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Environmental sustainability and footprints of global aquaculture

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ABSTRACT

While aquaculture is critical to global food and nutrition security, the fast development of aquaculture production systems has been accompanied by resource overconsumption and environmental impacts. Understanding how sustainable is current global aquaculture practice is important given its potential impacts on key sustainable development goals (SDGs). Here, for the first time, we developed a food-energy-water-carbon (FEWC) composite sustainability index (0–100) to assess the sustainability of global aquaculture across countries. Results indicate that the overall sustainability of global aquaculture is low (average score = 26) with none achieving a high sustainability score (75–100) and almost all practicing aquaculture in a relatively low sustainable way (0–50). Considering the sub-sustainability at a sector level, 80% of countries had at least two sectors among FEWC falling into the low sustainable zone (score less than 25). Regarding the environmental impacts, global aquaculture production accounted for approximately 1765.2 × 10^3 TJ energy use, 122.6 km^3 water consumption, and 261.3 million tonnes of greenhouse gas emissions in 2018. China led all countries by contributing to more than half of global aquaculture water consumption and greenhouse gas emissions, followed by India and Indonesia. This study highlights the significance of cross-sectoral management and policymaking to achieve global aquaculture sustainability.

1. Introduction

Sustainable aquaculture production has implications for global food security due to the challenges that humanity faces including climate change, population growth, and environmental degradation (Bank et al., 2020; Bush et al., 2013). The global demand for aquatic food products is expected to increase with population growth and economic development, even matching or exceeding the demand for other animal-based protein foods (Belton et al., 2020; Costello et al., 2020). For example, the global food fish consumption rate increased by about 3.1% per year from 1990 to 2018, a rate higher than that of all other animal protein foods during the same period (FAO, 2020). With relatively stagnant capture fishery and already overexploited resources for fish stocks across the globe, aquaculture is considered to have great potential for supplementing the animal protein demand of an ever-growing population (Naylor et al., 2000; Subasinghe et al., 2009). Global aquaculture production has increased by 500% since the late 1980s (Yuan et al., 2019). In 2018, global aquaculture fish production reached 82.1 million tonnes (Supplementary Figure 1), accounting for 46% of global fish production (FAO, 2020). It played a significant role in achieving the United Nations Sustainable Development Goals (SDGs) (De Graaf and Garibaldi, 2015; Moffitt and Cajas-Cano, 2014; Naylor et al., 2009). Notably, aquaculture is considered to have strong potential to add resilience to the global food system in the face of climate change and increased demand for animal protein (Troell et al., 2014).

Despite its significance in achieving global food security and other SDGs, aquaculture production is associated with substantial resource consumption and environmental impacts, such as overconsumption of water and energy, greenhouse gas emission (GHG), eutrophication, and degradation of aquatic, benthic, and coastal habitats and ecosystems (MacLeod et al., 2020; Meng and Feagin, 2019; Troell et al., 2014). Aquaculture requires higher inputs of energy than livestock production in most cases (Hilborn et al., 2018) and contributes to the degradation of fresh and coastal water quality (Langford et al., 2014). During 2006–2017, aquaculture production contributed to a 1.6 Mt/year of nitrogen and 0.2 Mt/year of phosphorous release to Chinese freshwater and coastal seas (Wang et al., 2019). As aquaculture production becomes more extensive (increase in production area) and resource-intensive with time, its environmental impacts will continue to increase (Henriksson et al., 2015; Hilborn et al., 2018; Yuan et al., 2019).

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However, a comprehensive understanding of aquaculture sustainability at a global scale, including resource consumption and environmental threats associated with aquaculture production, is lacking. A study at such a scale is challenging yet important given the implications aquaculture has on global sustainability. Sustainable aquaculture directly relates to some of the key SDG targets. For example, SDG 14 (Life below water) aims to conserve and sustainably use the ocean, a prime aspect of sustainable aquaculture. In addition, sustainable aquaculture supports SDG 1 (No poverty) and SDG 2 (Zero hunger) by helping reduce poverty and providing food for people, respectively (Naylor et al., 2000; Valderrama et al., 2010). Consumption of fish is associated with health benefits with rich protein and contributes to healthy diets for both people and climate (Gephart et al., 2016; Golden et al., 2021), which relates to SDG 3 (Good health and well-being) and SDG 13 (Climate Action). Hence best management strategies need to be devised based on a thorough analysis of the current status of the sustainable aquaculture production systems.

One way to expand our understanding of global aquaculture sustainability is the use of the “nexus approach” that was first introduced in the natural resource realm and then later applied to understand connections among different sectors such as food, energy, water, and climate change (Liu et al., 2018; Xu et al., 2020). A nexus approach allows the comprehensive analysis of multiple sectors, adopting an integrated and coordinated tool to reconcile potential conflicting interests. It moves beyond traditional sectoral thinking and aims to achieve overall sustainability of every aspect considering synergies and trade-offs (Boas et al., 2016; Rasul and Sharma, 2016). This approach, however, has received little attention in terms of understanding the environmental impacts of aquaculture production, as much focus has been given to terrestrial livestock production. In the past, studies have analyzed the nexus of seafood by focusing on a single seafood-water nexus or seafood-carbon nexus, which shows that freshwater systems are increasingly under pressure due to increased demand for seafood (Gephart et al., 2017; Pahlow et al., 2015). The increasing stress on freshwater systems exerted by aquaculture becomes clear when considering significant resource consumption from intensively farmed species. For example, farmed tilapia in Mexico requires two to four times more freshwater than beef and pork during production (Guzmán-Luna et al., 2021), and consumes significant energy (2.92×10^8 kWh) and water (4.23×10^7 m^3) during processing, packaging, distributing, and marketing (Liu et al., 2020). Sustainability assessment of global aquaculture from an integrated food-energy-water-carbon (FEWC) perspective is key for contributing to food security without unintended environmental consequences. A complete analysis of the global aquaculture production system provides insight regarding the current production efficiency and environmental impacts. This in turn will allow for optimizing diets for food security and environmental sustainability (D'Odorico et al., 2018; Gephart et al., 2016). It will furthermore inform the development of adequate strategies to maximize productivity while reducing GHG emissions and conserving energy and water (Nhamo et al., 2020).

To address the aforementioned research gap and provide useful information regarding the sustainability of global aquaculture production systems and their environmental impacts, this study aimed to answer three research questions: (1) What are the current water, energy, and carbon footprints of global and country-scale aquaculture productions? (2) How sustainable are these aquaculture production systems based on FEWC composite sustainability and sub-sustainability (food/energy/water/carbon) perspectives? and (3) How different are the sustainability performance of aquaculture production in developed and developing countries? To answer these questions, we collected data from the Food and Agriculture Organization of the United Nations (FAO) and existing literature. Firstly, the energy, water, and carbon footprint of global aquaculture production were calculated for each country. Then we developed a composite food-energy-water-carbon (FEWC) sustainability index (0–100) to explore resource consumption efficiency and the environmental impacts of aquaculture. Finally, evenness (variation in sub-sustainability score across sectors) was employed to investigate the difference in the performance of each sector, which could guide adaptive strategies for policy-makers. Our findings reveal a low sustainable state of the global aquaculture system from a FEWC nexus perspective and highlight the need for international cooperation to achieve global seafood sustainability.

2. Materials and methods

2.1. Definition and conceptual model

In this study, we define sustainable aquaculture from a Food-Energy-Water-Carbon nexus perspective as a system that allows for minimal resource consumption and environmental impacts while ensuring adequate food supply and economic efficiency. To measure resource consumption and environmental impacts of aquaculture, we employed the footprint method based on a set of life cycle inventory data from existing literature (Kim and Zhang, 2018; MacLeod et al., 2020; Pahlow et al., 2015; Yuan et al., 2017). Country-level energy footprint, water footprint, and carbon footprint of aquaculture were calculated. The country-level inland and marine aquaculture (aquatic plants are excluded) production 2018 datasets were collected from the FAO FishStat database (http://www.fao.org/fishery/), which includes fish, shrimp, and bivalves cultivated in freshwater and marine environments. The country shapefiles used for mapping global patterns were downloaded from Natural Earth (https://www. naturalearthdata.com/; accessed on June 30, 2021).

2.2. Water footprint

The water footprint (WF) introduced by Hoekstra et al. (Hoekstra et al., 2011) reflects the water consumption (green and blue water) and the degree of pollution (gray water), here caused by seafood production. We used the feed-related method to estimate the water footprint proposed by Pahlow et al. (Pahlow et al., 2015), which quantifies the amount of water consumed during the production and usage of aquaculture feed. First, the amount of aquafeed used per species is calculated as,

$$P_{feed} = FCR_i * P_i * Perc_{feed,i}$$

where P_{feed} is the total amount of aquafeed consumed by species i, FCR_i is the feed conversion ratio (kg of feed/kg of fish) of this species, P_i is the production (ton/year) of species i and $Perc_{feed,i}$ is the fraction of aquafeed of total feed.

Second, the amount of specific feed ingredient used per species is determined as,

$$Feed_{i,p} = f_{i,p} * P_{feed}$$

where $Feed_{i,p}$ is the annual amount of feed ingredient p in ton/year fed to species i, and $f_{i,p}$ is the fraction of feed ingredient p in the composition of the aquafeed applied to species i. The water footprint related to aquafeed WF_{feed} (m^3/year) is determined for each species i as:

$$WF_{feed,i} = \sum_{p=1}^{n} Feed_{i,p} * WF_{p,i}$$

where $WF_{feed,i}$ is the green, blue and gray water footprint of species i, and $WF_{p,i}$ is the water footprint of feed ingredient p, and n the number of feed ingredients. Moreover, the water footprint results of 22 selected species were also extracted from Yuan et al. (Yuan et al., 2017) with a more detailed water consumption inventory considering the average feed consumed, which was incorporated into the analysis for China's aquaculture due to its exceptional role in seafood production.

2.3. Carbon footprint

The emissions intensity of the main aquaculture groups (bivalves, catfish, cyprinids, salmonids, shrimps, tilapia, etc.) were adapted from MacLeod et al. (MacLeod et al., 2019, 2020), who considered GHG emissions from feed material production and transportation, pond fertilizer production, on-farm energy use, and aquatic N_2O. Transport, processing, and distribution are not included in that “cradle to farm-gate” system. We assigned the regional emission intensity of main species groups to each country, and missing values were filled in by the mean emissions intensity values. For a specific country, we calculated the carbon footprint (CF) as follows,

$$CF = CF_{feed} + CF_{energy} + CF_{fertilizer} + CF_{N2O} = \sum_{i=1}^{n} EI_i * P_i$$

Where EI_i is the emissions intensity of a specific species group i, and n is the total number of farmed fish species in the specific country.

2.4. Energy footprint

Accurate quantification of energy consumed in aquaculture production is challenging because it varies widely depending on farmed species, system intensity (i.e., extensive, semi-intensive), culture technology, and other local factors. Moreover, different activities require diverse forms of secondary energy, thus adding to the complexity of the problem. The country-level energy footprint (EF) of aquaculture was extracted from Kim & Zhang (Kim and Zhang, 2018), which established an energy intensity model with consideration of culture species, culture system intensity, culture technology, and climatic condition. Data of direct energy input per kg fish produced was collected from peer-review literature and considered as a dependent variable in the regression analysis. The current energy use of global aquaculture was found to be strongly influenced by the use of marine-based technologies or ponds. We matched the energy intensity for different regions and species, and missing values were filled in by the average energy intensity grouped by developed/developing and continental regions.

$$EF = \sum_{i=1}^{n} EEI_i * P_i$$

where EEI_i is the energy intensity of a specific species i, P_i is the production (ton/year) of species i, and n is the total number of farmed fish species in the specific country

2.5. Sustainability assessment framework

To assess the four sectors (food, energy, water, carbon) together, we designed a composite sustainability index based on the FEWC nexus with four dimensions and nine indicators build upon indices developed in recent studies(Fernández-Ríos et al., 2021; Nhamo et al., 2020; Simpson et al., 2020). Indicators were identified based on the following criteria:

a. Global relevance: The indicators selected are closely related to real-world sustainability targets and indicators, such as FAO indicators 1.2 (average value of food production) and SDG indicators 12.2.1 (Material footprint, material footprint per capita, and material footprint per GDP),

b. Global applicability: Data must be available for the majority of the countries,

c. Data quality: The data should closely represent the best available measure for food, energy, water, and carbon of aquaculture from official national and international sources, and

d. Statistical adequacy and replicability: Data collected and processed are statistically reliable and robust, and the indicators should be simple, transparent, and easy to calculate and replicate.

As a result, a set of indicators (Table 1) was developed in our index framework, which includes Food production (FP), Food economy value (FE), Food self-sufficiency (FS), Energy productivity (EP), Energy intensity (EI), Water productivity (WP), Water intensity (WI), Carbon productivity (CP) and Carbon intensity (CI). To calculate and compare the composite sustainability index among countries, we took the following steps:

(1) Normalization of indicators. To improve the consistency and ensure comparability of indicators, raw indicator values were rescaled from 0 to 100, whereby 100 means higher sustainability and 0 means lower sustainability. The min-max normalization was selected for data standardization in terms of the following formula:

$$S_i = \frac{S_i - S_{min}}{S_{max} - S_{min}} \times 100$$

where S_i denotes the sub-indicator of food, energy, water and carbon, S_{min} and S_{max} are the minimum and maximum values of S_i, respectively.

(1) Integration of indicators. To get a composite sustainability index score, we calculated arithmetic means of adjusted raw indicator values with equal weights assigned to each sector. This method has been used by authoritative sustainability assessments such as the global SDG index.

$$S_{FEWC} = \left(S_{Food} + S_{energy} + S_{water} + S_{carbon}\right) /4$$

where S_{FEWC} is the composite sustainability index. S_{Food}, S_{energy}, S_{water} and S_{carbon} are the sub-sustainability score of the FEWC nexus.

(1) Definition of performance intervals. Each index was scored on a scale from 0 to 100 for comparison among countries, where 0 means least sustainable and 100 means most sustainable. But this is a measure of the relative performance of sustainability: a score of 100 does not mean that aquaculture in a country is sustainable, which is consistent with Müller's study (Müller et al., 2021; Steffen et al., 2015). To avoid subjective partitioning of sustainability, we used the traffic-light color scheme to show the level of sustainability with equal intervals, which has been

Table 1

Food-energy-water-carbon (FEWC) composite sustainability indicators.

FEWC	Indicators	Description	Units
Food	Food production (FP)	Total aquaculture seafood production.	t
	Food economic value (FE)	Value added per unit of aquaculture seafood produced.	\$/t
	Food self-sufficiency (FS)	Proportion of aquaculture seafood produced per capita.	t/capita
Energy	Energy productivity (EP)	Value added by aquaculture per unit of energy used.	\$/TJ
	Energy intensity (EI)	Energy consumed per unit of aquaculture seafood produced.	TJ/t
Water	Water productivity (WP)	Value added by aquaculture per unit of water used.	\$/m3
	Water intensity (WI)	Water used per unit of aquaculture seafood produced.	m3/t
Carbon	Carbon productivity (CP)	Value added by aquaculture per unit of GHG emitted.	\$/CO_2-eq
	Carbon intensity (CI)	GHG emitted per unit of aquaculture seafood produced.	CO_2-eq/t

employed in many sustainability assessment studies (Müller et al., 2021; Zhang et al., 2021). As such, the index scores between 0 and 25, 25–50, 50–75, and 75–100 correspond to the red, orange, yellow zone, and green zones, respectively. Hence, the green zone with values closer to 100 denotes relatively higher aquaculture sustainability, and the red zone with values closer to 0 denotes relatively lower aquaculture sustainability (Table 2).

2.6. *Evenness*

Evenness is a widely used index in ecology. The concept of 'evenness' originated as a supplementary of species richness in the measurements of biodiversity, which describes the distribution of relative abundance among species. A large number of species with equal distributed relative abundance is considered as 'high biodiversity' (Liu et al., 2020). Here it was used to investigate the differences in the sustainability among all food-energy-water-carbon sectors of aquaculture systems. For example, a 100% performance on food production but a 0 performance on carbon emission/water consumption is uneven, and this may lead to the same composite sustainability score if a country had 50% performance on food production and 50% performance on carbon emission/water consumption. An improved radar chart method was employed to compute the evenness score from indicators of food, energy, water, and carbon. The evenness score refers to the ratio between the total area S_i of the radar chart formed by each sectoral indicator and the area of a circle with the same perimeter L_i (the evenest distribution of all indicators with the same perimeter), which is calculated step by step using the following equations:

$$S_i = \sum_{j=1}^{n} S_j = \sum_{j=1}^{n} \pi w_j r_j^2$$

$$L_i = \sum_{j=1}^{n} L_j = 2\left|r_{max} - r_{min}\right| + \sum_{j=1}^{n} 2\pi w_j r_j$$

$$ES = \frac{S_i}{\pi\left(L_i/2\pi\right)^2} \times 100 = 400\pi S_i / L_i^2$$

where the score of j^{th} indicator at country-level was used as the radius of each sector r_j, and r_{max} and r_{min} represent the maximum and minimum among all indicators, w_j is the weight of j^{th} indicator. The evenness score is highest when all indicators have the same score.

3. Results

3.1. *FEWC footprint of the global aquaculture*

In 2018, the global aquaculture production used 1765.2 × 10^3 TJ energy, 122.6 km^3 water and emitted 261.3 million tons of CO_2-equivalent greenhouse gas (GHGs) to the atmosphere, representing approximately 0.47% of total anthropogenic emissions (Fig. 1). The top three countries with the highest footprints are China, India, and Indonesia, respectively. Notably, developing countries produced nearly 90% of the aquaculture seafood and accounted for a significant portion of energy (93%), water (95%), and carbon (96%) footprints (Supplementary Table 1). As the largest aquaculture production country, China produced about 47 million tonnes of fish and bivalves, while accounting for 37%, 51%, and 56% of global energy consumption, water use, and GHG emissions, respectively. Norway, the largest aquatic seafood producing country in Europe accounted for 45% of energy use, 62% of water use, and 49% of GHG emissions in Europe (Supplementary Table 2).

Considering the continents, Asia is the largest user of water and energy (both 88%) contributing to almost 90% of global GHG emissions. After Asia, Europe contributed most to global water/energy consumption and GHG emission, followed by the Americas, Africa, and Oceania. At regional-scale Southeast Asia has the highest footprints of energy-water-carbon in aquaculture (Supplementary Figure 2).

3.2. *FEWC nexus intensity & productivity*

With respect to the intensity (resource consumed or environmental impact per unit aquaculture seafood produced) and productivity (value added per unit aquaculture production) level of energy, water and carbon, the energy-, water- and carbon-intensive countries are concentrated in the Middle East and Sub-Saharan Africa. Interestingly, China is less energy-intensive than most countries despite its largest aquaculture production (Fig. 2). Generally, European countries have lower resource consumption and environmental costs than other countries, except for Norway, which operates large-scale industrial aquaculture using commercial feed contributing to about 5.4 million tons of GHG emissions. Considering the performance of the countries under different development stages based on FAO (FAO and Statistics, 2020), developed countries generally have lower water and carbon intensity and higher productivity than developing countries (Supplementary Figure 3 & Table 1), which means they generally produced high-value seafood with less water consumption and carbon emission. On the other hand, the least

Table 2
Classification of relative composite sustainability.

Zones	Red zone	Orange zone	Yellow zone	Green zone
Intervals	0 - 25	25 - 50	50 - 75	75 - 100
Degree	Low ⟵ Relative Sustainability ⟶ High			

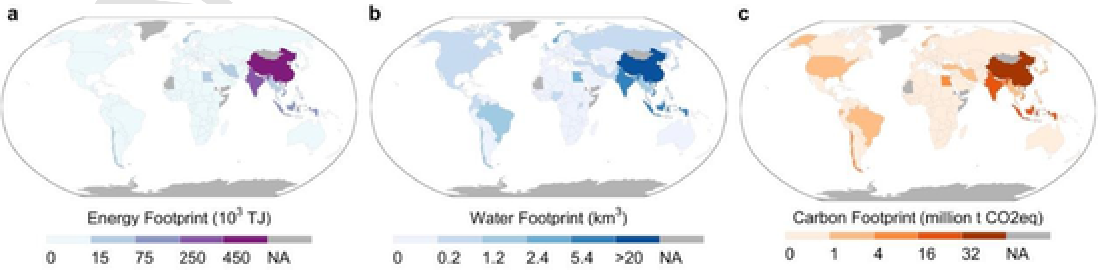

Fig. 1. Energy, water, and carbon footprints of global aquaculture production in 2018. **(a),** Country-level energy footprint. **(b),** Country-level water footprint. **(c),** Country-level carbon footprint. The calculations do not include footprints associated with the production of aquatic plants and animals.

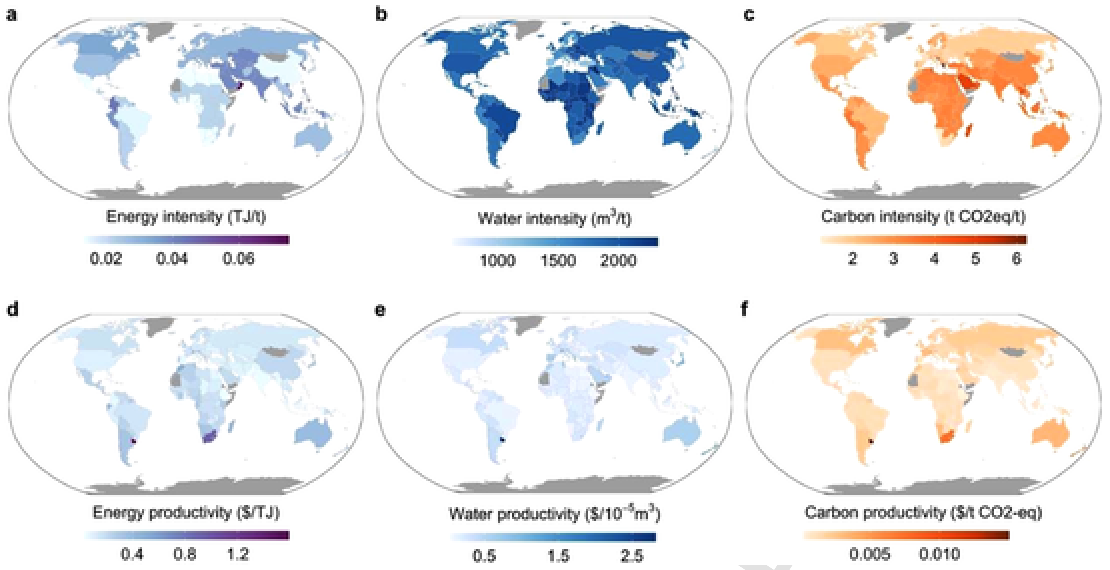

Fig. 2. Country-scale assessment of energy, water, and carbon intensity and productivity. **(a),** Energy intensity. **(b),** Water intensity. **(c),** Carbon intensity. **(d),** Energy productivity. **(e),** Water productivity. **(f),** Carbon productivity. Intensity is defined as the resource consumption per unit of aquaculture seafood production, while productivity is the aquaculture value added per unit of resource used.

developed and developing countries use more energy and water to produce seafood of equivalent value and emit more GHG.

3.3. FEWC composite sustainability and sub-sustainability

Based on the FEWC composite sustainability index, sustainability varies around the world with an average score of 26 (Fig. 3a), falling into the orange zone indicating relatively low sustainability (Table 2). Overall, almost all assessed countries were in the red zone (52%) and orange zone (47%), while no countries achieved a score in the top interval (75–100), i.e., the green zone indicating a high degree of sustainability (Supplementary Table 3). The comparison of composite sustainability scores between developed, developing, and least developed countries showed that the least developed countries scored much lower than developed and developing countries (Fig. 4a). This suggests that the aquaculture practices in the least developed countries are less sustainable, which include high resource consumption and lower resource efficiency at the cost of high environmental impacts. Of all assessed countries in the red zone (0–25) indicating the worst performance of composite sustainability, nearly 88% come from least developed ($n = 32$) and developing countries ($n = 36$). Uruguay ($S_{FEWC} = 74$), South Africa ($S_{FEWC} = 47$) and New Zealand ($S_{FEWC} = 46$) performed better compared to the rest of the world. Moreover, regarding the sub-sustainability of FEWC, 80% of countries had at least two sectors among food, energy, water, and carbon falling into the red zone (0 25). China scored relatively high in the food ($S_{Food} = 40$) and energy ($S_{Food} = 55$) sectors but scored much lower in the water sector ($S_{water} = 13$), much lower than those of Japan (Fig. 3c).

When considering the evenness (variation in sub-sustainability score across sectors), 64% of countries were uneven regarding the sub-sustainability performance, and only a few countries such as Uruguay, Norway, and Switzerland were classified as both moderately sustainable (orange and yellow zone, 25–75) and even (Fig. 3b & d). Overall, 27% of countries were both uneven and low sustainable (red zone). Considering continents, countries in Sub-Saharan Africa generally scored lower in composite sustainability but higher in evenness than other continents (Fig. 3a & b), while the Americas (North and South) and European countries typically showed both higher composite sustainability and evenness scores compared to the other continents (Fig. 4b).

4. Discussion

4.1. Global sustainability of aquaculture system

The FEWC analysis provides integrated information in order to identify gaps in efforts to achieve aquaculture sustainability, in particular for the developing countries which are also the major suppliers of the world's seafood. This study provides the first FEWC sustainability assessment of global aquaculture systems considering multiple cross-sector sustainability indicators. Results reveal that the overall sustainability of the global aquaculture system is low, with 80% of studied countries having at least two sectors within the FEWC nexus falling within the low and the high-risk zone (i.e., red zone). In terms of practicing sustainable aquaculture, large inequalities appear to exist among the countries around the world with developing countries generally having relatively less resource efficiency and large environmental impacts. This suggests the need to make environmental impact assessments across multiple sectors of aquaculture and the potential to achieve overall sustainability across countries by reducing inequalities among countries with different economies.

Varying levels of aquaculture types, farmed species, feeding technology, and management in developed and developing countries may result in differing FEWC sustainability outcomes. Developing countries such as China, Indonesia, and Bangladesh, are the main contributor to global aquaculture production. Their farming types and farmed species vary from ponds to the intensive industrial system. For example, China cultivated 86 different species of aquatic organisms in a variety of production systems in 2017, whereas Norway cultivated only 13 different species known to have less environmental impacts mostly in the marine cage systems (Naylor et al., 2021). The current research shows that developing countries generally have higher water/energy intensity (water/energy consumption per unit aquaculture production), which is likely due to inefficient farming technology, low feed conversion ratio, and resource-intensive farmed species. (Watson et al., 2016) found that increased exports from some developing countries including India, Myanmar, Thailand, Vietnam, and Indonesia generally corresponded well with increased imports and consumption in some developed countries such as the USA, Canada, Australia, and France. In developing countries, some poor-quality fish are retained for domestic consumption, while higher valued fishes are exported. Hence the differences between high-valued fish and low-value fish farmed in different countries

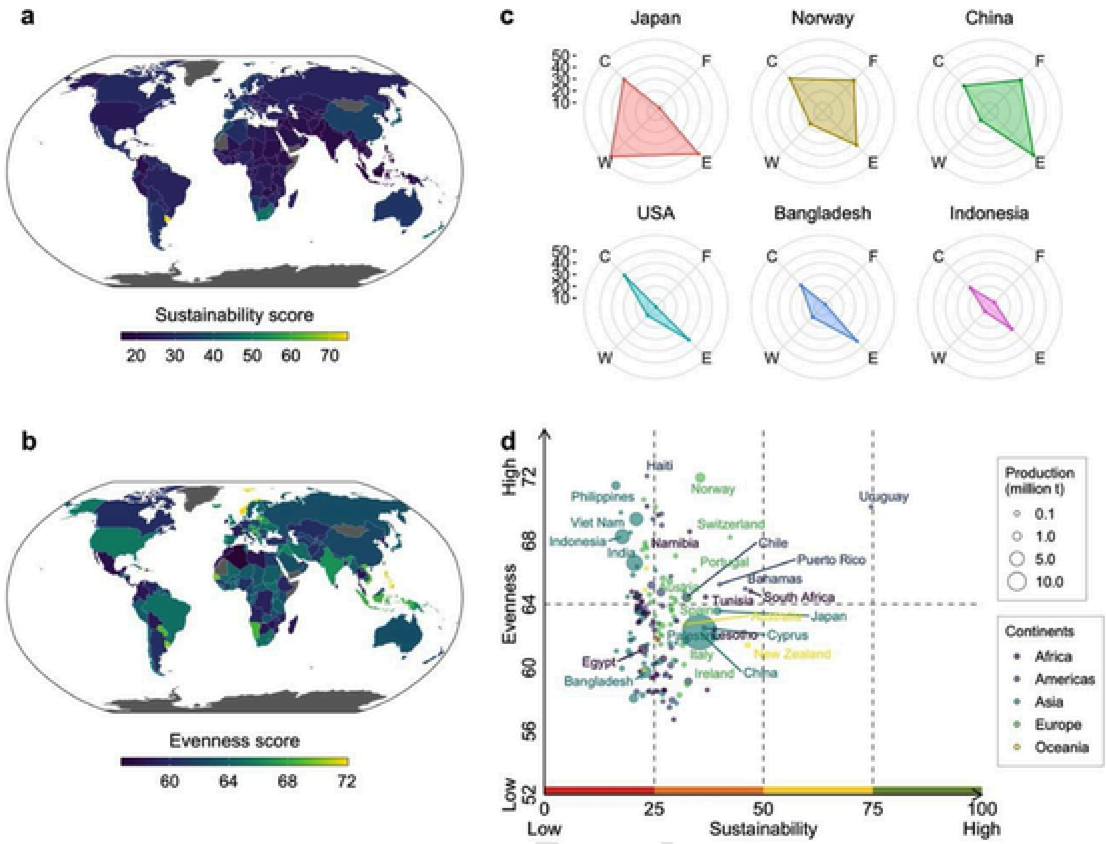

Fig. 3. Global aquaculture sustainability showing (a), Composite sustainability based on FEWC nexus. **(b),** Evenness of global aquaculture sustainability. **(c),** Sub-sustainability performance of each subsystem (food/energy/water/carbon) for selected countries. **(d),** Distribution of individual country when considering both composite sustainability and evenness. The compositive sustainability index values range from 0 to 100 with 0 suggesting the lowest level of aquaculture sustainability and 100 showing the highest level of aquaculture sustainability and the threshold of evenness was set up by the K-mean method used in Liu et al. (Liu et al., 2020).

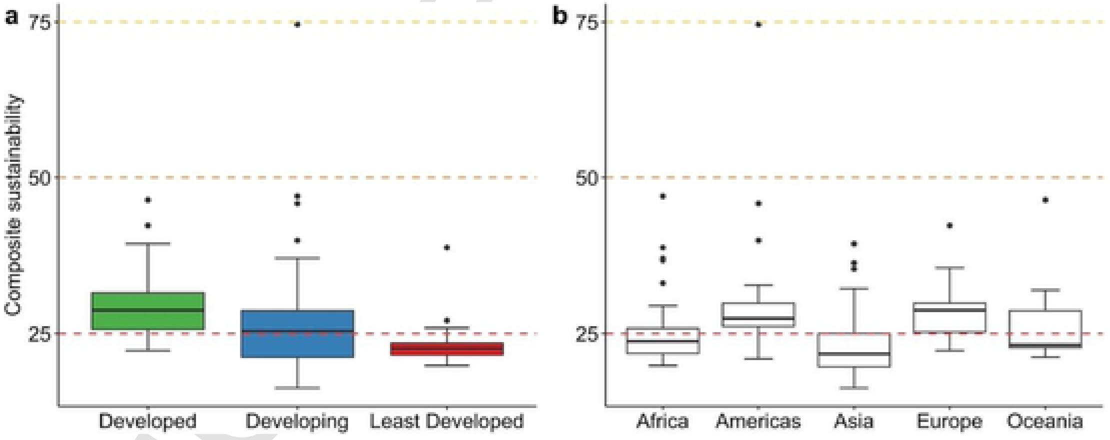

Fig. 4. Boxplots showing composite sustainability scores of aquaculture systems across countries in different **(a).** continents and **(b).** economic groups. The compositive sustainability index values range from 0 to 100 with 0 suggesting the lowest level of aquaculture sustainability and 100 showing the highest level of aquaculture sustainability.

can explain the current gap in resource efficiency among developing and developed countries. This gap may be attributed to the differences in the culture technology suggesting opportunities for improvement in developing countries. In particular, in China and Bangladesh, a reduction of water consumption and associated impacts on biodiversity and climate can be achieved through the promotion of mariculture (Cisneros-Montemayor et al., 2021), where nature-based feeding is used.

A comparison between Norway (developed country) and Egypt (developing country) demonstrates opportunities to achieve sustainability. Though the aquaculture production in these countries is similar in terms of volume, the sub-sustainability score of food and water for Norway is over ten and two times larger than that of Egypt, respectively. This difference may be mainly explained by their different culture environment (marine vs. freshwater), as nature-based mariculture generally need less input of aquafeeds. Other factors, such as farmed species, feed technology, management could also influence the sustainability of aquaculture (Crab et al., 2012; Soliman and Yacout, 2016). There is a great potential for Egypt to optimize the aquaculture system, innovate feeding technology, and change the management mode, which can be all learned from Norway (Olaussen, 2018). This also suggests a need for international cooperation by sharing knowledge on successful operation and management solutions and advanced farming technology to feed a growing population around the world, while reducing the environmental impacts, creating new jobs, and improving food security to achieve UN SDGs.

4.2. Comparison across animal sourced food

From a FEWC nexus perspective, environmental impact from consumption of aquaculture seafood and terrestrial livestock, such as beef, sheep, pork, and chicken are complex (Gephart et al., 2016; Hilborn et al., 2018). Seafood-based diets are generally considered more environmentally sustainable. Considering only carbon footprint, seafood products derived from aquaculture systems (4–75 kg CO_2 per kg protein) produced relatively much lower GHG emissions than livestock such as beef (45–640 kg CO_2 per kg protein) and lamb (51–750 kg CO_2 per kg protein) (MacLeod et al., 2020; Nijdam et al., 2012; Parker et al., 2018). But when considering water footprint, some intensive farm species such as tilapia (126 l/g protein) require two to four times more freshwater (embodied water) than beef (51 l/g protein) and pork (33 l/g protein) during production (Guzmán-Luna et al., 2021). As aquaculture is expanding and becoming more resource-intensive, especially across developing countries where technologies are not as advanced as those in developed countries (Yuan et al., 2019). Moreover, developing countries like China, Thailand, and Vietnam still rely on low-value feed-grade fish as input for feeds, which led to larger environmental impacts (Zhang et al., 2020). The resource consumption (energy and water consumption) and associated environmental costs (carbon emission) associated with such expansion should be considered using a nexus perspective. The proposed sustainability index can be employed to compare the sustainability scores of a terrestrial animal protein and seafood protein and is not limited to the single sector of water or carbon, as in the case of most studies (MacLeod et al., 2020; Yuan et al., 2017). Policymakers should be cautious when promoting fish consumption for environmental benefits since not all farmed fish outperform other terrestrial animal food products when considering different perspectives of environmental impacts. This study highlights the importance of using integrated analytical tools that can help to better understand the complex relationships between food security, energy, and water.

4.3. Reducing environmental costs of aquaculture

Reducing seafood production pressure on the environment should be a focus of less developed and developing countries, in particular aquaculture production hotspot countries such as China, India, Indonesia, and Bangladesh. These hotspot countries have extensive fish farming and pond systems. Implementation of resource-efficient technology driven by science should be prioritized (Cottrell et al., 2020; Froehlich et al., 2018). Because these countries are the primary suppliers of seafood, reducing their environmental footprints is critical to ensure global aquaculture sustainability, especially with the expected increase in global demand. The international seafood trade between developed and developing countries should support interventions to help the global exporters reduce environmental costs. There is a need for international cooperation among seafood trading countries, and sharing knowledge and technology will lead to a reduction of the negative effects of aquaculture production. While international trade contributes to SDG 1 (poverty alleviation) by creating new jobs and improving livelihoods in less developed and developing countries, it introduces further challenges to achieve SDG 6 (ensuring clean water) and SDG 13 (combating climate change) because of the negative effects of these environmental costs. In addition, there are potential adverse environmental impacts associated with packaging, marketing, and transportation in the seafood supply chain, which could be even larger than that of the production process (McKuin et al., 2019), which warrants future research.

Integrated thinking and analyses such as the work presented here can help to strengthen the role of aquaculture in achieving the SDGs, but also the challenges associated with it. This research proposes a composite sustainability index based on FEWC that integrates multiple resources or environmental sectors to quantify the interactions between different sectors within the aquaculture system. This information will prove useful for policymakers to develop sustainable development plans to reduce environmental impacts, such as climate change, and address challenges associated with water scarcity and energy shortage.

4.4. Future directions and uncertainties

Although we provide a comprehensive sustainability assessment based on the FWEC nexus for different countries, uncertainties exist in our study primarily associated with data limitations. Disparities in data availability may have contributed to bias in index values for different countries that have different farming systems, farmed species, feeding technology, and standards of operations, which could lead to different levels of water and energy use intensity. At a farm scale, recirculating farm systems have no water seepage while semi-closed farm systems, such as aquaculture ponds, have significant water loss resulting from evaporation, seepage, and water exchange (Gephart et al., 2017). Besides, the recirculation of water in the aquaponic system can achieve remarkable water re-use efficiency of 95–99%, which makes their water footprint considerably better than traditional agriculture (Joyce et al., 2019). Moreover, aquafeed was used as the only component to calculate water footprint following existing literature (He et al., 2018; Kim et al., 2020; Vanham et al., 2016), which may lead to the underestimation of water footprints. For carbon footprint, The GHG intensity of extensive and semi-intensive systems (3.59 $kgCO_2$-eq kg^{-1}) is about 4.5-fold greater than intensive systems (0.66 $kgCO_2$-eq kg^{-1}) (Yuan et al., 2019). At the species level, the environmental impacts of different farmed species vary substantially with their demand for water, pesticides, fertilizer, and habitats (Hilborn et al., 2018). Farmed species like silver and bighead carps could have 2.6 times the water use than other carps, and 4.4 times the water use than catfish and while milkfish. Carbon emission for farmed salmon could be about 5 times larger than that of bivalves (Gephart et al., 2021). In this study, many uncertainties exist as we mostly used country-and species-specific parameters from published literature, but assumed that the composition of aquafeed for the specific species is the same across different countries. The energy footprint values for a number of countries are not available and we used the average values based on countries' development categories. And for missing values of carbon values, the GHG emission intensity was also selected as a region-averaged value. These uncertainties could be reduced in future research by developing more indicators at a subnational level considering the environments (freshwater or marine), species, and types (i.e., recirculating, semi-closed, and open-closed) of aquaculture. With more reliable life cycle inventory data for environmental impact assessment at a regional scale or farm scale, the results of sustainability assessment could have more granularity. In addition, by promoting holistic sustainability assessment of aquaculture, more environmental impacts could be explored to generate indicators, such as N & P footprint, land footprint, biodiversity footprint. Then our FEWC nexus-based assessment framework could be easily expanded to "food-energy-water-carbon-nitrogen", "food-energy-water-carbon-land" or "food-energy-water-carbon-biodiversity" with improved results by capturing more environmental consequences. To further improve the assessment of the sustainability of future farming technology, aquafeed, and investments, we should collect more consistent indicators representing different types of aquaculture across time and scape. The spatiotemporal assessment will be helpful in terms of making targeted interventions and policymaking decisions to achieve the goal of sustainable food production.

Finally, in future work, a refined index could be developed by integrating the socioeconomic factors associated with local aquaculture production. Import and export of seafood among developed and developing countries through international seafood trade networks should also be taken into consideration. As aquaculture is among the fastest-growing food sectors, our study lays the foundation for future national and subnational sustainability assessment studies and provides useful information for the transformation of the current food system towards a sustainable future.

Author contribution

Z.X. and Q.J. designed the study. Q.J. collected and analyzed the data. Q.J. and Z.X. drafted the manuscript. Q.J., N.B., M.P. and Z.X., interpreted the results. N.B., M.P. and Z.X. reviewed and edited the manuscript.

CRediT authorship contribution statement

Qutu Jiang: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Nishan Bhattarai:** Formal analysis, Writing – review & editing, Methodology, Software, Validation. **Markus Pahlow:** Formal analysis, Writing – review & editing, Methodology, Software, Validation. **Zhenci Xu:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare no competing financial interests.

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Supplementary materials

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