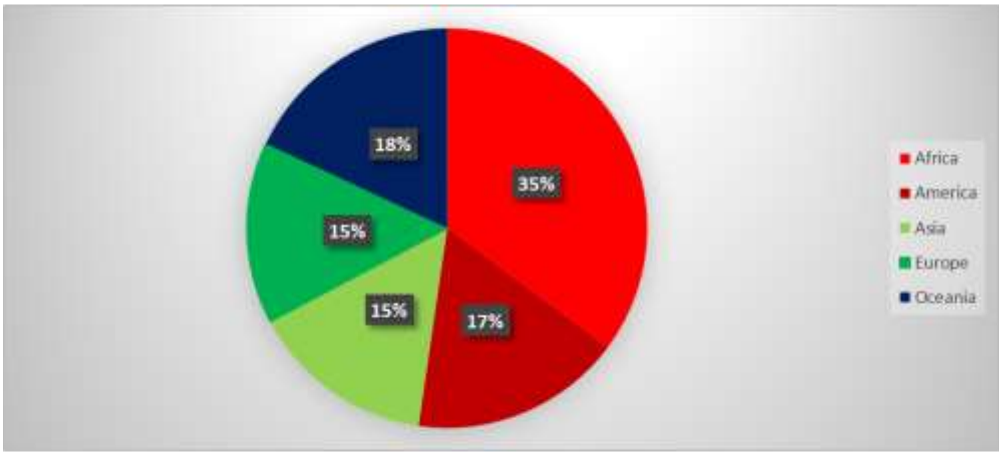

Fig. 4. Climate Change Exposure by Continent (1991–2021) [17]

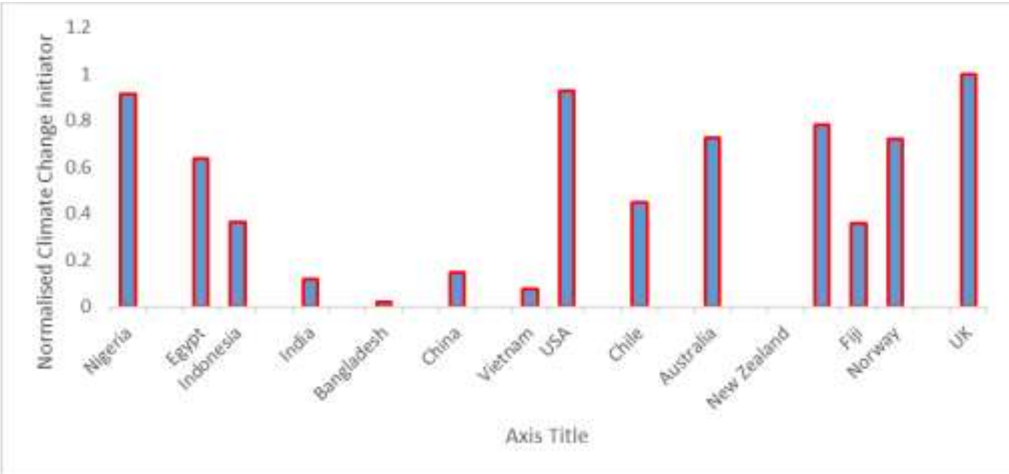

Fig. 5. Climate Change initiator (1991–2021) (Data Source: World Development Indicator 2023)

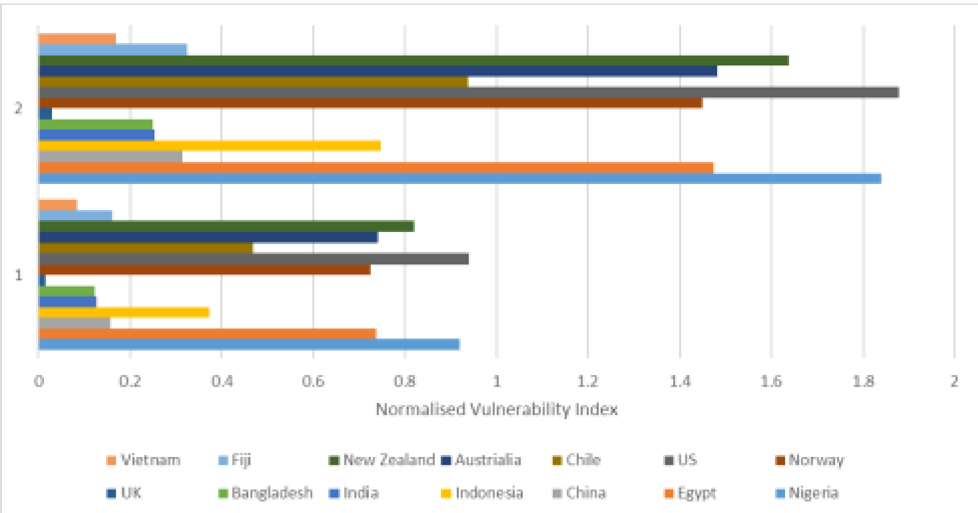

Fig. 6. Climate Change Vulnerability Index (1= 1991-2021; 2=30years Projected vulnerability level) [20,17] (World Development Indicator 2023)

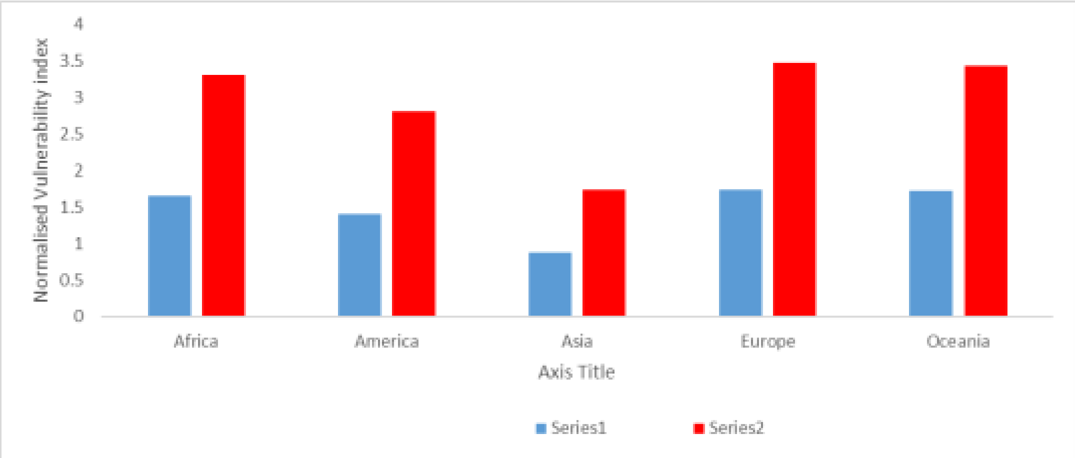

Fig. 7. Climate Change Vulnerability Index by continent (Series 1= Vulnerability level 1991-2021; Series2= 30years Projected vulnerability level) [20,17] (World Development Indicator 2023)

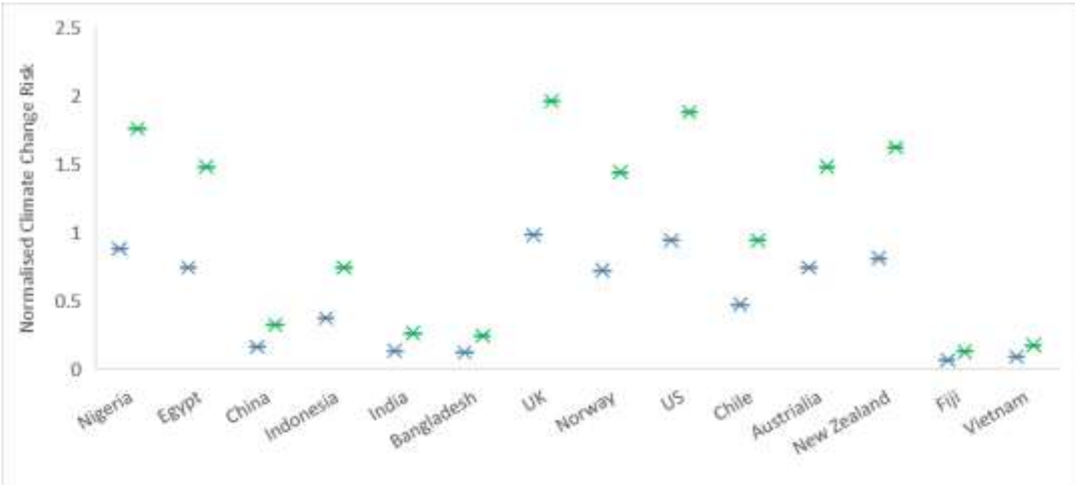

Fig. 8. Climate Change Risk by Countries [20,17] (Development Indicator 2023)

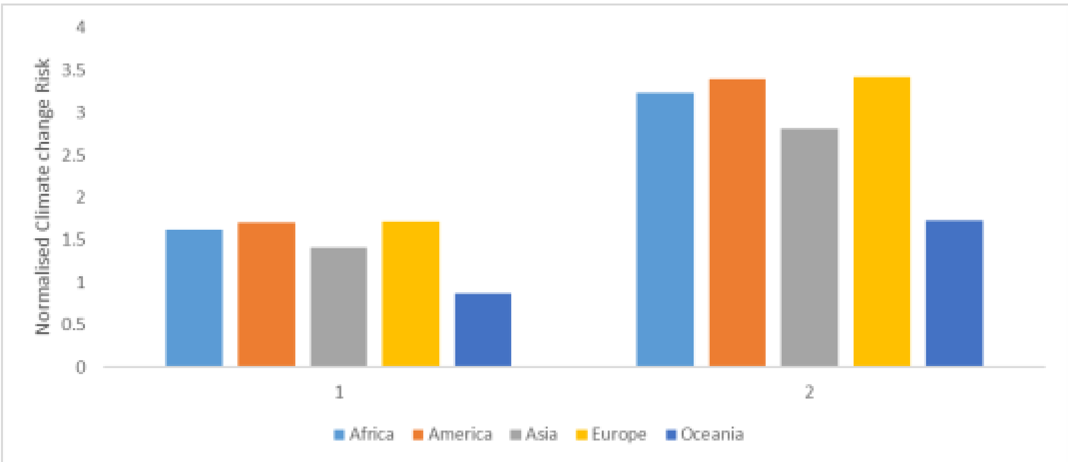

Fig. 9. Climate Change Risk by Continent. Series 1= Vulnerability level 1991-2021; Series2= 30years Projected vulnerability level). [20,17] (World Development Indicator 2023)

Africa's aquaculture vulnerability level is 1.66, with America's 1.41, Asia, Europe, and Oceania having vulnerability levels of 0.87, 1.74, and 1.72, respectively (Fig. 7).

United Kingdom Aquaculture has a normalised climate change risk of 0.98. Nigeria has 0.88, while India, Egypt, Fiji, New Zealand, and Norway have 0.13, 0.74, 0.16, 0.16,0.81 and 0.72 (Fig. 8).

Continental, Africa has 1.62, Europe has 1.7, and America, Oceania, and Asia have 1.41, 1.71, and 0.865, respectively (Fig. 9).

4. DISCUSSION

4.1 Climate Change Exposure, Initiator, and Production Indices

Egypt has the highest exposure rate at 0.11; this finding is similar to reports from Adeleke et al. [21], which state that 76% of fish farmers are aware that the aquaculture industry is exposed to climate change. The USA exposure results are also corroborated by Lam et al. [22] with findings stating that aquaculture is increasingly exposed to climatic changes. Norway's exact results are similar to Sandersen et al. [23] reports concerning exposure to climate change. The United Kingdom exposure results are similar to findings from Stewart-Sinclair et al. [14], who find out that the United Kingdom exposure risk has increased over time since 2020, and it has been predicted that this will be so until at least 2100, even with countries like Norway and Vietnam. The least exposed countries are Bangladesh, Vietnam, and Fiji, at a normalised value of 0.003, 0.006, and 0.004, respectively. Vietnam is showing a low exposure rate. Stewart-Sinclair et al. [14] data show that Vietnam has a high exposure rate to climate change. However, continental Africa is the most exposed to climate change at 0.115, followed by America and Oceania at 0.055 and 0.059, respectively, while the least exposed continents are Asia and Europe at normalised values of 0.049 and 0.048, respectively (Tab. 7). Africa, despite its low greenhouse gas emissions, is the most exposed continent to climate change.

Fiji has the highest productivity rate at 0.19, followed by the United States, Norway, the United Kingdom, Egypt, and Nigeria at 0.023, 0.02, 0.007, and 0.001, respectively. This is due to the optimal utilisation of available water resources in relation to the quantity of fish culture. The least productive countries are China, Indonesia, India, Bangladesh, Chile, Australia, New Zealand, and Vietnam, with a normalised value of 0.00 (Tab.4), showing that the water resources available can be used to produce a greater quantity of cultured fish. Also, this is corroborated by FA0 [20] findings that discovered that China only uses 35% of the water that is good for aquaculture, thus over 75% of the water is not put into aquaculture use, which reduces their aquaculture production.

Continentally, Oceania and Europe have a productivity normalised value of 0.198 and 0.028, while America and Africa have 0.023 and 0.008 (Tab. 4). This indicates that Oceania and European countries optimally utilize the water available for aquaculture, while America and Africa has low water use utilisation compared to the quantity of aquaculture fish they produce.

Fig. 8 indicates that the UK releases more CO_2 compared to other aquaculture countries, followed by the USA and Nigeria. This is similar to findings by the EU.

2023, which categorise the UK as the top emitter of greenhouse gases after Germany in the EU, with the USA also being a leading CO_2 emitter.

However, continentally, Oceania countries top the chart for the major cause of climate change with respect to aquaculture production, followed by Europe, Africa, America, and Asia. This is corroborated by Aljazeera 2023, who, on the basis of CO_2 per capita, ranks Oceania top after North America, with Africa having the least value of CO_2 emissions on a per capita basis [24].

4.2 Climate Change Vulnerability and Risk Index

The results indicate United Kingdom aquaculture is the most vulnerable to climate change, followed by United States and Nigerian aquaculture (Fig. 10). This result is unlike reports from [25], who found that there is little evidence that UK aquaculture is affected by climate change despite visible impacts from environmental variability because of rapid technological development. Murray *et al.,2022* found that despite the fact that temperatures remain suitable for salmon aquaculture until the century ends, Northern Ireland and Southwest Scotland might experience some changes in environmental parameters.

Continentally, Europe, Oceania, and Africa's aquaculture are the most vulnerable and have a high climate change risk (Figs. 9 and 10). Despite findings that indicate that Africa is generally considered the most vulnerable to climate change [26], it is important to note that Europe and Oceania aquaculture are also facing serious threats, while America and Asia aquaculture are the least vulnerable. This lower vulnerability of America and Asia could be attributed to high GDP and great financing of climate change projects, as America (USA) and Asia (China) have been the global powers economically. The results obtained in this analysis (Fig. 10) has a close link with Fig. 11 [27]. below, which shows a close relationship between the areas vulnerable (Fig. 10) to climate change and areas exposed to various degrees of anthropogenic activities (Fig. 11).

Also, it is important to note that some of the countries and regions vulnerable to climate change are not included in at least one of the NDCs (National Determined Contributions) (Fig.12) submitted to the UNFCCC (United Nations Framework Convention on Climate Change) which are created to address climate change impacts on communities and livelihoods within fisheries and aquaculture [28,30].

Fig. 10. Climate Change Vulnerability and Risk Index of the Top Aquaculture-Producing Countries

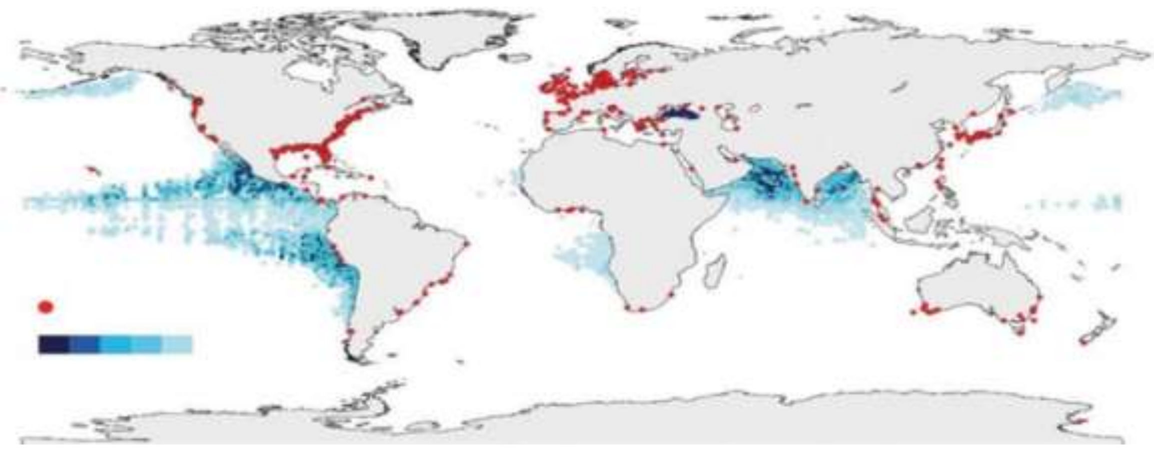

Fig. 11. Areas exposed to anthropogenic activities in blue and hypoxic areas in red [27]

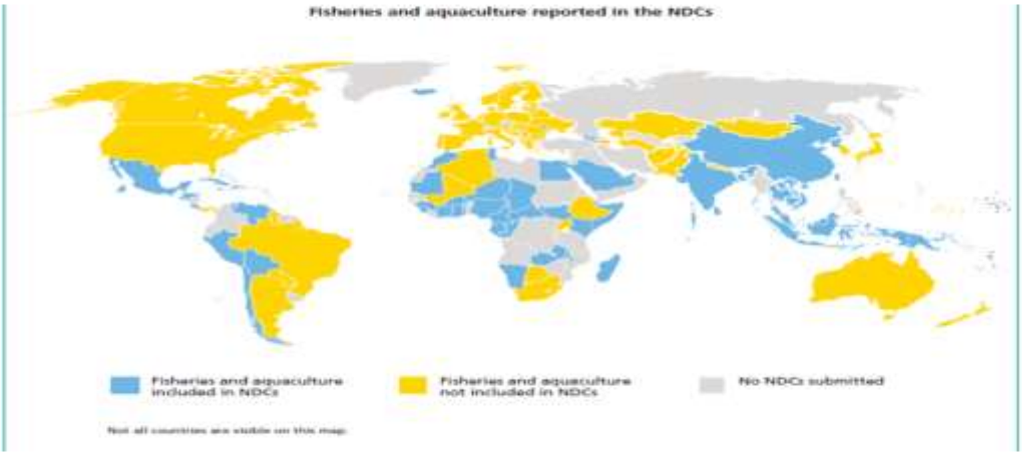

Fig. 12. Climate Change Vulnerability and Risk Index of the Top Aquaculture-Producing Countries [29]

5. NOVEL ADAPTATION STRATEGY

Nanotechnology is an emerging area of science that deals with applications of extremely small materials in many scientific fields, including biology, agriculture and aquaculture. These materials have excellent, unique properties (both chemical and physical) that make them suitable in many fields.

In aquaculture, it has been used in the dietary supplementation of certain minerals such as iron, zinc, and chitosan for improved feed conversion ratio, growth rate performance, and efficiency [31]. Nanotechnology is also critical in aquaculture water treatment, pollution remediation, biofuel production, and, most importantly, GHG emission reduction (Fig. 13).

These nanocomposites, nanocatalysts, nanocoatings, and nanolubricants are essential for GHG reduction. For instance, nanocatalysts assist in complete fuel combustion by storing oxygen, thereby limiting greenhouse gas emissions. Nanolubricant and nanocoating, on the other hand, help reduce engine friction, which greatly limits CO_2 emissions [33].

Nanotechnology-based products and NPs are also important in improving the efficiency of the use of renewable energies like biofuels and solar, which ultimately decrease fossil fuel dependency and thus reduce global warming [32]. The Following are nanomaterials that can be used to trap greenhouse gases in biofuels and Solar powered aquaculture operations (Table 7).

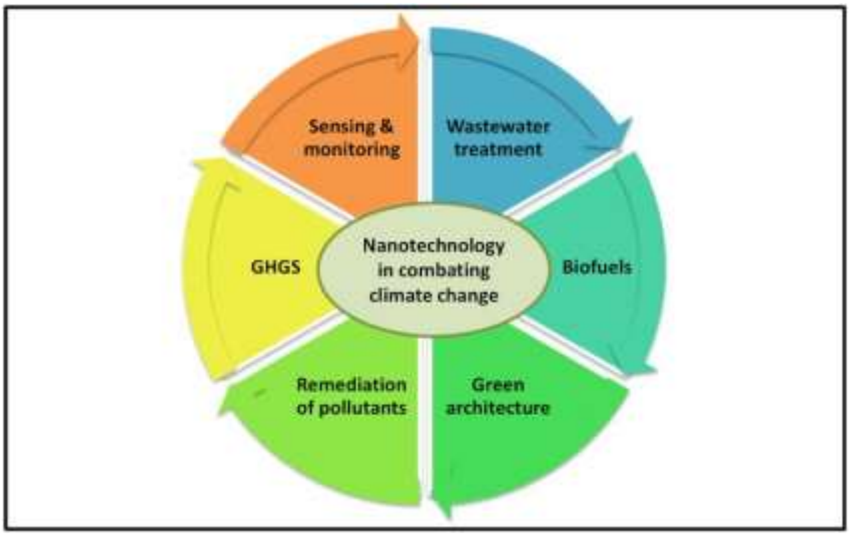

Fig. 13. Nanotechnology Use in Sustainable Aquaculture [32]

Table 7. Nanoparticles used for the reduction of greenhouse gases

Nanomaterial	Green-house gases that can be captured
Nano zeolites	CO_2 [34]
Modified activated carbon	SO_2 [35]
Carbon nanotubes (CNT)	CO_2 [36]
Mesoporous silica nanoparticles (MCMBs)	CH_4, CO_2 [37]
Graphene	CH_4, CO_2 [38]
Kerogen nanopores	CO_2, CH_4 [39]
Metal organic frameworks (MOFs)	
Organic hybrids materials (NOHMs)	CO_2 [40]
Cu nanoparticles	CO_2 [41]
Immobilized silver nanoparticles	CO_2 [42]
Chitosan-Sio2	CO_2 [43]
Polyphosphoric acid-modified MMT hybrids	CO_2 [44]
DD3R zeolite	Methane and CO_2 [45]
Gold nanoparticles (Au NPs) and Cu_2O	CO_2 [46]
Nickel Nanoparticles (NiNPs)	CO_2 [47]
Aluminum Oxide	CO_2 [48]
Tio_2	CO_2 [48]
$CaC0_3$ Nanoparticles	CO_2 [48]
Nanogel particles having amine groups	CO_2 [49]
Ionic Liquids (ILs)	CO_2 [50]
Gold-silver alloy and silver nanoparticles	CO_2 [51]
Fe_2O_3	CO_2 [52]
Fe_2O_3@glutamine	CO_2 [52]
Black gold nanoparticles	CO_2 [53]

It is important to note that recirculatory aquaculture system research was first carried out in Japan in the 1950s [54,55] and has been considered as a potent adaptation tool to climate change [56]. GHG emissions from RAS are released via energy consumption by the system [57] due to the fact that energy is continuously needed to pump and recycle water in fish tanks and perform other operations. Carbon emission in RAS has been estimated to be high as seen in Table 8 even from different sources.

However solar powered RAS has shown to reduce energy consumption than all other energy source [58]. Thus, Babiyola and Selva [59] designed a system that can be used for aquaculture using solar photovoltaic polycrystalline solar panels and cells that generates direct current which produces electricity for 8000 sq. ft aquaculture field. This reduces fossil-fuel powered operation dependency and greenhouse gases emission thereby making aquaculture environmentally friendly and sustainable (Figs.14 and 15) [59].

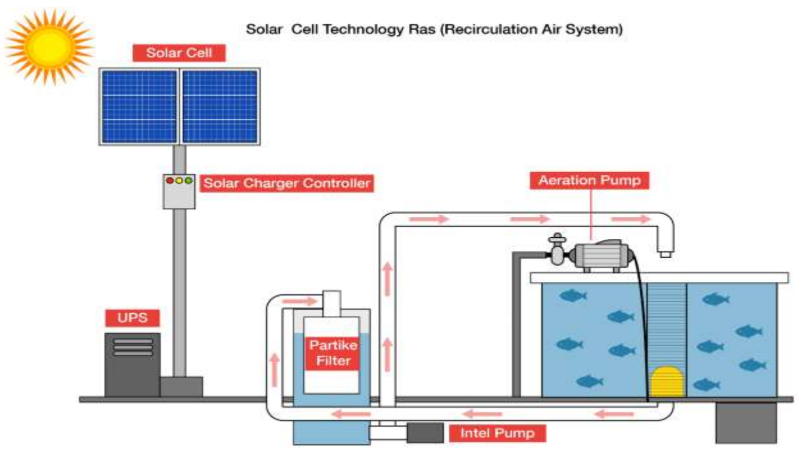

Fig.14. Solar Cell Powered Recirculatory Aquaculture System [60]

Table 8. CO_2 emission from RAS powered from different sources [56]

Aquaculture system	Country	Species	Emission ($kgCO_2$ eq/kg live weight)
RAS (hydropower electricity)	USA	Salmon	3.73
RAS (typical electricity)	USA	Salmon	7.01
RAS (100% non-renewable energy)	Spain	Cod	$16-27$
RAS (50% renewable and 50% non-renewable energy)	Spain	Cod	$12-18$
RAS (electricity and oil-fired heater)	Canada	Salmon	28

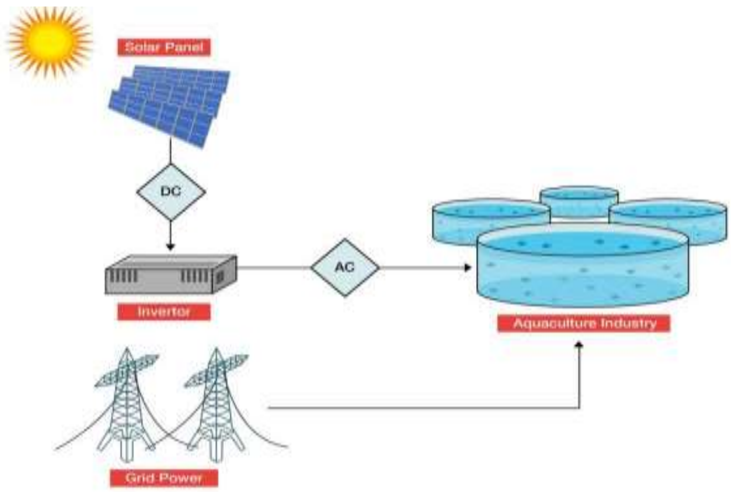

Fig. 15. Solar Panel Recirculatory Aquaculture System [60]

Many countries in Europe and America are continually investing in recirculatory systems to limit the environmental impact of aquaculture and adapt to climate change. While in Africa aquaculture, there is growing interest in this climate-smart aquaculture method (RAS) to adapt to the impact of climate change while also enhancing profitability and the continued interest of farms in aquaculture [61] Asia, the largest producer of cultured fish in the world, including many countries in the region, has adopted climate-smart ways of culturing fish. For instance, China has invested massively in the use of recirculatory aquaculture systems, while in India and Indonesia, it is relatively new. However, most of this recirculatory system are powered using fossil fuel source or non-renewable source which contributes to high release of greenhouse gases but Solar-powered recirculatory has shown to be a powerful, smart-aquaculture system to adapt to climate change because of the drastic reduction in GHGs emission. Coupling this solar panels with Nanomaterials screens that absorbs the small quantity of greenhouse gases emitted which are used to power various operations in Aquaculture zone, aquaponics, Biflocs and integrated aquaculture system leads to very efficient way of adapting to climate change.

6. CONCLUSION

The vulnerability of selected Aquaculture producing countries, such as the UK, USA, and Nigeria, to climate change is significant. These countries are highly prone to the effects of climate change, which can have profound impacts on their Aquaculture industries.

To address these vulnerabilities, it is crucial for these countries to implement adaptive measures and policies. This includes diversifying aquaculture species and systems that are more resilient to climate change, the use of Nanosolar technology and investing in research and development for better breeding techniques and disease prevention measures. Additionally, improving water management practices, such as efficient water conservation methods, can help mitigate the impacts of changing water availability.

International collaboration and knowledge sharing can also play a significant role in implementing effective adaptation strategies. Sharing best practices and technologies, as well as providing financial assistance to support vulnerable countries in building their adaptive capacity, can contribute to the long-term sustainability of aquaculture industries globally.

In conclusion, the vulnerability of the UK, USA, and Nigeria to climate change poses significant risks to their aquaculture industries. Timely and concerted efforts are needed to develop and implement adaptive measures such as the novel NanoSolar powered aquaculture system to ensure the resilience and sustainability of these industries in the face of climate change.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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