Vulnerability level of Selected Aquaculture Producing countries to Climate Change.

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 adaptation strategies. 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 freshwater aquaculture systems leading to low water usage in aquaculture despite vast marine water resource. Strict measures 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.

1.0: INTRODUCTION

Fish is an important source of protein and omega-3 polyunsaturated fatty acids(Li and Hu, 2009). 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 (AskarySary *et al.,* 2012; FAO, 2020). According to FAO (2020), 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 (OECD and FAO, 2021). Global aquaculture production has been steadily increasing over the past few years (Naylor *et al.*, 2021).

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 (Sahya *et al.,* 2021). Climate change is expected to have a much greater effect on global aquaculture production (IPPC, 2007; Sahya *et al.,* 2021). Rising temperatures, changes in precipitation patterns, and ocean acidification are all expected to have a negative effect on aquaculture production (IPPC, 2007). Warmer temperatures can lead to increased disease outbreaks, while changes in precipitation patterns leads to water shortages and increased salinity levels (Fleming *et al.,* 2014; Zolnikov, 2019), having a significant impact on aquaculture production, which is considered a risk to the world food production metrics (Beach and Viator, 2008; Myers *et al.*, 2017), especially the dietary protein intake (Kandu, 2017). 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.

2.0: MATERIALS AND METHOD

2.1. Study Area

The study area (Tab.1) is spatially segregated based on continent, with the major producing country (FAO, 2022) on each continent.

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

Bangladesh
Indonesia

Table 1: Major aquaculture countries surveyed

Studies about climate vulnerability with respect to aquaculture have focused on rainfall and temperature (Stewart-Sinclair *et al.*, 2020), 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:

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

$$A_{WU} = (F_Q.\ 45m_3)_n \text{ ………………………… equation 2}$$

Assuming 45 m^3 is needed to produce 1kg of fish (Verdegem and Bosma 2009),

45m^3/kg according to Verdegem *et al.*, 2006 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.

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 2: List of parameters that describe climate exposure, sensitivity, and climate change initiator (1991–2021) (World Development Indicator 2023; Climate Knowledge 2023)

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.

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

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

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 (IPCC 2007). 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.

Exposure variables consider temperature and precipitation because temperature and precipitation are critical climate variables that directly affect aquaculture productivity (Mehrim, and Refaey, 2023; Siddique *et al.*, 2022). 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.

3.0: RESULTS

3.3: 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)

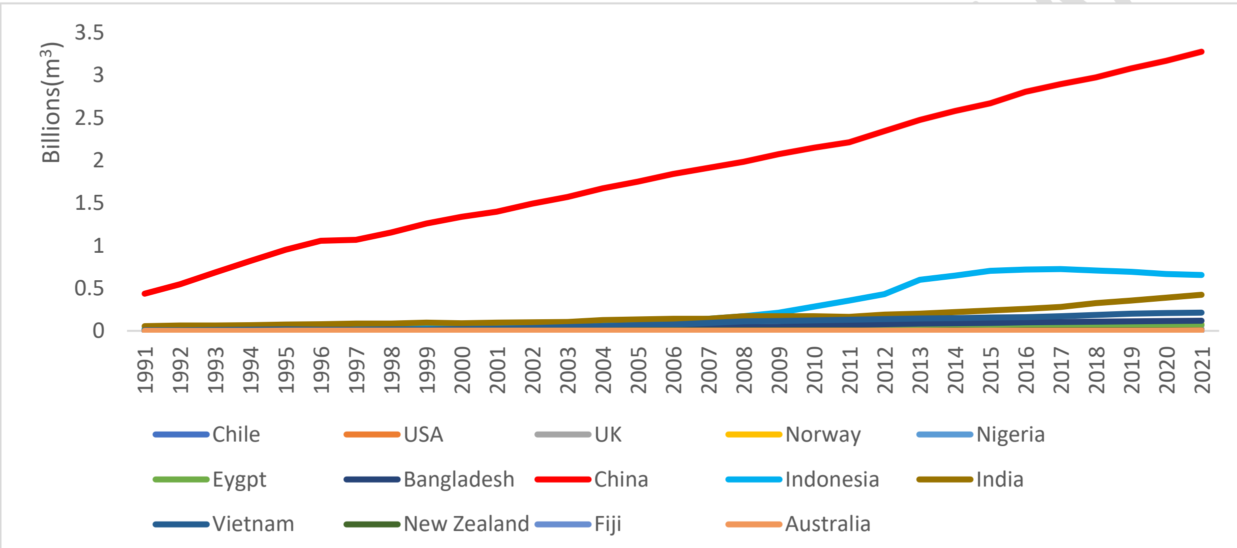

Fig. 1: Aquaculture Water Use (1991–2021). Values should be multiplied by 1.33 cubic metres to get the actual volume of water used in aquaculture in m^3. (Data source: FAO 2023)

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).

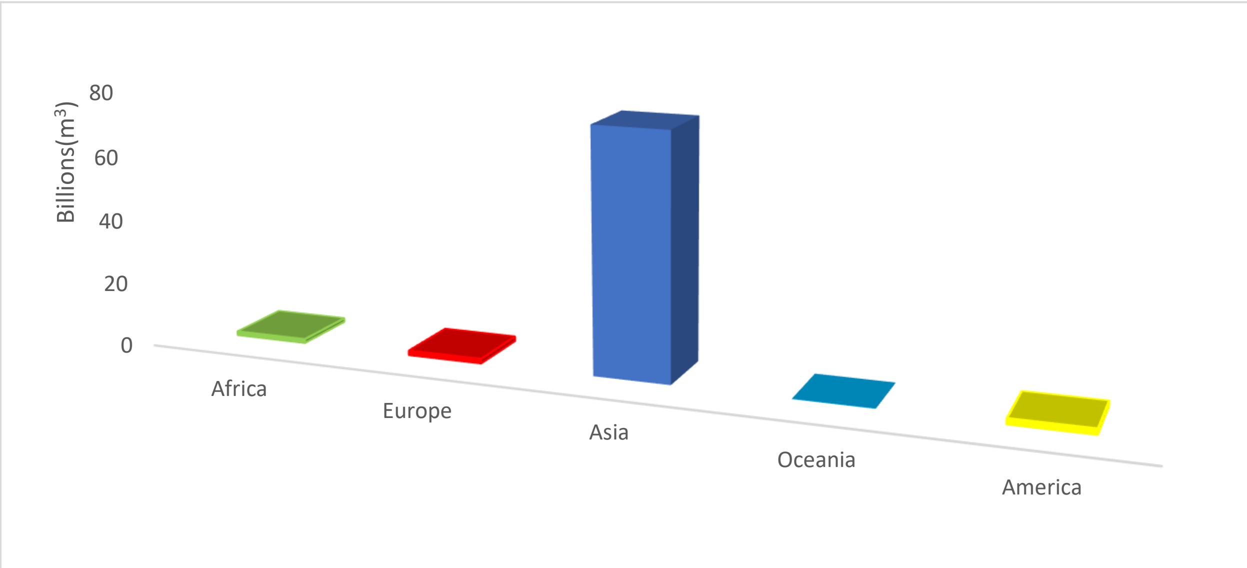

Fig. 2: Aquaculture Water Use (1991–2021)*1.33m^3 (Data source: FAO 2023)

3.4: 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

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

Table 4: Normalised productivity (1991–2021) (Data source: FAO 2023)

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).

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

Table 5: Normalised Production Value by Continent (1991–2021) (Data source: FAO 2023)

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).

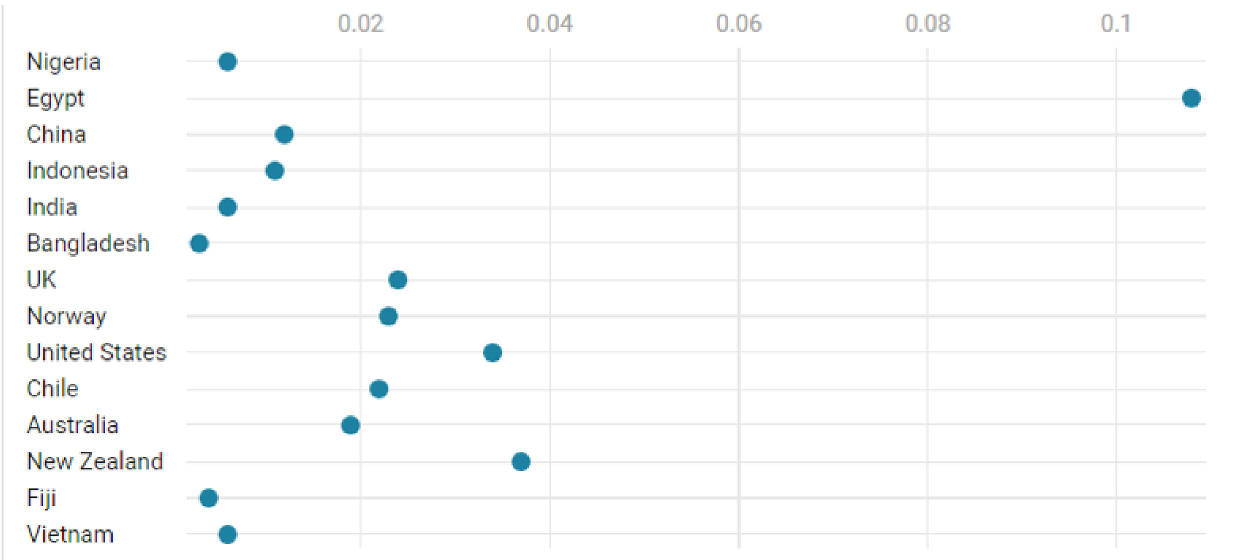

Fig. **3: Climate Change Exposure by Top Aquaculture Producing Countries (1991–2021) (Data Source: Climate Knowledge 2023)**

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%).

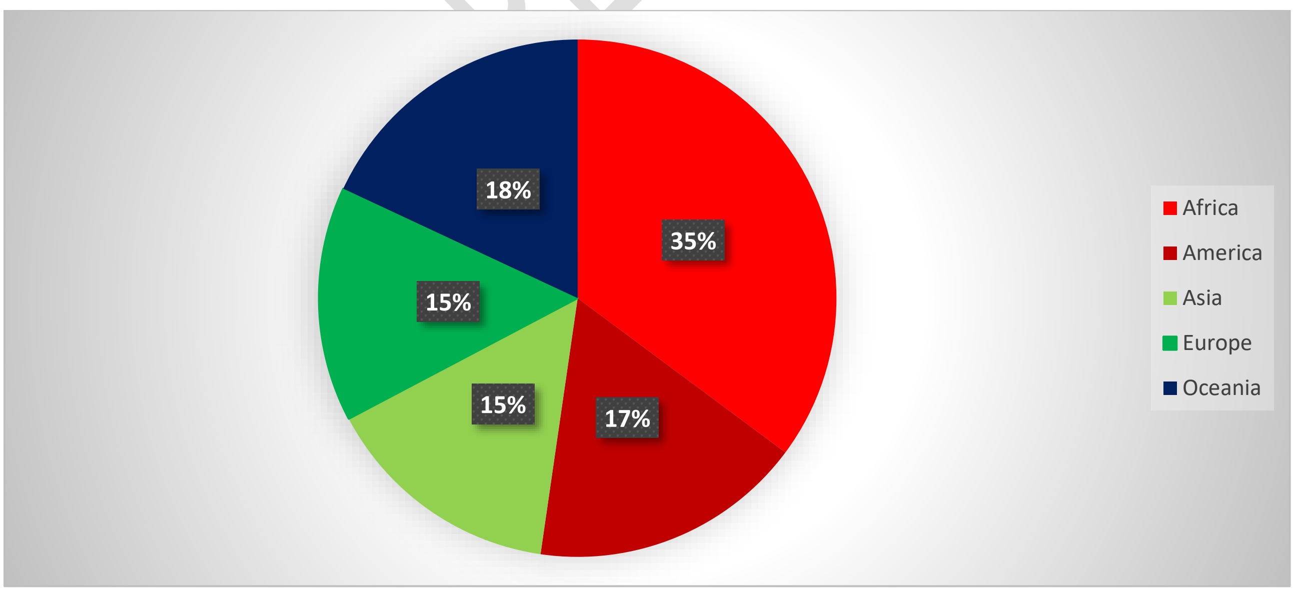

Fig.4: Climate Change Exposure by Continent (1991–2021) (Data Source: Climate Knowledge 2023)

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).

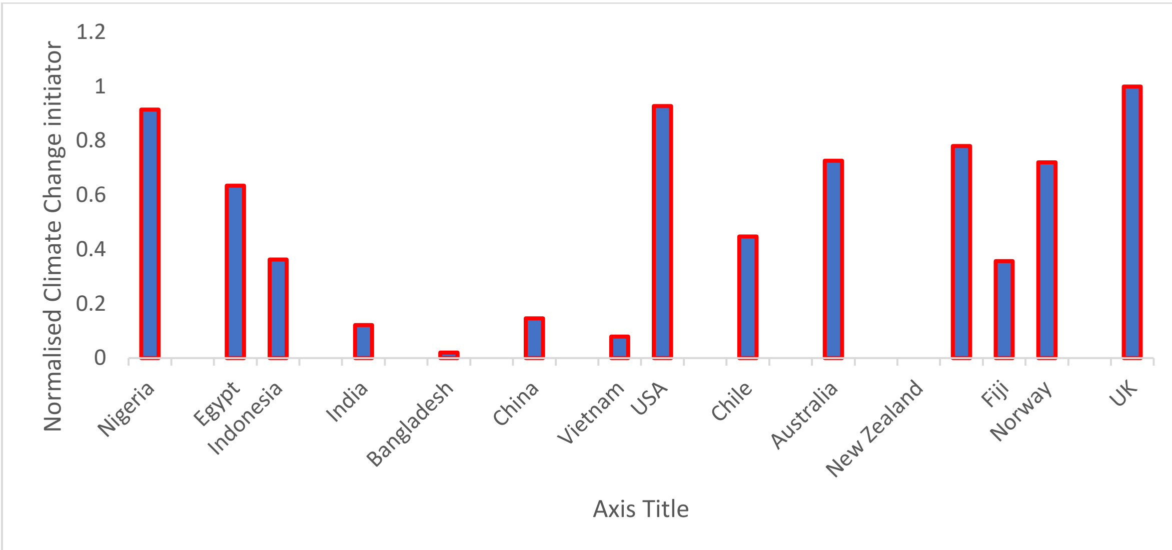

Fig. 5: Climate Change initiator (1991–2021) (Data Source: World Development Indicator 2023)

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).

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

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

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).

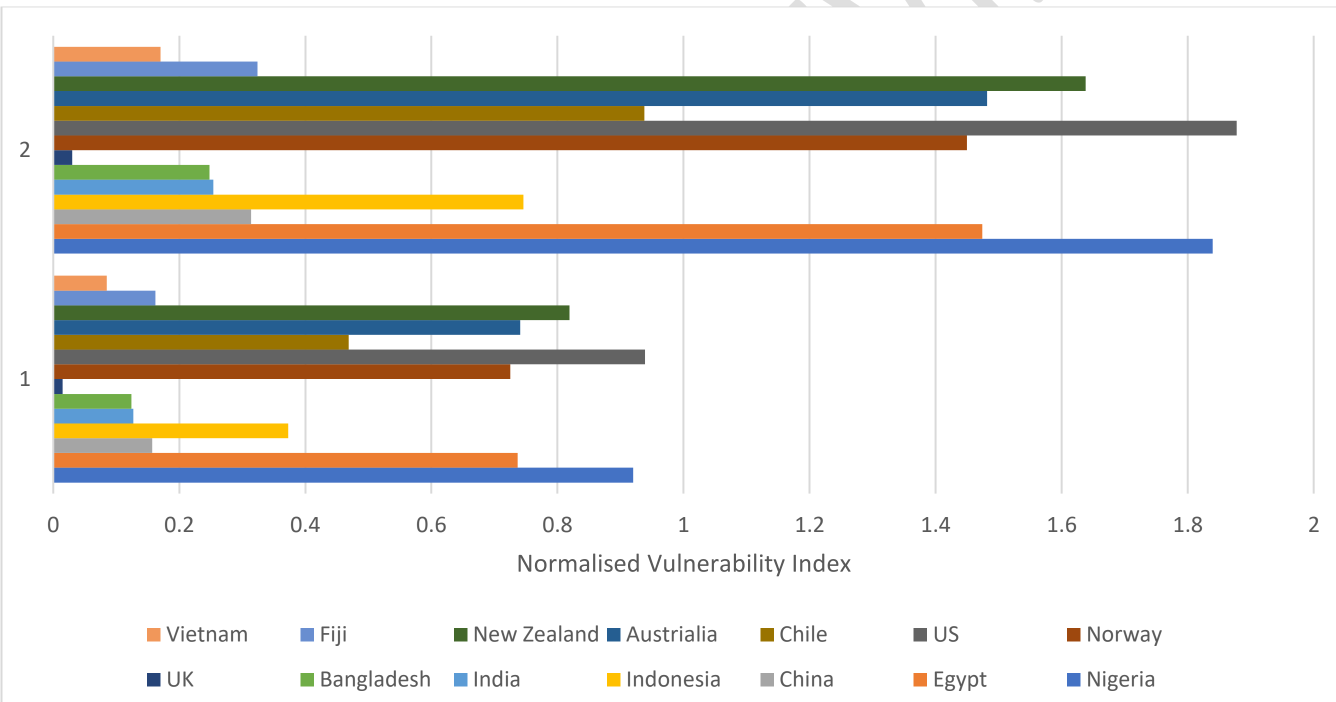

Fig. 6: Climate Change Vulnerability Index (1= 1991-2021; 2=30years Projected vulnerability level) (Data Sources: FA0 2023, Climate Knowledge 2023World Development Indicator 2023)

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).

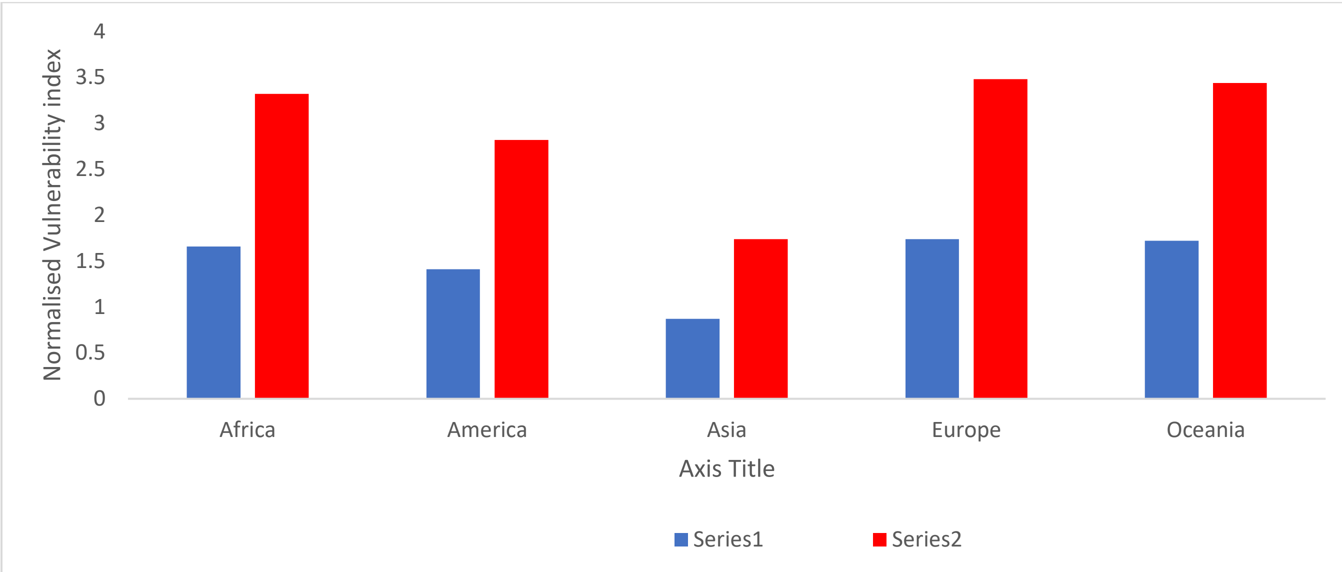

Fig.7: Climate Change Vulnerability Index by continent (Series 1= Vulnerability level 1991-2021; Series2= 30years Projected vulnerability level) (Data Sources: FA0 2023, Climate Knowledge 2023World Development Indicator 2023)

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).

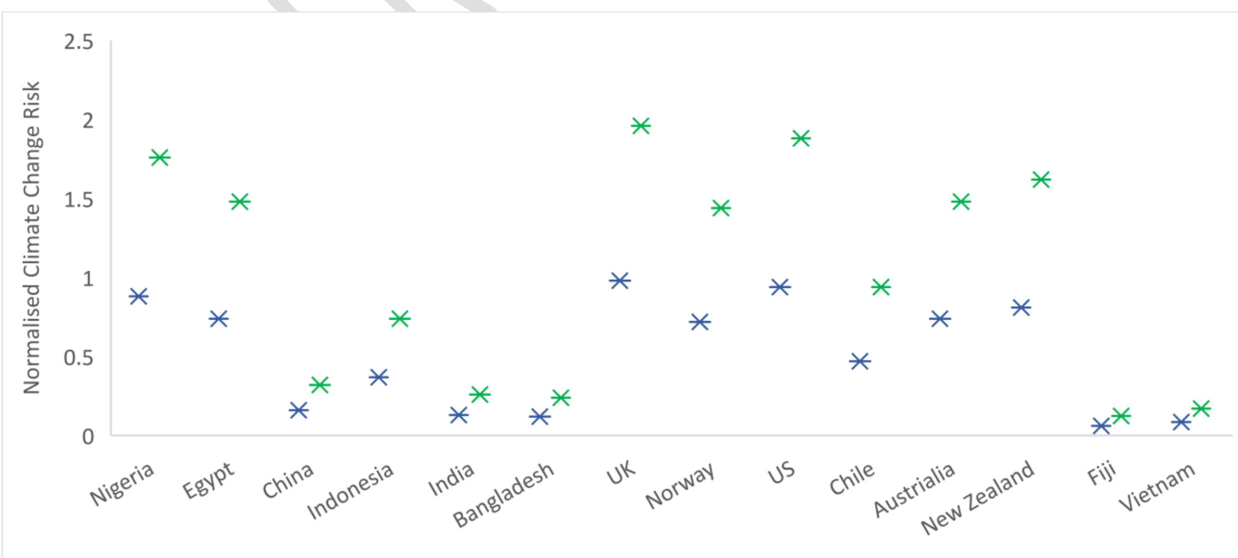

Fig. 8: Climate Change Risk by Countries (Data Sources: FA0 2023, Climate Knowledge 2023World Development Indicator 2023)

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).

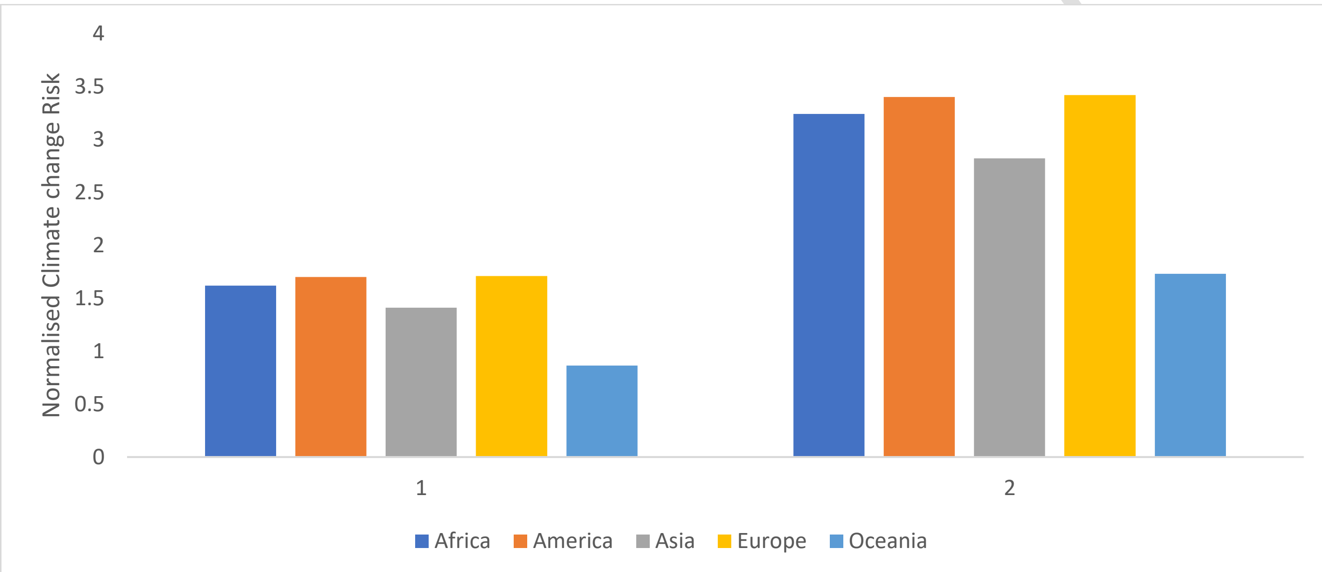

Fig. 9: Climate Change Risk by Continent. Series 1= Vulnerability level 1991-2021; Series2= 30years Projected vulnerability level). (Data Sources: FA0 2023, Climate Knowledge 2023World Development Indicator 2023)

4.0 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. (2021), 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.*, 2020, with findings stating that aquaculture is increasingly exposed to climatic changes. Norway's exact results are similar to Sandersen *et al.*, 2020 reports concerning exposure to climate change. The United Kingdom exposure results are similar to findings from Stewart-Sinclair et al. 2020, 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.'s 2020 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 FA0,2023 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 (Aljazeera, 2023)

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

(Callaway *et al.,2012),* 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.

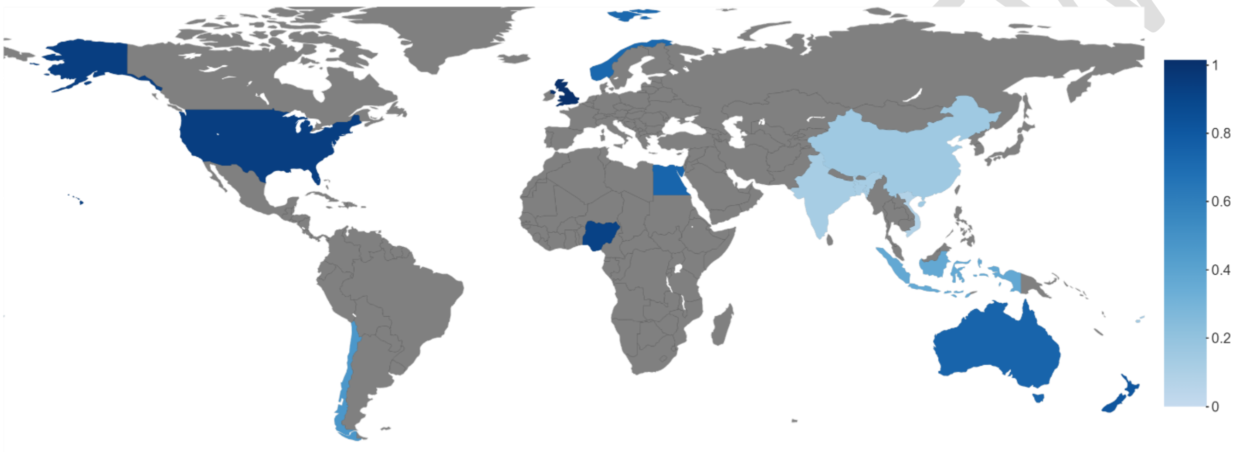

Fig. 10: Climate Change Vulnerability and Risk Index of the Top Aquaculture-Producing Countries.

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 (Kendon *et al.*, 2019), 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 (Breitburg *et al.*, 2018) 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).

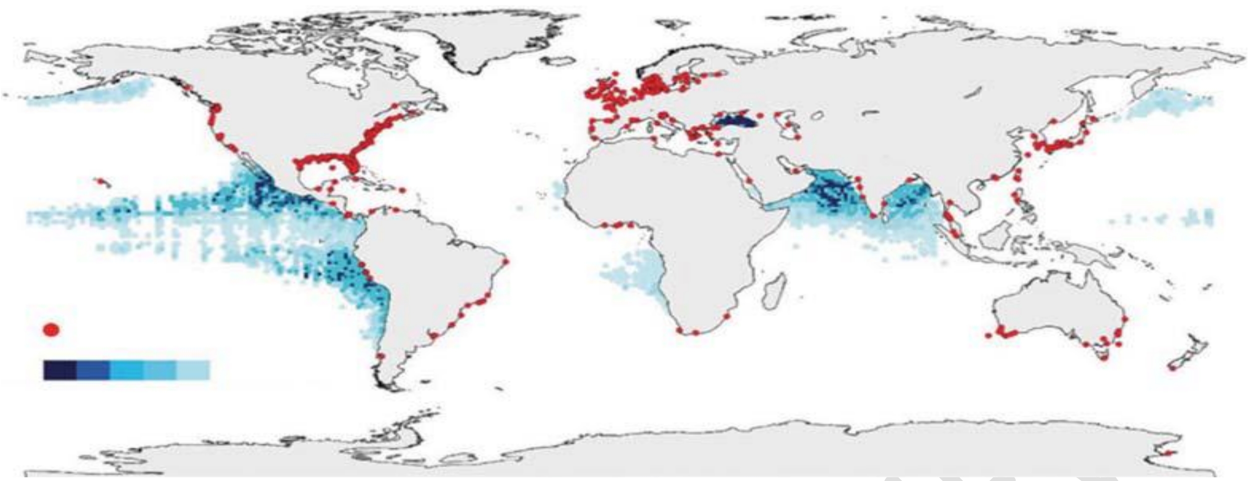

Fig. 11: Areas exposed to anthropogenic activities in blue and hypoxic areas in red (Breitburg *et al.*, 2018).

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 (FAO 2015).

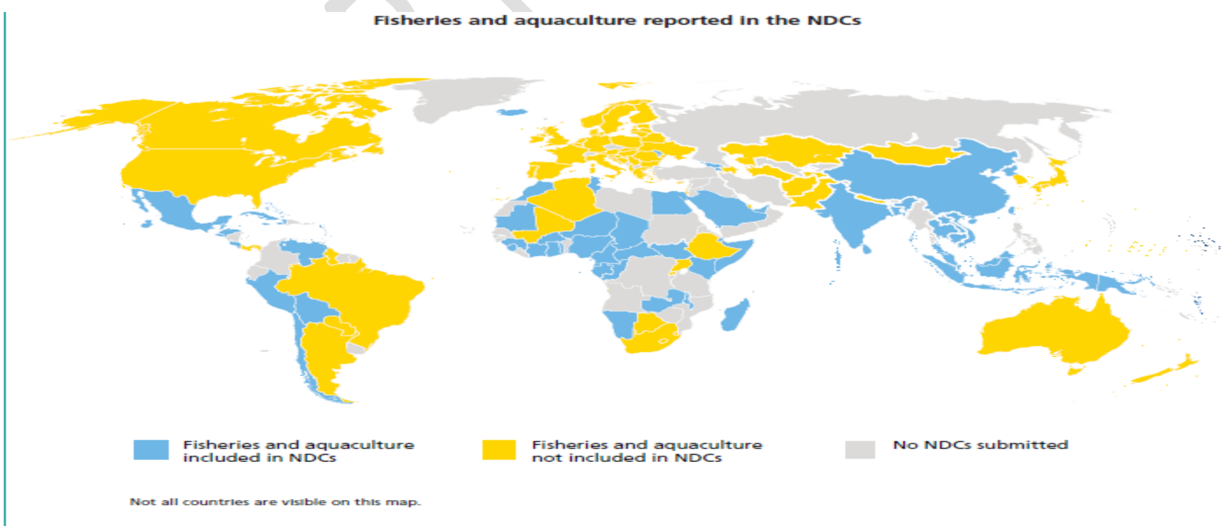

Fig. 12: Climate Change Vulnerability and Risk Index of the Top Aquaculture-Producing Countries (Barange *et al.*, 2018)

4.0: 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 to ensure the resilience and sustainability of these industries in the face of climate change.

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