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Review

Rethinking Freshwater Cage Aquaculture: A Case in Ghana

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Abstract: Lakes around the world, including Ghana's Lake Volta, are facing insidious threats from pollutants due to high dependency on aquatic ecosystems. Cage aquaculture is expanding across Africa because of its potential to address food insecurity, provide livelihoods, and boost local economies. However, the uncontrolled expansion of cage aquaculture can have significant negative impacts on water resources, including environmental footprints that threaten biodiversity. Given the intensification of cage aquaculture for tilapia farming on Lake Volta, we advocate for a transition to inland-integrated aquaculture systems that promote circularity. Strengthening stakeholder collaboration is essential for enhancing competence in mapping inland aquaculture areas, identifying eco-friendly alternatives and reinforcing aquaculture regulations, with particular emphasis on cage culture on Lake Volta. These strategies can reduce the pressures imposed by tilapia cage farms on the lake while promoting best management practices. Additionally, capacity building must be an ongoing process to address knowledge gaps, including the development of effective preparedness plans executed during emergencies. The ongoing pollution from illegal mining in the Black Volta River, a tributary of Lake Volta, along with endemic diseases in the lake, further compounds fish health and welfare issues. This underscores the urgent need to implement inland transition strategies to protect the lake, mitigate disease spread, and ensure safe fish food production.

Keywords: Lake Volta; cage aquaculture; mapping inland areas; law enforcement; best management practices; collaboration and capacity building; emergency preparedness

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1. Introduction

Cage aquaculture began in Ghana in the mid-2000s with the establishment of the first commercial farm on Lake Volta [1,2]. Fish farming in Ghana, however, started in 1953 with the conversion of irrigation reservoirs in the Northern region [3]. Currently, most fish farmers prefer Lake Volta (Figure 1) for several reasons, including its good water quality, optimal flow rate, and appropriate water depths [4,5]. Lake Volta contributes approximately 90% of Ghana's annual farmed production of Nile tilapia (*Oreochromis niloticus*) and African catfish (*Clarias gariepinus*). In 2021, Ghana earned approximately $140 million from a total aquaculture production of 89,400 metric tonnes (Figure 2) [6]. Of this production, tilapia accounted for 68,740 metric tonnes, while catfish constituted 20,660 metric tonnes [7,8].

The socio-economic benefits derived from Lake Volta have made it the aquaculture hub in Ghana. Currently, Lake Volta remains one of the few water resources in Ghana that is not visibly polluted. However, future projections suggest that Lake Volta may lose its relevance and importance due to the increasing water pollution caused by illegal mining in Ghana [9]. The effect of this illegal mining in the Black Volta River, a tributary of Lake Volta, is causing much concern among cage farmers downstream. If the illegal mining activities, which have already destroyed almost all major water bodies and tributaries in the country, continue, the conditions necessary to support life in the lake might be compromised. Furthermore, forecasts indicate that expanding tilapia cage culture beyond the lake's carrying capacity could lead to chemical and nutrient pollution, the introduction of non-native species and pathogens, as well as increased sediment and organic matter loading [10–14]. Some of these concerns have already been substantiated [11,12]. Therefore, the objective of this paper is to present alternative perspectives on rethinking cage aquaculture in Lake Volta to better protect its ecosystem services and biodiversity. This is particularly important for informing trans-regional management decisions, as Lake Volta connects to the Volta Basin, which borders Benin, Burkina Faso, Côte d'Ivoire, Mali, and Togo.

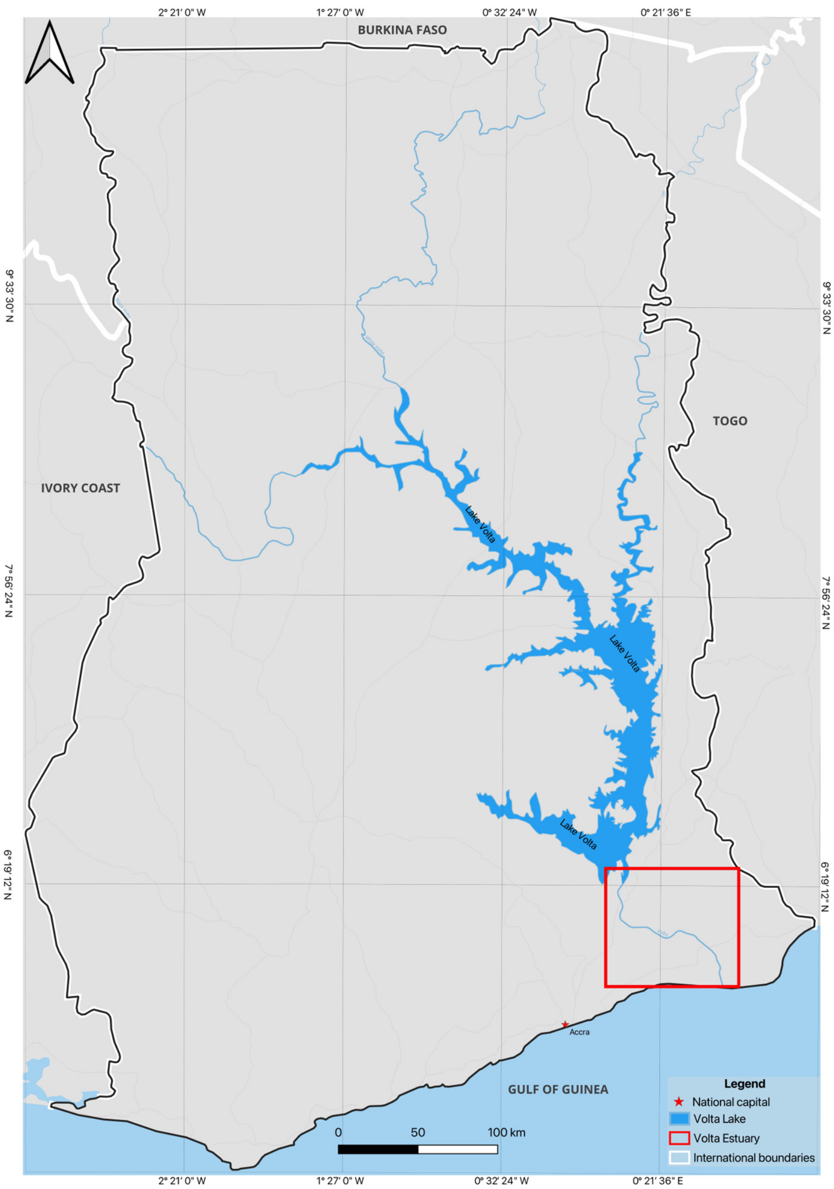

Figure 1. Map of the Volta Lake, situated in the eastern part of Ghana. The lake generally flows southward through Ghana into the Volta estuary, where it empties into the Gulf of Guinea.

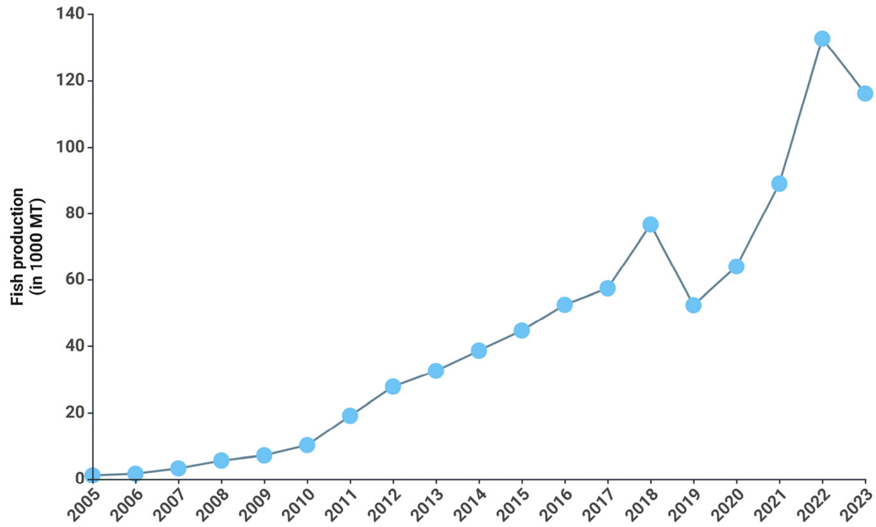

Figure 2. Annual aquaculture production in Ghana (2005–2023). The graph was created using data from [6].

Many studies have assessed the potential effects of cage aquaculture on the physico-chemical properties of Lake Volta. The majority of these studies concluded that there were no significant changes in water quality parameters such as ammonia, pH, nutrient levels, dissolved oxygen and total suspended solids in the lake. [1,15–22]. However, drawing definitive conclusions about the overall water quality of Lake Volta is challenging because these studies focused on localized areas rather than the entire basin. For instance, dissolved oxygen, biochemical oxygen demand, and total suspended solids or turbidity were within acceptable limits [23–25] or exceeded the thresholds expected for unpolluted water bodies [26–28]. This suggests that the water quality of Lake Volta fluctuates between pristine and poor levels, highlighting the need for continuous management to protect this vital water resource.

Concerns have been raised about the impacts of fish farming, specifically effluents affecting the water quality of the lake, in discussions about the social acceptance of cage aquaculture on Lake Volta [29]. These concerns extend to effluents from households, the Akosombo textile industry and agricultural activities [29–32]. Additionally, pollutants from sand and mineral mining have been documented in the Black Volta River, which flows downstream into Lake Volta [10,33,34]. These pollution sources are not unique to Lake Volta but reflect the overall increase in water pollution across Ghana. The Ministry of Water Resources confirmed this in a report linking rising water treatment costs in Ghana to mining, industrial, agricultural, housing, and commercial activities [9]. Despite these challenges, Lake Volta remains a critical source of drinking water, treated by the Ghana Water Company Limited (GWCL). If pollution persists, the GWCL may face higher treatment costs, leading to broader socio-economic consequences for Ghana.

Since 2018, ongoing disease outbreaks and unusual mortalities in Lake Volta have created increasingly stressful conditions for farmed tilapia. A recent study conducted by Zornu et al. [10] investigating unusual tilapia mortalities in Lake Volta identified a combination of pathogens and non-infectious factors contributing to these mortalities. The study linked fish mortalities to water pollution from human-mediated pollutants, aquaculture wastes, and other non-infectious factors [10]. Despite these challenges, the Fisheries Commission (FC) has projected an 8% annual growth in aquaculture production over the next three years [7]. Meeting this projection could lead to intensified production and the establishment of new tilapia cage farms on the lake. Assuming that each lake farm operates with an average Feed Conversion Ratio of 1.5 and an 8% annual growth rate [7], more tilapia cages could lead to a significant increase in feed input, resulting in larger volumes of aquaculture waste. This, in turn, could further degrade the water quality of Lake Volta. The pursuit of higher fish production also increases the risk of aquatic diseases with medium to large-scale effects. These range from localized outbreaks affecting individual farms to widespread disease outbreaks across the country. Consequently, Lake Volta could become a repository for chemicals used to combat fish diseases (Figure 3). The rise in bacterial fish diseases in Lake Volta has led to increased antibiotic use, contributing to the development of resistance [35,36]. While land-based aquaculture operations have their peculiar environmental issues, cages, being open systems, can aggravate negative environmental impacts on native species and contribute to the overall deterioration of the lake. Native species in Lake Volta may contract diseases that could have originated from the importation of unapproved fish species (Figure 3).

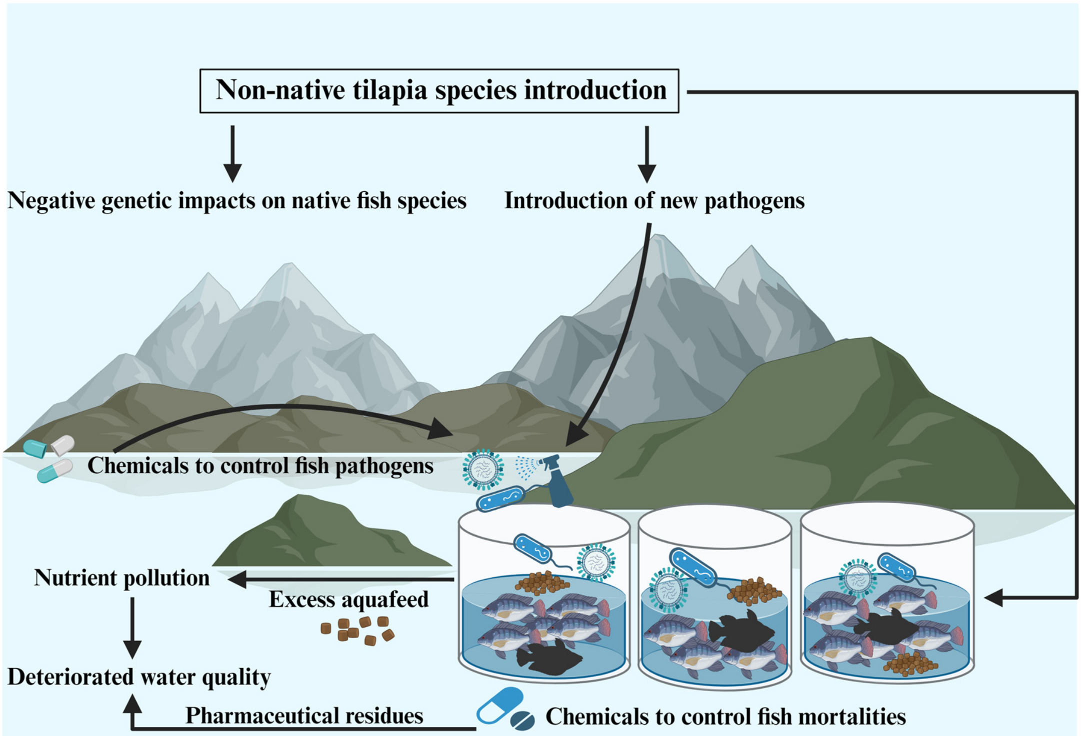

Figure 3. Negative impacts of unregulated tilapia cage aquaculture on Lake Volta. This figure illustrates the aquaculture-mediated introduction of non-indigenous tilapia species and pathogens. This includes potential genetic effects on indigenous fish species as non-native tilapia species escape from floating cages. The intensification of tilapia cage aquaculture on the lake becomes a catalyst for the proliferation of fish pathogens of exotic and endemic origins, leading to the establishment of diseases. Consequently, the excessive use of chemicals to manage fish diseases, along with increased feed usage due to aquaculture intensification, contributes to water pollution. Created with BioRender.com.

Most fish farms are located downstream from the lake, below the Akosombo dam. Any planned or unplanned spillage from the dam could have devastating effects on floating cages and riparian communities. The 2023 water spillage from the Akosombo dam caused massive destructions to fish farms and affected over 100 fishing communities. To safeguard the socio-economic wellbeing of fish farmers and riparian communities, it is prudent to explore alternative production systems. Cage fish farmers incurred losses of GHC 46 million due to the dam spillage. This event also raised ecological concerns as unapproved foreign fish species from the cages escaped into the Lake. Non-native fish species can outcompete local species, disrupt the lake's ecosystem balance, and alter ecological relationships [37]. The introduction of foreign tilapia species through aquaculture (Figure 3) has led to the loss of genetic integrity, as reported by Anane-Taabeah et al. [12]. The environmental consequences of escaped fish are multifaceted and have long-term implications for ecosystem stability. Therefore, mitigating the risks associated with introducing non-native species into the wild is crucial to maintaining the integrity of aquatic ecosystems.

Given these challenges, it is essential to consider environmentally sustainable alternatives rather than focusing solely on the intensification of cage aquaculture. Many countries within and outside Africa are actively pursuing diverse aquaculture systems to enhance production and maximize socio-economic benefits. Advances in aquaculture engineering and research have made it possible to farm fish using alternative culture methods, eliminating the need to farm directly in natural water bodies. Some of these systems include raceways, aquaponics, Recirculatory Aquaculture Systems (RASs), ponds, and tanks constructed from concrete, tarpaulin, fiberglass, and wood lined with plastic or other waterproof materials. Shifting to these alternative systems can reduce the environmental footprints of aquaculture compared to the dominant open-water fish farming. Countries like the United States, Norway, and Canada have implemented strict measures to regulate open-cage fish farming [38,39]. Coastal British Colombia in Canada is planning to consider only marine or land-based closed-containment systems for future aquaculture licenses [38]. Adopting such best practices is crucial to encouraging the exploration of alternative culture systems suited to the country's terrain. Otherwise, any future disaster related to cage aquaculture could severely affect Ghana's fish food security. By considering the effects of cage aquaculture in Ghana, this review proposes a paradigm shift towards land-based culture systems. To achieve this, the study provides a global snapshot of the environmental impacts of cage aquaculture, juxtaposing it with the Ghanaian narrative. It also recommends strategies for transitioning to inland systems through improved aquaculture governance and infrastructure, while addressing both present and future challenges (Figure 4).

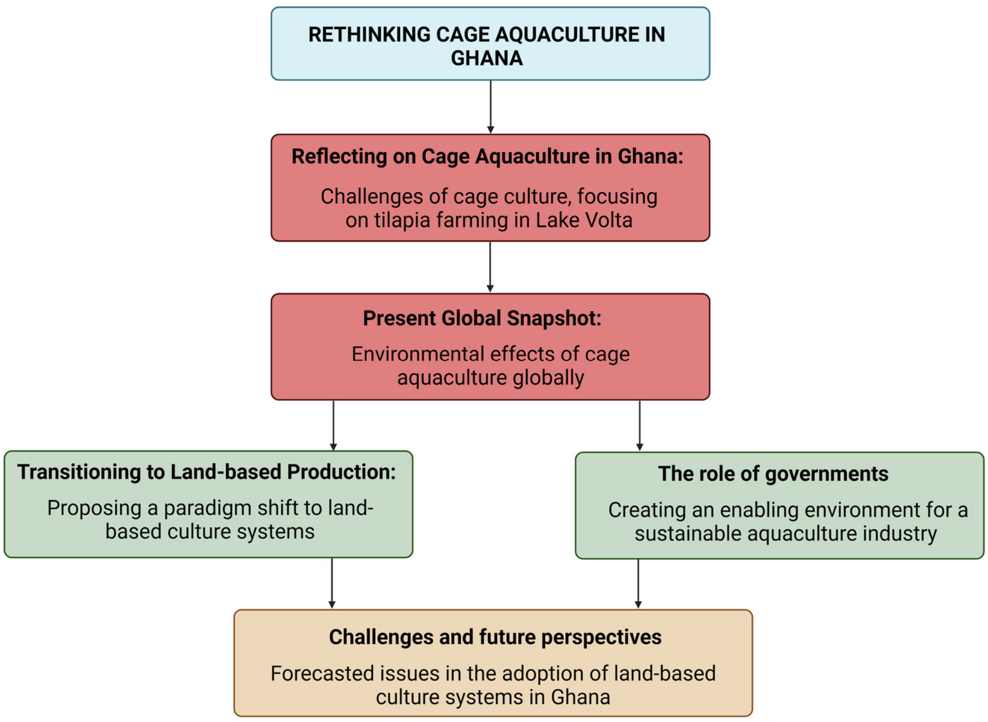

Figure 4. A flowchart summarizing the review outline and goals. Created with BioRender.com.

2. Global Snapshot of Environmental Effects of Cage Aquaculture

Over the past 40 years, aquaculture has made significant contributions to global seafood production [40]. In 2020, global fisheries and aquaculture production reached 178 million tonnes, with aquaculture accounting for 49% (88 million tonnes) of the total volume [41]. Among the various aquaculture systems, ponds are the oldest and most dominant system [42]. However, over the last 20 years, cage aquaculture has expanded rapidly; garnering global attention for its ability to intensify production in both natural and artificial water bodies [43–45].

The exponential growth of cage aquaculture poses serious threats to essential aquatic ecosystem services and can significantly influence global freshwater and marine biodiversity [46–57]. Fish escaping from cages are almost unavoidable due to accidents, flooding, and equipment failure. The problems of escapees and their effects on biodiversity include predation on native stocks, hybridization, and disease transmission. The increased interaction between escapees and wild fish heightens the risk of disease and parasite transmission to wild populations [58,59]. The excessive use of antimicrobials to mitigate disease risks has subsequently accelerated the development of antimicrobial resistance [60,61]. Additionally, biological interventions through cleaner fish to reduce parasitic infestations are linked to the transmission of diseases to wild fish populations [62,63]. Furthermore, farmed fish selectively bred for faster growth, with broodstock often modified to produce infertile fry, and hormonal sex reversal techniques are not 100% accurate. As a result, escapees including modified broodstock demonstrate superior competitive abilities, disrupt ecosystem health, introduce alterations to wild fish population habitats, and risk species extinction [64–73]. For instance, tilapiines, frequently incriminated as aquaculture-mediated invasive species, have displaced many native species [49,74–76].

An often-overlooked issue affecting marine and freshwater biodiversity in West Africa is the depletion of capture fishery resources used in aquafeed production. Fishmeal and fish oil, derived from small pelagic fish such as anchovies, sardines, Atlantic herring, and menhaden, are limited resources [77,78]. Over the past decade, global fishmeal and fish oil production have remained relatively stable at approximately 5 million tonnes and 1 million tonnes, respectively [79]. In 2020, 86% of fishmeal and 73% of fish oil were heavily used in aquaculture [80]. Unlike freshwater aquaculture, the demand for these resources is particularly high in mariculture [81–83], mostly practiced in advanced countries. This practice exacerbates the overexploitation of capture fisheries, especially in poorer countries [84]. This diverted use of seafood in aquafeed production, which otherwise would have been used for human consumption, forces affected countries to farm fish to meet their nutritional needs.

The dispersion of fecal matter, dissolved nutrients and feed waste from floating cages, is a major source of pollution in receiving waters, demonstrating the harmful impacts of aquaculture on biodiversity [85–87]. Unlike emerging closed cages, poorly sited and mismanaged open cages can lead to significant consequences, including changes in aquatic microbial diversity, abundance, and community structure [88–90]. Benthic environmental footprints are another concern from aquaculture practices, as biofouling from organic waste leads to sedimentary stress and a decline in benthic communities [91–93]. Additional evidence also suggests that aquaculture reduces zooplankton diversity and species richness near cage sites [94]. Despite these negative effects, aquaculture can offer benefits to biodiversity, including reducing fishing pressure on overexploited wild stocks, supporting conservation efforts by stocking native fish, and increasing species diversity, abundance, and richness [95–100].

In response to the environmental footprints of cage aquaculture, aquaponics, In-pond Raceway Systems (IPRSs), integrated multi-trophic aquaculture (IMTA) and RASs offer more sustainable approaches. Aquaponics combines plant cultivation with fish farming in a symbiotic environment where fish waste becomes nutrients for plants. This system promotes resource efficiency while reducing environmental impacts [101,102]. Similarly, IPRSs ensure resource efficiency through efficient water use, improved yields, and reduced global gas emissions [103]. IMTA also mimics natural ecosystems by integrating species from different tropic levels, such as fish, shellfish, and seaweed to enhance nutrient recycling and reduce waste production [104,105]. This makes IMTA a more eco-friendly alternative to traditional cage farming. Integrated Poultry/Livestock–Fish farming is a variation of IMTA where animal waste is used to fertilize fishponds, reducing the need for artificial feed and fertilizers [106,107]. Though an RAS requires significant capital investment, it operates by continuously filtering waste from recirculating water in a closed system, minimizing the risks of escapees, pollution, and disease transmission to wild populations [108,109]. By adopting these innovative systems, aquaculture can significantly reduce its ecological footprints while maintaining productivity and promoting sustainability in global fish farming.

3. Transitioning from Lake Volta Cage Aquaculture to Land-Based Fish Production

This section outlines strategies for transitioning from cage aquaculture on Lake Volta to more sustainable land-based fish farming systems. The goal is to protect the lake's ecosystem while ensuring the socio-economic benefits of aquaculture continue. The strategies consider legal, environmental, and socio-economic dimensions needed to preserve Lake Volta's ecological integrity for future generations.

3.1. Capacity-Building (CB)

Capacity-building, both for individuals and institutions, is crucial for the successful transition from Lake Volta cage aquaculture to land-based production systems (Figure 5). Since 2004, the Water Resources Commission (WRC) in Ghana has led awareness-raising campaigns (1a. Figure 5) which extend beyond aquaculture to include broader environmental management. Regulatory bodies like the Fisheries Commission, the Environmental Protection Agency (EPA), and the Volta River Authority (VRA) have also organized workshops and seminars aimed at educating fish farmers and key stakeholders throughout the aquaculture value chain. These educational efforts must focus not only on sustainable fish production and Lake management but also on promoting a shift towards eco-friendly aquaculture systems [110,111]. The aquaculture sector requires balanced collaboration between academia, private industry, and public sector institutions. Strong partnerships among these sectors can foster knowledge sharing and practical-oriented education, which are necessary for addressing sustainability challenges in aquaculture. Partnership-driven capacity-building efforts can thus emphasize the following:

(1) Innovation in inland-integrated aquaculture systems that promotes circularity, including farmer technical skill development for good husbandry and fish health management;
(2) Environmental awareness among aquaculture stakeholders, highlighting the long-term environmental impacts of cage aquaculture on Lake Volta, along with the advantages of land-based alternatives;
(3) Regulatory compliance to ensure authorities and farmers become more conversant with legal requirements and the consequences of non-compliance.

However, limited collaboration currently exists in Ghana between academia, the government, and the private sector in tackling sustainability issues, as noted by Zornu et al. [112]. Strengthening these relationships could help identify industry needs and guide appropriate interventions for the transition to land-based fish farming. Capacity-building campaigns should extend beyond formal settings to reach a wider audience, particularly through media. The media can play an essential role in raising awareness about the environmental, social, and economic drawbacks of open-water cage aquaculture. Disseminating this information can help shift public opinion and practices towards more sustainable land-based systems. Furthermore, research and diagnostic institutions, as well as universities (1b. Figure 5), must be equipped to bridge knowledge gaps and address industry setbacks by providing science-based solutions. The knowledge acquired can guide the establishment of fish health management systems (1c. Figure 5) that the industry desperately needs as disease incidences persist. In summary, capacity-building is a cornerstone of the transition strategy, ensuring that farmers and institutions are equipped with the knowledge, skills, and resources necessary for a successful shift to land-based aquaculture.

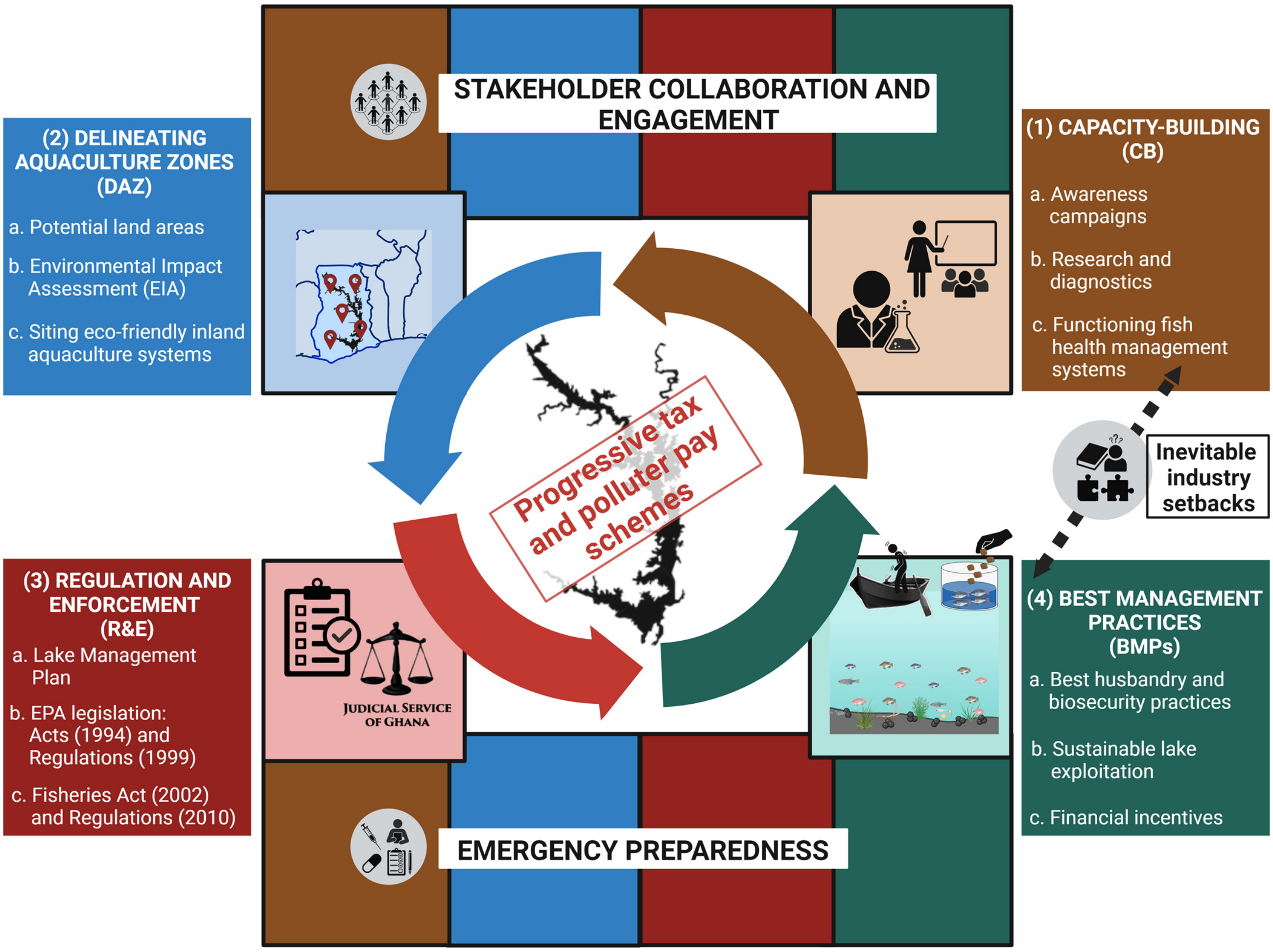

Figure 5. Transitioning from Lake Volta cage aquaculture to land-based production. The strategies involve deepening stakeholder collaborations among institutions and individuals to build the capacity (CB) for delineating aquaculture zones (DAZ), identifying eco-friendly options, as well as Regulating and Enforcing (R&E) environmental and aquaculture regulations. Enforcing existing legislations will encourage farmers to pursue best management practices (BMPs). CB is necessary for bridging knowledge gaps and finding innovative ways to address inevitable industry setbacks. Emergency preparedness can also benefit from stakeholder collaborations to ensure robust and swiftly executed plans during adversities. Created with BioRender.com.

3.2. Delineating Aquaculture Zones (DAZ)

Capacity-building efforts will also be essential in equipping stakeholders with the necessary skills and knowledge to effectively map and manage areas designated for inland holding systems. The delineation of aquaculture zones (DAZ) is a critical component of Ghana's aquaculture planning (Figure 5). Current mapping efforts aim to identify suitable locations within aquatic ecosystems, as highlighted in the 2012 Ghana National Aquaculture Development Plan discussed by Zornu et al. [113]. This plan emphasizes the identification of high-priority aquaculture zones, particularly in Lake Volta. However, with the lake already heavily populated with floating cages and the pollution from illegal mining activities, designating additional aquaculture zones may exacerbate the environmental burden on the ecosystem. To protect Lake Volta and other vulnerable water bodies, it is essential to explore inlands areas that are suitable for aquaculture. Transitioning from cage aquaculture to land-based production systems can help protect sensitive habitats, preserve biodiversity and minimize environmental impacts on aquatic ecosystems. Inland aquaculture zoning is more helpful in disease prevention through effective surveillance monitoring, compared to the high-risk open waters of Lake Volta. The fish farm demography in Ghana is highly fragmented, predominantly among small operators. Therefore, zoning can also help cluster small-scale farms into specific zones [114], enabling better regulation, access to extension services, and containing disease outbreaks. The United Nations Environmental Programme highlights the environmental impact assessment (EIA) as a crucial tool for evaluating the environmental, social, and economic impacts of a project, offering a pathway to mitigate negative effects. After identifying and zoning potential inland areas, conducting an EIA becomes essential for safeguarding environmental health (2b. Figure 5). A comprehensive environmental assessment that considers social, physical, chemical, and other factors would provide a robust foundation for protecting ecosystems.

Having successfully zoned suitable inland areas and conducted an EIA, eco-friendly aquaculture systems described above, like ponds and raceways, including circularity-driven integrated systems like IMTA, must be sited (2c. Figure 5). It cannot be overemphasized that these systems create a controlled environment between the fish and the ecosystem, minimizing environmental impacts compared to open-water cages. While the majority of Ghanaian fish farmers prefer cage aquaculture for various reasons, leading producers like Egypt, China, and Bangladesh are inclined toward earthen pond production [115,116]. Ponds offer a natural alternative with lower environmental footprints but are limited by factors, namely land suitability and availability, water supply, and dissolved oxygen levels [117,118]. Nevertheless, ponds like any other closed-containment system, allow for waste containment and the possibility of processing waste before discharge [119]. One challenge with pond aquaculture is the potential contamination of aquifers that recharge the ponds. This risk can be mitigated by reducing chemical use in pond aquaculture, including integrated systems through nutrient recycling and bioremediation [119]. These approaches optimize resource utilization and enhance overall productivity while protecting environmental health.

3.3. Regulation and Enforcement (R&E)

Most fish farms in Ghana are not registered, thereby failing to comply with regulations established by the FC, EPA, WRC, District Assembly, and the VRA. Strict implementation of these regulations is vital for effectively managing cage farming on the lake and inland aquaculture farms. This includes setting limits based on the lake's carrying capacity and ensuring that the VRA's lake management framework for sustainable exploitation [10] is applied effectively (3a. Figure 5). The EPA has established guidelines and regulations regarding EIA, which are enforceable through the EPA Act [120] and related Regulations [121] (3b. Figure 5). The EPA must be empowered to routinely enforce these mandates, particularly concerning water quality standards, in collaboration with the WRC and the VRA—the main authority responsible for managing Lake Volta. This collaboration will facilitate effective monitoring as land-based fish farms source water from the lake and other water resources. The FC has also banned the importation of unapproved foreign fish strains through Acts 2002 [122] and Regulations 2010 [123] (3c. Figure 5). In collaboration with port and harbor authorities, checkpoints established must ensure that only approved species with well-documented health statuses are imported into the country. This will help preserve native fish diversity while reducing the risk of introducing exotic fish diseases and pathogens into the industry.

3.4. Adopting Best Management Practices (BMPs)

Fish farmers must adopt best management practices (BMPs) alongside complying with regulations to ensure responsible farming (Figure 5). BMPs can promote optimal husbandry practices and biosecurity measures that minimize environmental impacts and prevent fish diseases (4a. Figure 5). Consequently, implementing these practices can help reduce the reliance on synthetic chemicals, thereby ensuring sustainable Lake Volta exploitation (4b. Figure 5), minimizing antimicrobial resistance, and reducing the environmental footprint of the aquaculture. Farming practices devoid of environmental degradation enhance the social acceptability of aquaculture and support international fish trade [113].

It is important that the financial incentives provided to fish farmers are for pursuing best husbandry and the implementation of biosecurity measures (4c. Figure 5).

Like all food production systems, even the best husbandry and biosecurity practices may not guarantee everlasting industry sustainability. There will be 'inevitable setbacks' (Figure 5), namely massive mortalities caused by emerging pathogens and parasites. Therefore, it is important that there is ongoing capacity building to adequately prepare the industry to bridge knowledge gaps and address these setbacks. Moreover, addressing inevitable setbacks in the industry requires collaborative and multidisciplinary approaches to develop comprehensive emergency preparedness plans (Figure 5). Partnership-driven efforts led by regulatory authorities are paramount for establishing contingency plans that protect both the industry and farmer livelihoods. For instance, collaboration between the FC and the Veterinary Services Directorate is essential for effective surveillance monitoring that enables rapid responses during fish health crises. Additionally, collaboration among regulatory authorities, researchers, farmers, and other stakeholders will guide aquaculture development and ensure its integration into the wider ecosystem without compromising ecosystem functions and services. In brief, without collaboration, processes such as capacity-building, delineating aquaculture zones, and enforcing legislations to drive best management practices become more challenging.

4. Governments' Role in Transitioning from Open-Water to Land-Based Aquaculture

Good aquaculture governance is essential for creating an enabling environment that fosters productivity and long-term growth in the industry [124]. In Ghana, one of the primary challenges is the limited technical knowledge among fish farmers. While some may possess basic skills in fish husbandry practices, many lack an awareness of sustainable practices and the effects of fish farming on the wider ecosystem [5,125,126]. The government plays a crucial role in addressing this gap by identifying and developing the necessary human competencies and infrastructure to support sustainable aquaculture practices [124]. In collaboration with the Ghana Chamber of Aquaculture [113] or the National Aquaculture Committee, the government can pinpoint key areas for improvement and help build a more sustainable industry. Alternatively, the government's active collaboration with farmers, academic, and research institutions is key to generating critical knowledge for the sector. Through the sector Ministry, the government can solicit innovative proposals via competitive bidding, focusing on industry issues and scientific and technological advancements for viable solutions.

One of the key ways the government can contribute is by investing in diagnostic laboratories, and supporting educational and research institutions with relevant logistics. These investments will enhance the industry's ability to manage fish health, implement biosecurity measures, and ensure compliance with environmental regulations. Moreover, knowledge institutions can provide technical expertise in areas such as fish reproductive biology, culture systems, husbandry management, and legislation enforcement. Through media channels, the government can amplify new knowledge and discoveries among stakeholders. To facilitate the transition from open-water cage aquaculture to land-based systems, it is imperative that the government guarantees the availability of essential infrastructures, like electricity and road networks. These resources are necessary for transportation and access to key inputs and outputs within and beyond aquaculture zones. Additionally, the government must deploy skilled aquaculture and veterinary officers to support these initiatives through extension services.

One significant challenge in Ghana's aquaculture sector is the complexity of farm registration, which is burdened by bureaucratic processes across multiple institutions. This often results in the weak enforcement of regulations and standards. The ongoing Fish for Development in Ghana project, in collaboration with the FC, seeks to streamline this process through the introduction of a one-stop-shop regime for farm registration and permits. By simplifying farm registration processes, the government can better monitor and regulate aquaculture operations to ensure compliance with the Aquaculture Code of Conduct, including environmental and ethical standards. Drawing from international models, such as Coastal British Columbia's plan to license only closed-containment aquaculture systems in the future [38], Ghana can adopt similar measures.

The introduction of the Progressive Tax System (PTS) and Polluter Pays Principle (PPP) policies by the government can serve as financial tools to promote sustainable fish farming practices (Figure 5). The PTS would impose higher taxes on farmers who continue cage farming on Lake Volta, while the PPP [127,128] would levy fines based on the amount of waste produced and discharged into the lake. Implementing these financial policies would gradually force reduction of the number of cages on the lake over a period of time. For example, applying the PPP first involves identifying cage farmers operating on small, medium, and large scales, followed by levying penalties based on the fish biomass produced. This approach would encourage farmers to transition to holding systems that offer greater control over waste treatment and disposal. The PTS is akin to the penalty unit system implemented by the government of Ghana in the capture fisheries industry [94]. In the aquaculture sector, these financial tools may be challenging to implement, especially for small and medium-sized farms with limited resources [127,129]. However, basing penalties on waste generation ensures fairness across all scales of production. In summary, adopting the PTS and PPP will not only inspire a shift toward eco-friendly aquaculture practices but will also discourage farmers from prioritizing short-term gains over environmental sustainability. In summary, the government must prioritize aquaculture development through effective policies and ensure that fiscal constraints do not hinder the sector's growth and sustainability.

5. Challenges and Future Perspectives

Adopting inland culture systems in Ghana offers promising sustainability opportunities for aquaculture, but it may face challenges beyond land and water availability. One major hurdle is the cultural resistance to adopting alternative land-based culture systems, given the long-standing popularity of cage aquaculture. The waste management advantages of inland-integrated aquaculture systems may not be fully realized if local farmers lack adequate husbandry knowledge in terms of water quality control and nutrient cycling [5,125,126]. The absence of careful management could lead to nutrient overload in the holding units, resulting in eutrophication, excess algae decomposition, and oxygen depletion. It is therefore important to prioritize capacity building to develop the right competencies for the use of such systems.

Additionally, the risk of disease transmission, including the transfer of resistant pathogens and genes between terrestrial animals and aquatic species in integrated systems, is another concern [130–133]. The sector is already vulnerable to emerging diseases, highlighting the need to establish passive and active surveillance, including strong biosecurity measures, to ensure the industry is well-prepared during fish health crises. Moreover, the requisite knowledge for efficiently implementing inland-integrated systems in Ghana is not widespread among fish producers. However, with the government's involvement by resourcing educational intuitions, emergent knowledge gaps can be bridged.

An RAS entails significant financial investments, alongside the need for advanced infrastructure, technology, and a dependable energy supply. Additionally, biofilm accumulation is one of the critical husbandry challenges in managing an RAS, further complicating its adoption and making it less accessible to a wider range of farmers [108,109]. However, energy accessibility can be improved through renewable sources like solar, wind, and biogas energy, which can reduce the reliance on insufficient hydroelectric power in Ghana. Furthermore, the availability of quality tilapia fingerlings and feed may continue to pose challenges in the future. Thus, access to these essential inputs and well-developed local supply chains is pivotal for ensuring the success of these systems and the overall growth of aquaculture.

One of the major causes of water pollution in Lake Volta that can persist in peripheral inland aquaculture is the leaching of agrochemicals [10], which results from inefficient irrigation technologies, improper fertilizer use, and unimplemented agricultural policies [134]. The government must protect inland aquaculture from runoff pollution and safeguard water bodies in Ghana through improved agricultural practices. Outside the periphery of Lake Volta, water availability throughout the year can be challenging. Through the Ghana Irrigation Development Authority, 5% of national irrigation schemes are reserved for aquaculture activities, potentially addressing land and water constraints for inland production [135]. Additionally, the construction of additional water retention dams or reservoirs to harvest rainwater, including boreholes and wells in the zoned areas across the country can further alleviate these constraints. Likewise, pursuing innovations such as IPRSs counteracts water availability crises for pond aquaculture through efficient water use, improved yields, and reduced global gas emissions [103,136].

6. Conclusions

This paper highlighted the significant environmental, social, and economic challenges posed by the expansion of cage aquaculture on Lake Volta, with particular emphasis on the threats to local biodiversity and the long-term sustainability of the lake. In response, several comprehensive strategies are recommended, ranging from capacity building to identifying suitable inland aquaculture areas, coupled with stringent environmental impact assessments to site eco-friendly holding units. The implementation of regulation and enforcement, and the adoption of BMPs across the industry would ensure environmentally sustainable aquaculture practices. This paper advocates for a collaborative, multi-stakeholder approach involving the government, research institutions, private sector actors, and fish farmers to ensure a successful transition from lake-based to land-based aquaculture. The future of aquaculture in Ghana hinges on careful management and good governance for sustainable production. By enforcing stricter pollution penalties and promoting education and research, the government can drive the sector toward more sustainable practices. At the same time, emergency preparedness, robust disease surveillance, and joint stakeholder engagement will be crucial in mitigating unforeseen challenges. The ongoing pollution from illegal mining in the Black Volta River, a tributary of Lake Volta, along with endemic diseases in the lake, further compounds fish health and welfare issues. This underscores the urgent need to implement inland transition strategies to protect the lake, mitigate disease spread, and ensure safe fish food production.

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