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Climate-smart aquaculture as a tool for blue economy revolution in Botswana: a review

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Climate Smart Aquaculture (CSAq) has the potential to transform Botswana's aquaculture sector and contribute to the development of a resilient blue economy. This study synthesizes existing literature on Botswana's climate, hydrology, and aquaculture prospects to evaluate the suitability of CSAq across the country. The analysis identifies three climatic regions: Okavango-Chobe, Eastern margin, and Arid Southern-Western regions. The Okavango-Chobe region, characterized by seasonal pans, lagoons, and lakes, is well suited to traditional aquaculture and can be further enhanced through integrated pond systems, integrated wetland aquaculture, recirculating aquaculture systems, biofloc technology, aquaponics, and Integrated Aquaculture-Agriculture systems, subject to strict conservation requirements. The Eastern margin presents moderate aquaculture potential, supported by constructed dams and capture-based aquaculture, with Recirculating Aquaculture System (RAS), biofloc, aquaponics, and Integrated Agriculture-Aquaculture Systems (IAAS) offering viable climate smart options. In contrast, aquaculture development in the Arid Southern-Western region is largely restricted to ultra-water efficient systems, including RAS, biofloc, and aquaponics. Key constraints to CSAq adoption include limited technical capacity, climate variability, unfavorable environmental conditions, and restricted access to finance. These challenges can be addressed through targeted capacity building, adoption of ultra-efficient production technologies, diversification strategies, increased research investment, and innovative financing mechanisms. The study recommends that successful CSAq adoption in Botswana be underpinned by policy and institutional frameworks that emphasize conservation compliance, sustainable water resource management, green energy technologies, and human capacity development.

KEYWORDS
blue foods, Botswana, climate resilient, climatic regions, food systems, sustainable aquaculture

1 Introduction

Climate-Smart Aquaculture (CSAq) is a revolutionary method of producing fish, tackling the interrelated problems of sustainable livelihoods, food security, and climate change adaptation (Lipper et al., 2014; Tanuja et al., 2025a). This tool has the potential to significantly transform aquaculture practices in Botswana, a semi-arid nation dealing with severe water scarcity and climate-related issues. CSAq offers a sustainable pathway toward resilient and productive food systems that can withstand the impacts of the country's changing climate. The concept of CSAq is based on three core pillars that include reducing greenhouse gas emissions, improving resilience to climate variability, and sustainably increasing productivity and income (van Wijk et al., 2020). In the broader "blue foods" discourse, aquaculture is increasingly framed not only as a supply-side solution for dietary protein and micronutrients, but also a sector whose future performance will be shaped by climate shocks, energy systems, feed supply chains, and water availability. Against this backdrop, CSAq seeks to find aquaculture solutions that are environmentally responsible and conducive to increased yields, consequently gearing toward improved livelihoods. Adopting CSAq in Botswana as a decision-oriented approach can support aquaculture's long-term sustainability and reduce its negative effects on the environment. Therefore, promoting CSAq and incorporating it into Botswana's national development strategies is crucial for driving the main goal of the Blue Transformation Program (Naylor et al., 2021).

Botswana's aquaculture industry remains underdeveloped, as aquaculture in its broader historical sense has had limited cultural and production significance in the country. The idea of aquaculture surfaced as a trial in the 1980's through the Aquaculture for Local Community Development Program (ALCOM) which attempted to drive utilization of small water-bodies for aquaculture and fisheries (Botswana Government, 2021a). Interest in aquaculture manifested in the country as people were getting aware of this form of food cultivation. The Department of Fisheries and Apiculture (DFA) confirm that small scale aquaculture, mostly utilizing simple pond systems gained momentum around 2010. Medium scale fish farm also surfaced around this period. By 2011, an estimated total of 21 operations including 20 small scale and 1 medium scale farms were recorded in Botswana. Among these, a total of 17 small scale operations utilized pond system covering a total area of 425 m^2 while 3 adopted basic Recirculating Aquaculture System (RAS) with a total volume of 3.5 m^3. The remaining one was the only medium scale operation which adopted a combination of the pond and the RAS in the farm. Altogether, the ponds covered an area of 1,600 m^2 while RAS volume stood at 15 m^3. Nevertheless, no production was reported by then because all ventures were all at their initial phase. No production was reported also in subsequent years (2012–2015). This was attributed to several challenges including poor management due to lack of knowledge, lack of locally produced fish feed, lack of quality fingerlings, and lack of reporting (Botswana Ministry of Agriculture, 2023). Overall, aquaculture in Botswana began gaining momentum after 2016 (FAO, 2020), with production estimated at about 20 tonnes in 2017, increasing modestly to approximately 25 tonnes in 2018 and 35 tonnes in 2019. This was followed by a marked expansion, with production rising to 146 tons in 2020 and 172 tons in 2021 (FAO, 2023). However, most of the reported output is attributed to the country's only commercial fish farm, which produces Nile tilapia (*Oreochromis niloticus*) and Threespot tilapia (*Oreochromis andersonii*). This farm, located along the Chobe River, operates a combination of production systems, including a RAS housed in a greenhouse tunnel and 20 outdoor earthen ponds, each with a surface area of 5,000 m^2 (Botswana Ministry of Agriculture, 2023).

Despite this growth, Botswana has a severe shortage of fish production output to meet national demand. Cumulatively, domestic output, from both capture fisheries and aquaculture, averages about 550 tonnes every year, which falls short of the country's estimated 5,000 tonnes of demand. This creates a shortfall of around 4,450 tonnes that is filled by imports (FAO, 2024; Maulu et al., 2024). This substantial supply gap highlights the urgent need to increase local fish production, particularly through the expansion and intensification of aquaculture. Compared to regional averages, Botswana consumes comparatively little fish, despite more than 20% of its population facing undernourishment (Maulu et al., 2024). At the same time, the national population continues to grow, rising from about 2.6 million and projected to reach 3.4 million by 2050 (World Health Organization, 2026). This demographic trend is expected to further increase demand for affordable and high-quality protein sources. Fish, being one of the most affordable and nutrient-rich animal protein sources, presents a viable pathway to address protein deficiencies and improve national food and nutrition security (Maulu et al., 2024).

However, the capacity to meet this growing demand is further constrained by environmental and climate-related challenges. Capture fisheries are inherently finite and increasingly threatened by overexploitation, while climate variability and change are already affecting water availability, increasing temperatures, and altering aquatic ecosystems, thereby reducing the productivity and reliability of both wild fisheries and aquaculture systems (Hountcheme and Simon, 2024). Climate change is increasingly constraining fish production through rising temperatures, shifting precipitation patterns, and heightened disease risks (Maulu et al., 2024; Jeyachandran, 2025), with impacts compounded by limited technical capacity, restricted access to finance, and weak policy integration. These challenges threaten both livelihoods and the sustainability of fish supply. These stressors are likely to intensify in the future, compounding existing supply constraints and increasing the vulnerability of the sector (Maulu et al., 2024). CSAq may help address these constraints by promoting resilient production systems through technological innovation, capacity building, improved access to finance, and stronger alignment with national climate policies (Mdoe et al., 2025). A recent global mapping study showed that CSAq research and adoption are growing but remain limited in climate-vulnerable developing regions, with integrated aquaculture agriculture identified alongside polyculture and aquaponics as key practices (Mdoe et al., 2025). Evidence from Tanzania shows that integrated aquaculture agriculture livestock systems enhance resilience to climate shocks and resource use efficiency, with adoption significantly influenced by education and financial support, and strengthened through integration into national adaptation frameworks (Mdoe et al., 2025). Lessons can further be drawn from the "Advancing Climate Smart Aquaculture Technologies (ACliSAT)" project which covered Egypt, Ethiopia and Eretria. Aiming to improve pond designs for efficient water utilization, and adopt improved fish feeding practices. Furthermore, the project advanced adaptation of improved culture practices of Nile Tilapia to stimulate growth in emerging and existing aquaculture sectors (Nasr-Allah, 2021). With this analogy, the project is a key example of CSAq adoption in water-limited, arid contexts, where technology choice is strongly shaped by resource scarcity.

More lessons can be drawn from other parts of the world beyond Africa. For example, Vietnam have advanced from conceptual CSAq to adoption and implementation in coastal production systems that are susceptible to recurrent climate shocks. The country utilizes various technologies that cover integrated aquaculture systems, climate-resilient pond management, and species and production adjustments to climatic stress. However, up scaling CSAq in the Vietnam is owed to strengthening access to CSAq information and improving technical understanding of CSAq practices (Le Quyen et al., 2019). Bangladesh is another evident CSAq country case with technologies implemented on artisanal salt farms covering Artemia pond culture, improved marine aquaculture (IMA) utilizing saline-tolerant species such as *Oreochromis niloticus* and *Penaeus monodon*, and shrimp nursery systems. It is shown that the interventions enhanced productivity, adaptation, and income while conserving carbon stocks and reducing green-house gas (GHG) emissions by utilizing existing salt beds without land use change (Hasan et al., 2026).

Botswana's broader agricultural sector continues to face structural constraints that threaten productivity and food security, particularly climate change impacts and water scarcity (Binge et al., 2023; Maulu et al., 2024; Mpinda et al., 2025). The country's arid to semi-arid conditions, characterized by highly variable rainfall, high evaporation, and limited surface water, increase vulnerability to climate variability (World Bank Group, 2021). These conditions make CSAq especially relevant, as water availability and climate risk largely determine the feasibility and scalability of aquaculture systems, requiring context specific approaches that align production systems with hydrological, infrastructural, and institutional realities. Although Botswana has made progress in climate smart agriculture through practices such as crop rotation, precision farming, and improved irrigation (Mpinda et al., 2025; Jagadeesh et al., 2025), aquaculture remains underutilized despite its potential to enhance food security and support economic diversification. This study therefore, examines how CSAq can be operationalized in Botswana by developing a regionalized implementation framework that aligns production systems with spatial variation in water availability, climate risk, infrastructure, and institutional capacity. It further identifies key adoption barriers and proposes targeted mitigation measures to support sustainable and climate resilient sector growth, providing a basis for prioritizing investments and avoiding maladaptive interventions. This paper's framework is designed to:

1 Differentiate aquaculture pathways in Botswana by hydrologic and climatic-risk context (i.e., where evaporative losses, drought frequency, and supply reliability impose distinct feasibility boundaries)
2 Connect system choice to measurable performance metrics (e.g., water productivity, nutrient availability), thereby avoiding purely aspirational "smart" labeling, and
3 Embed institutional and value-chain feasibility (skills, extension, input markets, financing) as co-equal determinants of CSAq suitability, consistent with adoption evidence from the region.

2 Materials and methods

This study was conducted based on an extensive review of literature on Botswana's climate, hydrology, fisheries, and aquaculture from reputable databases including the Web of Science, Scopus, and Google scholar. The study focused on published and peer-reviewed journal articles from these databases. Additionally, data sets and relevant reports issued by non-governmental organizations (NGO's) and governmental authorities were also included for review. Due to relatively limited literature focusing on Botswana, the study employed a narrative review approach with key literature search strategy including words (singular or in combination but with Botswana) such as "blue foods, aquatic foods, fish production, aquaculture, fisheries, food security, nutrition security, hydrology, climatic regions, climate resilient, food systems in Botswana" to retrieve information aligned to the research objectives of the study. No limit was employed for the years of publication to expand the search capture data on the topic, but the study prioritized recent literature published in English language and with open access. The study confined to CSAq, relevance to Botswana's blue economy and methodological rigor to ensure research's relevance and focus.

Time series climate data (1991–2020) including average annual precipitation and temperature adapted from World Bank Group (2021), and mean monthly hydrology data was used to extrapolate climate information and hydrology information. The study's climatic classification was multidimensional. First, meteorological data was analyzed to help classify the regions. Rainfall distribution and temperature variability were the two main data areas analyzed (Lemenkova, 2022; World Bank Group, 2021). Second, physical factors (primarily areas with abundant surface water-bodies) guided definition of climatic regions. Areas with abundant surface water bodies gives localized microclimates with increased precipitation and humidity (Xu et al., 2022). Lastly, agricultural potential was used to aid comprehensive delineation of the climatic regions (Masocha et al., 2024; Matopote et al., 2025).

Fish species composition data, utilizing catch per unit effort (CPUE) of the North-west and Northern Botswana water bodies was gathered through published literature. The selection criteria was narrowed down and selected a paper with spatial variation. Consequently, the less-explored and unpublished catch composition fisheries data of the dams in Botswana was sourced from Ministry of Lands and Agriculture, Department of Fisheries and Apiculture. Dam fisheries survey data spanning 2004–2020 were used to complement and align with the climate information. Independent (experimental fishing) data was collected from 6 major dams (Dikgatlhong, Letsibogo, Thune, Lotsane, Lotsane and Ntimbale) using multi-filament gillnets with 12 different panels (12, 16, 22, 28, 35, 45, 57, 73, 93, 118, 150 and 170 mm) arranged randomly to sample during wet and dry seasons every year. Each dam was sampled in 3 consecutive nights per season. Fisher's dependent data was submitted to the Department of Fisheries and Apiculture as monthly returns. This data was then used to estimate fish production output of the dams.

To ensure a comprehensive and transparent assessment, the study engaged two teams of specialists in fisheries and aquaculture, incorporating local expertise and contextual knowledge. Following team's formation, separate assessments of the body of literature and evaluation of time series data were carried out to establish practicability of aquaculture in climatic regions of Botswana. One team focused on the application of traditional aquaculture applications for CSAq in Botswana. This team followed basic literature review protocols that evaluated sustainability, efficiency, low-intensity, and integrated practices. The second team examined the potential of CSAq technologies to practically revolutionize aquaculture in Botswana. This team

reviewed literature on aquaculture scalability, environmental sustainability, and aquaculture adoption potential in Botswana. The findings were synthesized between the two teams to ensure coherence.

Challenges to CSAq adoption, corresponding mitigation measures, and the policy and institutional frameworks required for successful implementation were identified through synthesis of evidence from peer reviewed literature. This integrative approach provided the basis for a critical evaluation of aquaculture viability in Botswana and enabled the formulation of policy relevant insights to guide strategies for enhancing sustainable fish production.

3 Results and discussion

3.1 Botswana's climatic conditions and classification of climatic regions

Botswana's distinctive landscape and ecosystems are shaped by high temperatures and limited, sporadic rainfall (World Bank Group, 2021) and thus dictate agricultural production. Figure 1 shows the historical data (1991–2020) of average annual rainfall and temperature of Botswana while Figure 2 shows the trends of the observed average annual precipitation and temperature across Botswana. The two period moving average trend line for Botswana's rainfall from 1991 to 2020 typically displays year-to-year instability, displaying alternating dry and slightly wet spells. However, temperature shows a generally upward trajectory. Despite being mostly dry, there are minor geographical variations within the country. According to World Bank Group (2021), the country's Inter Tropical Convergence Zone (ITCZ) provides moisture to the northern region of the country throughout the summer months of November through March.

Water in the Okavango Delta is mostly supplied by rains in Angola rather than local precipitation, but the northern portion, especially that around the Okavango Delta and Chobe, see somewhat greater average rainfall (Wolski and Murray-Hudson, 2006, 2008). The driest and hottest region of the country is the Kalahari Desert in the south and west (World Bank Group, 2021). The average annual rainfall varies from 620 mm in the northern Maun-Kasane area to 250 mm in the South-western Tsabong area. The eastern margin of the country is marked by pleasant, dry winters and warm to hot summers with rainfall. Majority of rainfall falling is received between November and March. Along this axis, rainfall ranges from around 650 mm in the North-east to less than 250 mm in the South-west (World Bank Group, 2021). While winters are dry and occasionally falling below freezing in some areas, summer temperatures can rise, surpassing 35 °C in some instances (Statistics Botswana, 2017). The Limpopo River system forms part of the eastern margin of Botswana (Jury, 2016). Due to high seasonal rainfall and a network of seasonal river channels that drain into the Limpopo River, a number of dams, both for livestock watering and domestic water supply has been constructed in this region (Du Plessis and Rowntree, 2003). World Bank Group (2021) confirms that, cumulatively, the country experiences warm to hot temperatures most of the time. Mean monthly maximum temperatures ranges from 29.5 °C to 35 °C in summer and 19.8–28.9 °C in winter. In summer, mean monthly low temperatures range from 14.6 °C to 20.8 °C, while in winter, they range from 2.9 °C to 11.6 °C. However, warm-water fish may exhibit various impairments in response to extreme temperature events (Islam et al., 2022), which may directly impact on aquaculture production (Maulu et al., 2024). The potential effects of extreme temperature conditions on the exposure and thermal stress of warm water fish species are illustrated in Figure 3.

Following this analogue, the country was divided into three main climatic regions including the Okavango-Chobe climatic region, the Eastern margin and the Arid Western and Southern climatic region. These classifications are based on agro-ecological characteristics. CSAq in Botswana is therefore critically analyzed following these regional perspectives.

3.2 Climate-smart aquaculture (CSAq) in Botswana: regional perspectives

CSAq technologies comprise an integrated suite of production systems and management innovations designed to enhance productivity, resilience, and environmental sustainability under increasing climate variability. In Botswana, these technologies span a continuum from traditional, ecosystem-based systems that harness seasonal

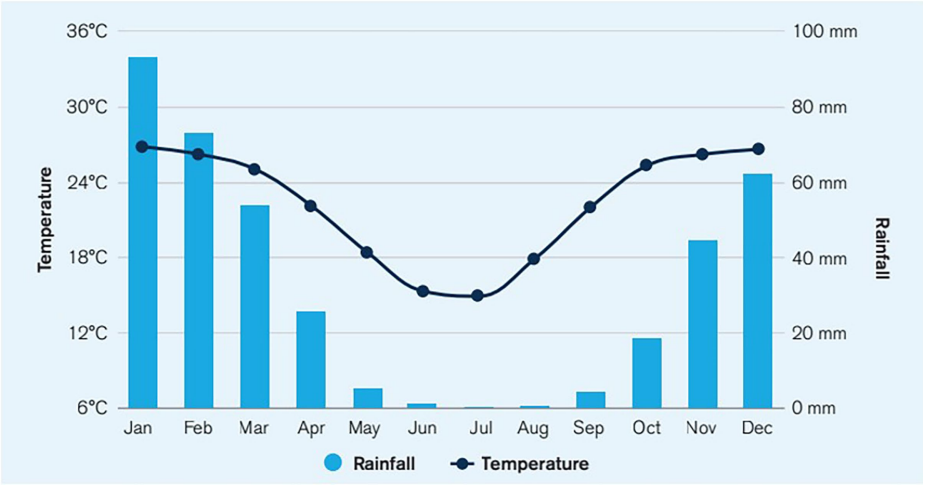


FIGURE 1
Historical average annual rainfall and temperature of Botswana: 1991–2020 data. Source: World Bank Group (2021).

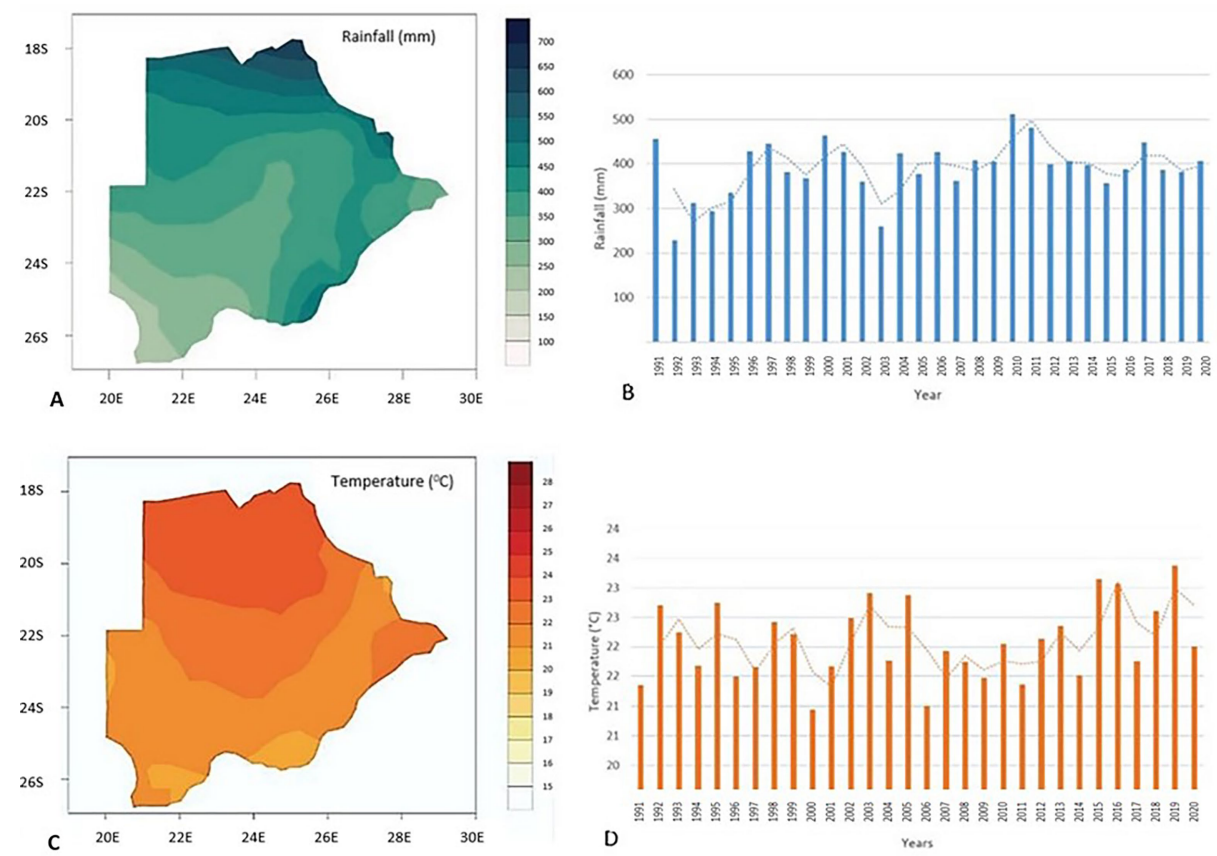


FIGURE 2
Historical spatial variation in precipitation **(A)** and temperature **(C)**, and trends in precipitation **(B)** and temperature **(D)** across Botswana: 1991–2020. Adapted from World Bank Group (2021).

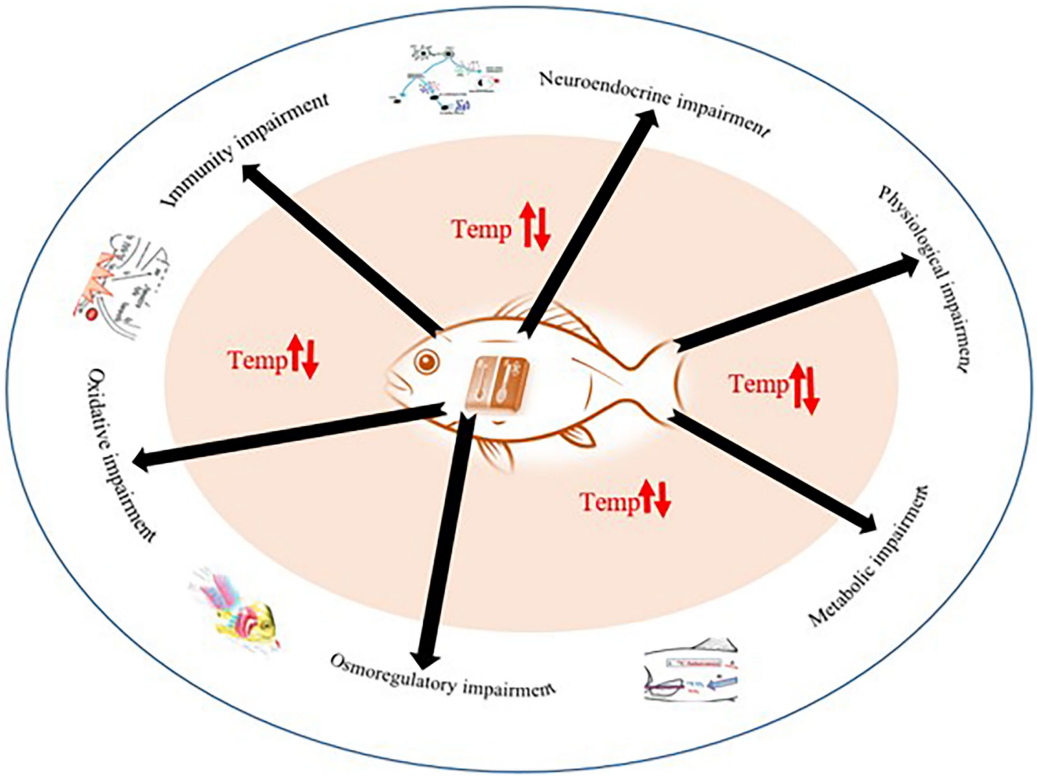


FIGURE 3
Possible impairments in freshwater fish that may result from extreme temperatures.

hydrological dynamics to modern intensive systems that optimize water, feed, and energy efficiency. Across the country's diverse agro-ecological zones, CSAq approaches such as integrated aquaculture agriculture, aquaponics, biofloc systems, recirculating aquaculture systems, and capture-based aquaculture offer context-specific solutions that align production with local environmental constraints and opportunities. Collectively, these technologies provide a strategic framework for transforming aquaculture into a more adaptive, resource-efficient, and climate-resilient sector that supports food security, livelihood diversification, and sustainable natural resource management. The successful implementation of CSAq systems is shaped by both agro-ecological conditions and the socio-economic context of communities. In Botswana, regional differences necessitate context-specific approaches, requiring careful evaluation of local environmental characteristics, resource availability, and livelihood systems to maximize the effectiveness and sustainability of CSAq interventions.

3.2.1 Okavango-Chobe region

The unique hydrological landscapes of the Okavango-Chobe region coupled with favorable environmental conditions, make the region ideal for sustainable aquaculture production. The Okavango Delta and the Chobe River systems receive annual or seasonal pulse of life-sustaining water that support ecological productivity (Wolski and Murray-Hudson, 2006). Average annual precipitation and temperature trends of this region is shown in Figure 4. Annual precipitation from 1991 to 2020 showed some variability, marked by alternating wet and dry periods. The two-period moving average trend show high inter-annual volatility rather than a smooth, consistent linear trend, whereas the average annual temperatures show a consistent warming trend. River systems naturally clean and oxygenate water through physical, chemical, and biological processes (Chin, 2012), reducing the need for costly water management infrastructure and, enabling more economical aquaculture production. Access to high quality, relatively clean water is fundamental to successful aquaculture enterprises (Yusoff et al., 2024). Establishing aquaculture facilities along the major rivers of the region is therefore a critical strategy for transforming and advancing aquaculture development.

In terms of biodiversity, the Okavango-Chobe region hosts a rich aquatic ecosystem with a variety of fish species (Bruton et al., 2018; Moliner Cachazo et al., 2023). This offers several advantages for aquaculture. First, because native species are already acclimated to the environment, farming them may increase survival rates and decrease susceptibility to diseases. Additionally, there is growing consumer preference for locally produced, sustainably sourced fish. Several commercially valuable indigenous species, including Threespot tilapia (*Oreochromis andersonii*) and Sharptooth catfish (*Clarias gariepinus*), thrive in the region's warm, subtropical climate, characterized by long, hot summers and moderate winters (Bruton et al., 2018; Mokatse et al., 2022; O'Brien et al., 2025). The extended growing season further enhances the economic viability of warm-water aquaculture by reducing the need for costly energy inputs to maintain optimal water temperatures (Velasco-Blanco et al., 2019).

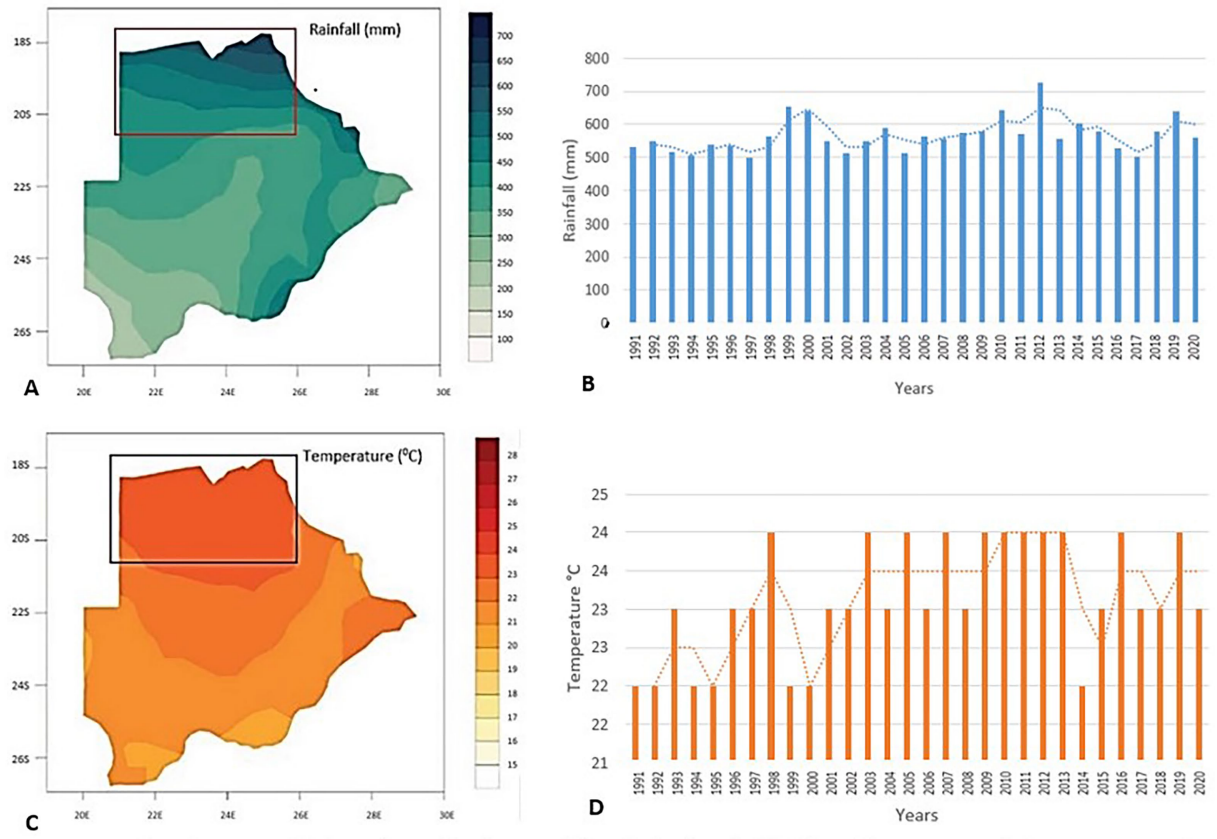


FIGURE 4
The Okavango-Chobe region reflecting spatial variation in rainfall **(A)** and temperature **(C)**, average annual rainfall, and trends in rainfall **(B)** and temperature **(D)**. 1991–2020 historical data: Adapted from World Bank Group (2021).

Known for its strong commitment to conservation and high-value, low-impact tourism, Botswana (Stone et al., 2017) provides an ideal foundation for developing conservation-focused aquaculture models in the Okavango-Chobe region. Aquaculture here can support national conservation goals by promoting sustainable practices, efficient water use, and minimal environmental impact, illustrating that ecological stewardship and economic development can coexist. In this context, an aquaculture park model (Canzi et al., 2017; Tamilarasu et al., 2024) is particularly well suited, functioning like an industrial estate for aquaculture by offering leased plots with infrastructure, utilities, and technical support to investors and farmers (White et al., 2013).

However, even if the environmental conditions are overwhelmingly favorable for aquaculture production in this region, meticulous planning and execution are necessary to fully realize this potential. Okavango Delta as an example, is a UNESCO World Heritage site (Keitumetse et al., 2023) and therefore it is necessary that thorough environmental impact assessments and adoption of extremely sustainable methods be prioritized to protect its fragile ecosystem from harm. Stringent regulatory measures must be enforced for sustainable aquaculture production in the region. In line with Schøning et al. (2023) who noted in the context of Norwegian aquaculture that few laws fully support sustainability and that ambitions are unlikely to be met under business-as-usual conditions, rigorous management protocols are required. Key concerns include water abstraction (Kolcheva and Ilcheva, 2016), environmental pollution (Sarfraz et al., 2016), and the risk of invasive non-native species (Britton et al., 2023), all of which must be addressed to secure the long-term viability of aquaculture in the region.

CSAq adoption in the Okavango-Chobe region can be unearthed using the traditional and intensive modernized aquaculture approaches. According to Nash (2010) and Edwards (2015), traditional aquaculture is guided by extensive and or semi-intensive fish production systems. These systems involve less sophistication and mostly rely on natural water sources like perennial rivers for filling water. Fish species used are often native varieties, stocked at lower densities and depend largely on the natural productivity of the culture unit (zooplankton, phytoplankton, insect larvae, etc.) for food. Environmental conditions always favor productivity. With this perspective, we therefore move that traditional aquaculture in the Okavango-Chobe region can be described with low-input, small-scale techniques that make use of already-existing resources and knowledge such as utilizing seasonal pans/lagoons/lakes for fish production. Emphasis placed on resilient, native species that are well-suited to the local environment and climatic conditions. In contrast, intensive modernized aquaculture is described with fish farmed greatly dependent on nutritionally complete feed with little or no contribution from natural food, usually agro-industrial formulated pelleted feed. This method utilizes systems like raceways, recirculation systems, and biofloc systems (Edwards, 2013). With this underpinning, we argue that both the traditional and intensive modernized aquaculture can be leveraged to sustainably drive aquaculture production in the Okavango-Chobe region. The discussion of this potential is elaborated below.

3.2.1.1 Traditional aquaculture approach in Okavango-Chobe region: stocking fish in seasonal pans/lagoons/lakes

The river systems, in the northern part of Botswana are characterized by ephemeral seasonal pans, lagoons, and flood-dependent lakes (Kurugundla et al., 2018; Mosepele et al., 2022) that can be a perfect setting for traditional aquaculture. These water bodies are not just mere temporary phenomena, but rather, they are dynamic ecosystems that offer convergence of natural advantages that make them incredibly productive for raising aquatic organisms (Mosepele et al., 2022). For example, Okavango Delta receives water around March to July every year, temporarily transforming the parched landscape into a bright wetland by this inflow of water (Figure 5). The lagoons of the delta are then formed when the floods recede from September to November, leaving behind isolated pockets (Mosepele et al., 2009; Wolski and Murray-Hudson, 2006).

Naturally, these changing ecosystems are essential to maintaining the fish populations in the Okavango (Mosepele et al., 2009, 2011). Mosepele et al. (2011) explored time series data collected between 2001 and 2005 and studied spatial variability in fish species assemblage and community structure in four subtropical lagoons (Matsaudi, Karao, Guma and Nxaraga) of the Okavango Delta. This study identified 63 fish species (Table 1) in these four (4) lagoons. The identified fish species represented about 65% of the known species of the Okavango Delta and this confirms that lagoons are

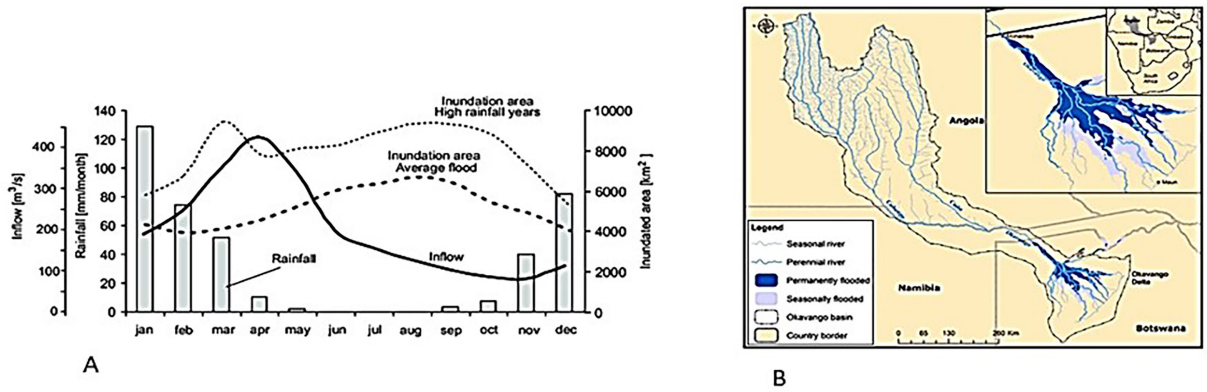


FIGURE 5
Flooding of the Okavango Delta. **(A)** Monthly means (1992–2000) of inflow, flood extent and rainfall pattern of the delta as adapted from (Wolski and Murray-Hudson, 2006). **(B)** Mosaic of changing river channels of the delta driven by the flood regime. Source: Mosepele et al. (2022).

important repositories of fish (Mosepele et al., 2022) which can further be harnessed through aquaculture to increase fish production.

Moreover, ecological dynamics that come with seasonal changing water bodies will contribute to high aquaculture productivity (Marmen et al., 2021). These dynamics are driven by various concepts and/ or principles including nutrient flush and concentration, explosive plankton blooms, and abundant natural food sources.

Nutrient flush and concentration: The Okavango and the Chobe Rivers are characterized by a diverse array of aquatic habitats, each exhibiting unique ecological features and distinct water chemistry. Swamps and lagoons range from oligotrophic to mesotrophic conditions due to fluctuations in nutrient availability, whereas floodplains, islands, and pools are predominantly mesotrophic to eutrophic. In contrast, permanent rivers and streams generally maintain an oligotrophic status, recognized by lower nutrient levels, enhanced water quality, reduced turbidity, and higher dissolved oxygen concentrations (Cronberg, 1995; Gondwe et al., 2021; Ramatlapeng et al., 2023). Key processes such as seasonal flooding, atmospheric deposition, river inflow, and wildlife activity drive these dynamics (Wolski, 2005; Mosepele et al., 2009). As floodwaters move through the system, decomposition of organic matter releases nutrients including nitrogen, phosphorus, potassium, and various trace minerals (Cronberg, 1995; Tsheboeng et al., 2014). This flow also leaches nutrients from the soil and involves the erosion of riverbanks and floodplains. Concurrently, fine sediments and organic matter are transported into isolated water bodies, further enhancing local nutrient availability (Mladenov et al., 2005). Fish populations thrive during this period, capitalizing on the increased habitat and food availability.

Explosive plankton blooms and abundant natural food sources: A combination of factors, such as abundant nutrients, sufficient sunlight, and favorable water conditions, often triggers plankton blooms (Kuo et al., 2025). They are particularly dominant following periods of high river flow or heavy rainfall, which introduce nutrient-rich runoff into the aquatic ecosystems (Lan et al., 2024). As highlighted by Smayda (1997), traditionally, a bloom is viewed as a significant population increase of plankton, during which the dominant species within the bloom and subordinate species in the community have equivalent ecological and physiological significance, and such blooms are intrinsically beneficial to food-web processes. However, Carstensen et al. (2007) emphasize that blooms are not solely defined by biomass levels but also by their ecological impacts and species composition. While plankton blooms can enhance aquatic food webs, uncontrolled growth may lead to adverse conditions, such as hypoxia, particularly when certain species are underutilized.

During periods of increased nutrient availability, often associated with seasonal flooding, the phytoplankton populations experience rapid growth. These processes give rise to a vigorous production of autotrophs (both phytoplankton, periphyton, and aquatic macrophytes) that support dense populations of zooplankton, notably *cladocerans* (Høberg et al., 2002). The blooms also support higher trophic levels, including fish (Mosepele et al., 2022). Aforementioned, the CSAq idea centers around stocking fingerlings of hardy, quickly growing, native fish species, like Sharptooth catfish (*Clarias gariepinus*) and bream species like Threespot tilapia (*Oreochromis andersonii*), when temporary water pools like pans and lagoons are full during the peak flood season. While culturally significant, these conventional stocking techniques are highly vulnerable to climate variability, limiting their scalability for commercial aquaculture.

3.2.1.2 Intensive aquaculture strategies: Okavango Chobe region

Intensive sustainable aquaculture strategies for the Okavango-Chobe region is centered on ponds designs which are in harmony with the region's environment, integrated wetland-aquaculture, recirculating aquaculture system (RAS), biofloc, aquaponics and integrated aquaculture-agriculture systems (IAAS) technologies. Sustainable adoption of these technologies in the Okavango-Chobe region is discussed hereunder.

Ponds: The pond system can be used to revolutionize aquaculture production in the Okavango-Chobe region. However, adopting this system must be a well-thought plan. The Okavango-Chobe region favors this system, but flood resilient pond design accounting for extreme variability in water availability is key in this region. In essence, pond system adopted need to be in harmony with the region's natural flood rhythm. We contend that, at the start of the flood season, which is usually April–May (World Bank Group, 2021), and water levels rising (Wolski and Murray-Hudson, 2006), optimal stocking should take place. Because of this timing, fish can take advantage of the better water quality and more food availability brought on by seasonal flooding (Mosepele et al., 2022). Harvesting should then be planned around February–March the following year, strategically leveraging the receding floodwaters to facilitate easier harvest. With this regard, adoption of pond system in the Okavango-Chobe region will have significant socio-economic implications. First of all, labor will be required for pond construction, operation, and maintenance, which will create employment opportunities for riparian communities. Additionally, the concept will provide a stable source of income for farmers, contributing to poverty alleviation (Mhina, 2015). The concept will provide a consistent supply of fish and improve access to fish in the community, combating malnutrition and food insecurity (Maulu et al., 2024). As an environmental benefit of this approach, confining production to controlled pond systems will reduce pressure on natural water bodies, thereby minimizing the risk of overfishing and habitat destruction (Yadav et al., 2024). Nevertheless, this system's success will be dictated by various environmental aspects and anthropogenic conditions, and thus the risks associated may challenge its commercial breakthrough.

Integrated Wetland-Aquaculture: Integrated Wetland-Aquaculture Systems can be utilized to revolutionize aquaculture in consistently flood-prone areas of Botswana. There are synergistic benefits when aquaculture and seasonal floodplain agriculture are combined (Serge, 2021). This system has been adopted in the environs of Lake Victoria, and it has positively impacted the livelihoods of riparian communities (Kipkemboi et al., 2007). The argument is that crops and vegetable production are supported by exposed floodplain soils that have been supplemented with nutrients from yearly flooding when floodwaters recede, effectively leveraging natural nutrient cycling. This approach can be replicated in the Okavango-Chobe region. As a sustainable multi-functional production model that combines aquaculture with wetland conservation, it fosters a confined, environmentally friendly approach that reduces waste and provides ecological, economic, and social benefits. Environmentally, this approach will provide a pollution purification effect as the concept efficiently treat wastewater, reducing ammonia, nitrate, and phosphorus concentrations (Melaku et al., 2024). Besides, the concept may reduce greenhouse gas emissions (Su et al., 2025), as well as promoting ecosystem protection (Bhattacharya et al., 2024) to the fragile Okavango and Chobe river

TABLE 1 Fish species sampled between 2001 and 2005 with different gears from 4 lagoons (Matsaudi, Karao, Guma and Nxaraga) of the Okavango Delta.

Fish species	Gear						
	Mosquito net	Basket	Subsistence hook	Subsistence net	Commercial net	Commercial hook	Recreational hook
Caridina spp	*	–	–	–	–	–	–
Enteromius haasianus	–	*	–	–	–	–	–
Aplocheilichthys hutereaui	–	*	–	–	–	–	–
Enteromius brevidorsalis	*	*	–	–	–	–	–
Enteromius multilineatus	–	*	–	–	–	–	–
Aplocheilichthys johnstoni	*	*	–	–	–	–	–
Hemigrammocharax machadoi	*	*	–	–	–	–	–
Aplocheilichthys katangae	–	*	–	–	–	–	–
Mesobola brevianalis	–	*	–	–	–	–	–
Hemigrammocharax multifasciatus	–	*	–	–	–	–	–
Enteromius fasciolatus	*	*	–	–	–	–	–
Nannocharax macropterus	*	*	–	–	–	–	–
Synodontis macrostigma	*	*	–	–	–	–	–
Enteromius barnardi	*	–	–	–	–	–	–
Microctenopoma intermedium	–	*	–	–	–	–	–
Synodontis macrostoma	*	*	–	–	–	–	–
Enteromius thamalakanensis	*	*	*	–	–	–	–
Clarias stappersi	–	*	–	–	–	–	–
Enteromius unitaeniatus	*	–	–	–	–	–	–
Brycinus lateralis	–	*	*	–	–	–	*
Enteromius paludinosus	–	*	–	–	–	–	–
Enteromius radiatus	*	*	–	–	–	–	–
Ctenopoma multispine	–	*	–	–	–	–	–
Hippopotamyrus ansorgii	*	*	–	–	–	–	–

(Continued)

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TABLE 1 (Continued)

Fish species	Gear						
	Mosquito net	Basket	Subsistence hook	Subsistence net	Commercial net	Commercial hook	Recreational hook
Enteromius poechii	–	*	*	–	–	–	–
Pharyngochromis acuticeps	–	*	–	–	–	–	–
Pseudocrenilabrus philander	*	*	*	–	–	–	–
Synodontis woosnami	–	–	–	–	–	–	–
Petrocephalus catastoma	–	*	–	*	*	–	–
Enteromius afrovernayi	*	*	–	*	–	–	–
Synodontis vanderwaali	–	–	–	*	*	–	–
Pollimyrus castelnaui	–	–	–	*	–	–	–
Synodontis thamalakanensis	–	–	–	*	*	–	–
Oreochromis placidus	–	–	–	–	*	–	–
Synodontis leopardinus	–	–	–	*	–	–	–
Serranchromis longimanus	*	–	–	–	–	–	*
Clarias theodorae	–	–	–	*	–	–	–
Marcusenius altisambesi	–	*	–	*	–	–	–
Sargochromis greenwoodii	*	–	*	*	*	–	*
Serranochromis thumbergi	*	*	*	*	*	–	–
Serranochromis macrocephalus	–	*	*	*	*	–	*
Tilapia sparrmanii	*	*	*	*	*	–	–
Tilapia ruweti	–	*	*	*	*	–	*
Sargochromis codringtonii	–	*	*	*	*	–	*
Sargochromis carlottae	–	–	*	*	*	–	–
Hemichromis elongatus	–	–	–	–	*	–	*
Synodontis nigromaculatus	–	*	–	*	*	–	–
Labeo lunatus	–	–	–	*	*	–	–

(Continued)

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TABLE 1 (Continued)

Fish species	Gear						
	Mosquito net	Basket	Subsistence hook	Subsistence net	Commercial net	Commercial hook	Recreational hook
Schilbe intermedius	*	*	*	*	*	–	–
Cyphomyrus discorhynchus	–	–	–	*	*	–	–
Oreochromis macrochir	–	*	*	*	*	*	–
Coptodon rendalli	–	*	*	*	*	*	*
Momyrus lacerda	–	*	–	*	*	–	–
Leptoglanis conspicuus	–	–	–	–	–	–	–
Serranochromis altus	–	*	*	*	–	–	*
Hepsetus cuvieri	*	*	*	*	*	–	*
Serranochromis robustus	–	*	*	*	*	*	*
Serranochromis angusticeps	–	*	*	*	*	*	*
Oreochromis andersonii	*	*	*	*	*	*	*
Sargochromis giardi	–	*	*	*	*	*	–
Hydrocynus vittatus	–	*	*	*	*	*	*
Clarias ngamensis	–	*	*	*	*	–	*
Clarias gariepinus	–	–	*	*	*	–	*

The "*" represent present whereas "–" represent absent. Adapted from Mosepele et al. (2022).

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systems. On the other hand, various socio-economic benefits will result from the adoption of this concept. Income will be diversified through integrated fish, crop, and livestock production, improving food security at low cost while enhancing access to high protein foods (Bhattacharya et al., 2024). However, like pond system adoption in Okavango-Chobe region, this system's success will depend on various environmental aspects and anthropogenic conditions, and thus the risks associated may challenge its commercial breakthrough.

Recirculating Aquaculture System (RAS): The merits associated with RAS are indispensable. As explained by Timmons et al. (2006), RAS, especially the indoor-based is environmentally friendly, sustainable, and infinitely extensible. It can also ensure the safety and quality of the fish produced all year round. This system allows for controlled product growth rates and predictable harvesting schedules because the fish are raised in a controlled environment. By reusing water after biological filtering with biofilters, RAS conserves water. RAS technology is transforming global aquaculture by facilitating land-based, high-density fish production through continuous water filtration and reuse. This high level of system control has the potential to substantially enhance commercial fish production in the Okavango-Chobe region. To protect the products from temperature changes, keep out predators and contaminants, and enable year-round production regardless of the weather, the system needs to be housed under temperature-controlled greenhouse tunnels or shade net structures. Small pumps and aerators that run on solar panels (e.g., 100–300 W) and solar batteries (24 V) for night-time operation are affordable components that can help the systems reach total off-grid independence (Kulshrestha et al., 2025). This will further imply, improved food security, employment, income generation and reduced reliance on imported fish (Maulu et al., 2024). Nevertheless, the adoption of RAS technology may be associated with relatively higher initial capital and operational costs compared to traditional pond-based systems.

Biofloc technology: Aquaculture revolution in Botswana is owed to the adoption of environmentally friendly systems, of which Biofloc-based systems fall within. Biofloc systems (Tidwell, 2012) placed within shade net enclosures can reduce temperature changes by 5–10 °C, avoid dust contamination, let in natural light, and cut evaporation by 70–80% (Alvarez et al., 2006). Biofloc technology operates with minimal water exchange by promoting the *in situ* recycling of nutrients through microbial flocs, thereby improving water-use efficiency and reducing effluent discharge (Rai et al., 2025). As a near-zero-discharge production system, biofloc systems substantially lower the risk of nutrient loading and environmental pollution, making them particularly suitable for ecologically sensitive landscapes. Consequently, this technology aligns strongly with the conservation priorities of the Okavango-Chobe region, where sustainable resource use, biodiversity protection, and reduced anthropogenic pressure on aquatic ecosystems are of critical importance. Just like RAS, adopting Biofloc technology in the Okavango-Chobe region could significantly increase the region's fish production, transforming it into a more sustainable and profitable venture (McCusker et al., 2023). Furthermore, its adoption will further address the issue of local fish feed (Maulu et al., 2024) as it can convert waste into microbial protein, which can function as a high-protein feed in this respect (McCusker et al., 2023). This may significantly reduce the costs of imported commercial fish feeds (Maulu et al., 2024).

Aquaponics: According to Tidwell (2012), aquaponics is an integrated system that blends fish culture with soilless crops production. It is an upgraded version of RAS. This system is associated with numerous advantages, but because of the symbiotic relationship between the two systems it provides, fish excrement provides all the nutrients required for plant growth, minimizing water pollution and the need for fertilizer. Furthermore, water is filtered by plants for fish to use again (Chen, 2022). Its characteristics make it applicable in Okavango-Chobe region. Just like in other parts of the world, aquaponics adoption may be capital-intensive initially but offers long-term cost savings by reducing the need for chemical fertilizers, minimizing water usage, and potentially requiring less labor per unit of production (Okomoda et al., 2023). The costs associated may further be reduced by adopting small pumps and aerators that run on solar panels (e.g., 100–300 W) and solar batteries (24 V) for night-time operation, helping the systems reach total off-grid independence (Kulshrestha et al., 2025). The products of this technology (aquaponically-produced vegetables and fish) offers a good market potential as the world shifts toward sustainably-grown food (Thanki et al., 2022). Moreover, this technology offers diverse job opportunities for local communities, enabling food production in areas which are traditionally considered unproductive, as well as providing training opportunities for locals as it is technology inclined (Okomoda et al., 2023). With this, food nutrition security will be fulfilled in Botswana as there will be increased access to nutritious food all year round.

Integrated Aquaculture-Agriculture Systems (IAAS): The sustainability of aquaculture depends on the synergistic effects and optimal resource utilization that come from integrating with existing farming activities (Bhattacharyya et al., 2020). The Pond-Garden Systems with Fish-Crop Integration, for instance, can be used to conserve water for vegetable irrigation during dry seasons in fish ponds (Ibrahim et al., 2023). The use of inorganic fertilizer is reduced when crops are organically fertilized by pond water that is rich in nutrients. The combination of cattle and aquaculture results in closed nutrient cycles (Ibrahim et al., 2023). Pond production can be raised by using organic fertilizers made from livestock manure, such as chicken, goat, and cattle dung. Manure treatment reduces the demand for extra feed by supporting natural food webs. This integrated approach offers a resilient and sustainable aquaculture framework that reduces reliance on external inputs and lowers production costs (Hasimuna et al., 2025). The Okavango-Chobe region is a region with more traditional agriculture activities in Botswana (Matopote et al., 2025). It is against this conception that IAAS can be a CSAq system of choice in this region. Like Integrated Wetland-Aquaculture Systems concept, adoption of this technology will play a significant role in mitigating climate change by reducing greenhouse gas emissions associated with synthetic fertilizer production and conventional farming practices. Additionally, the technology will enhance carbon sequestration in soils and aquatic ecosystems (El Deen and Khairy, 2025). IAAS is one technology evident with women taking leading roles in enterprises (Haque and Mahmud, 2025). Socially, this increases women economic independence, and thus boosts household nutrition, and gives women more control over productive resources.

Farming indigenous fish species is encouraged to shield local biodiversity from the possible detrimental effects of introduced species escaping from farms, such as hybridization and competitive exclusion (Ross et al., 2008). Nonetheless, fish species used in semi-arid aquaculture must exhibit tolerance to fluctuating water quality, the capacity to withstand brief oxygen stress, effective feed conversion, fast growth rates, and market acceptance (Khanjani et al., 2023). With this perspective, all fish species which are endemic to the Okavango-Chobe region are recommended for farming. For example, the African

sharptooth catfish (*Clarias gariepinus*) is native to Okavango-Chobe region (Skelton, 2024) and hence recommended. It can withstand harsh conditions (Kouřil et al., 2024; Langi et al., 2024) making it ideal. This species has a fast growth rate, attaining market size in a short period of time, has high rate of reproduction as they are always more fecund in comparison to other aquaculture species, and its feeding preferences can easily be manipulated, making it an excellent choice for culture (Kouřil et al., 2024). Threespot tilapia (*Oreochromis andersonii*) and Redbreast tilapia (*Coptodon rendalli*) are endemic to the Okavango-Chobe region (Skelton, 2024) and as such, they are recommended for farming in this region as well.

3.2.2 Eastern margin

The Eastern margin of Botswana presents a unique opportunity for aquaculture development, benefiting from relatively favorable rainfall. This region receive higher summer rainfall, largely driven by tropical depressions and low-pressure systems (Moses, 2019). Nevertheless, annual rainfall from 1991 to 2020 has been highly erratic, oscillating between wet and dry periods, with a general, albeit inconsistent, downward trend (Figure 6). However, heavy daily rainfall of the eastern Botswana in some occasions intensifies storm-water runoff, contaminates drinking water, and places a heavy strain on dams and wastewater systems (Moses, 2016). Despite the latter challenges, rainfall condition of the eastern margin in general make the region well-suited for most aquaculture production systems.

A major obstacle to adoption of basic, open aquaculture production systems in the eastern margin of Botswana is less favoring temperature conditions recorded, especially lower temperatures during winter World Bank Group (2021). Consequently, aquaculture in Botswana is underpinned against principles of warm water production. Figure 7 reflects on the trend in average annual temperature from 1991 to 2020 temperature time series data.

Through the water infrastructure initiative, Botswana has produced close to permanent aquatic habitats in the form of dams or reservoirs that offer indispensable benefits like domestic and industrial water supply, agriculture water supply, and recreation amusement (Perkins and Parida, 2022) in the eastern margin of Botswana. These dams range from small community dams mandated for livestock watering to major municipal dams (Gaborone, Nnywane, Bokaa, Shashe, Letsibogo, Ntimbale, Dikgatlhong, Lotsane, and Thune) constructed mostly for domestic water supply. Cumulatively, these municipal dams can capture up to 903.8 million of water. The water-holding capacities of the major dams are summarized in Table 2, whereas their morphological configurations are illustrated in Figure 8. Their structure and morphology allow adding of nutrients to the water column as large areas of land around them are flooded during rainy seasons. This creates intricate food webs that can sustain enormous fish populations.

The adaptability of fish communities in dams can be demonstrated by their population structure. However, just like in other seasonal water bodies, fish species assemblage in these dams can undergo seasonal changes driven by the flood regime. Nevertheless, water bodies with fluctuating conditions favor fish species that can withstand changing water quality parameters (Mosepele et al., 2022). Numerous fish species, from larger, more resilient fish like catfishes to smaller ones like *Enteromius* species, inhabit dams in Botswana. A checklist of fish species recorded during routine fish sampling surveys conducted between 2004 and 2020 in six major dams (Letsibogo, Dikgatlhong, Thune, Lotsane, Shashe, and Ntimbale) is presented in Table 3. With this fish species diversity, we argue the need for more utilization of the fish resource across the dams.

3.2.2.1 Traditional aquaculture approach in the eastern margin: capture-based aquaculture

As a traditional aquaculture technique, capture-based aquaculture may bring a significant change in Botswana's dams, turning them from passive storage spaces into dynamic, multipurpose ecosystems and essential sources of food security. Capture-based aquaculture in dams can be a more comprehensive, integrated method to aquaculture than normal known basic aquaculture, which involves raising fish in specially constructed ponds or tanks (Chandararathna et al., 2021). This method of fish utilization is built on scientific concepts of increasing yields while utilizing the ecosystem's natural production. This concept emphasizes understanding natural recruitment, improving underwater habitats, selective harvesting, species management, and community involvement in contrast to basic aquaculture, which includes

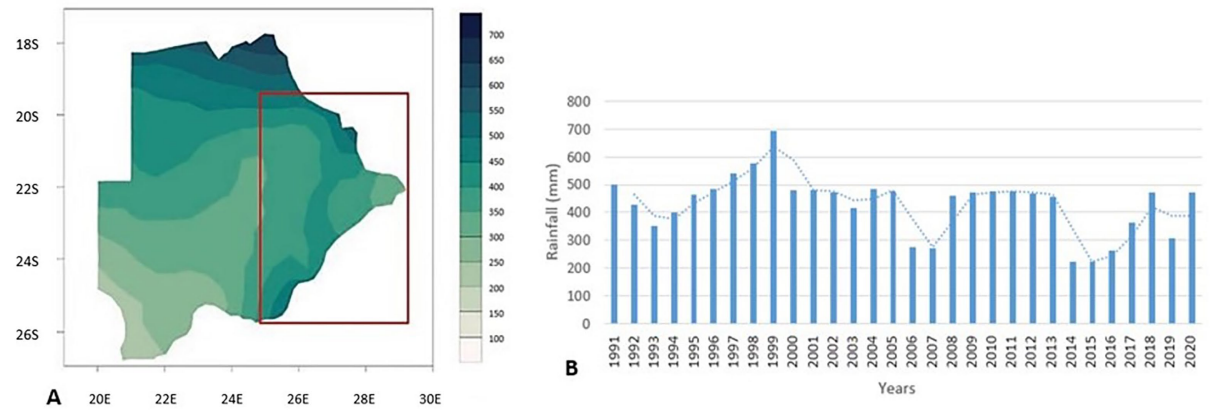


FIGURE 6
The spatial rainfall **(A)** and the trend in average annual rainfall **(B)** of the eastern margin of Botswana: 1991–2020 time series data. Adapted from World Bank Group (2021).

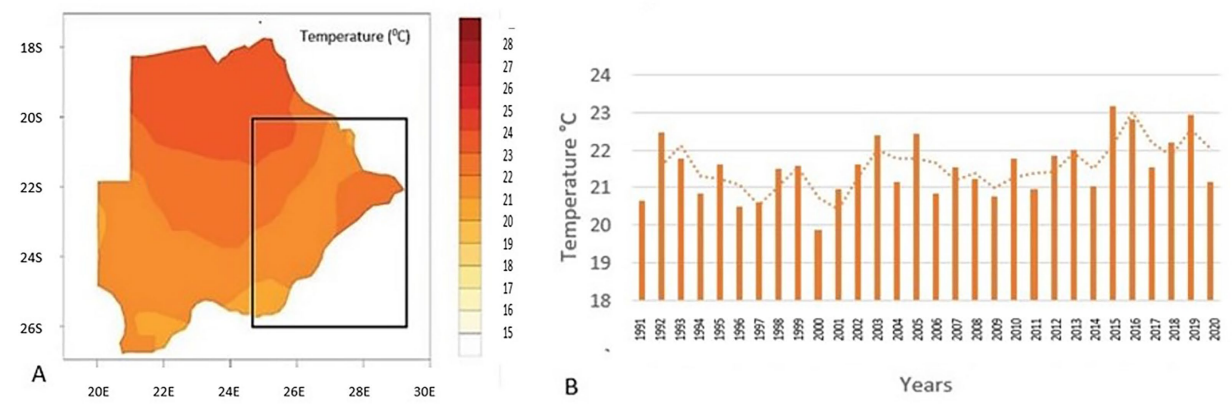


FIGURE 7
The eastern margin of Botswana (Marked with a black box), reflecting spatial **(A)** and trend **(B)** in average annual temperature of the region from 1991 to 2020 temperature time series data. Adapted from World Bank Group (2021).

TABLE 2 Major dams and their capacities.

Dam	Capacity (mm^3)
Gaborone	141.4
Bokaa	18.5
Letsibogo	100.0
Nnywane	2.3
Shashe	85.0
Ntimbale	26.6
Lotsane	40.0
Thune	90.0
Dikgatlhong	400.0
Total	903.8

Source: Statistics Botswana (2017).

stocking and intensive feeding of fish in culture units (Chandararathna et al., 2021).

The potential for capture-based aquaculture in Botswana's dams is substantial; however, only a small fraction of these resources is currently utilized. Analysis of time-series fish production data (2017–2020) collected by Ministry of Lands and Agriculture, Department of Fisheries and Apiculture through monthly fisher dependent record forms, gives an average of 0.03 tons yr^{-1} across 3 dams (Letsibogo, Dikgatlhong and Thune). Table 4 shows fish production (number and weight) in the 3 dams (Letsibogo, Dikgatlhong and Thune) from 2017 to 2020. Dikgatlhong recorded the highest output (86.703 kg), followed by Letsibogo (19.246 kg), and Thune, which had the lowest production (1.102 kg). The results presents non-normal data and as a non-parametric method, Kruskal-Wallis test was used to compare fish production (weights) amongst the dams. Confidence limits were set at 0.05. Even though production in terms of weight differed among the dams, there was no statistically significant difference between the dams fish production ($p = 0.183$). Fishing effort influenced fish production in the dams. Letsibogo dam was harvested by three fishers, Dikgatlhong by eight, and Thune by seven. Frequency of net setting also varied considerably: Thune recorded only 8 net settings, Letsibogo 80, and Dikgatlhong the highest with 230 net settings over the study period. Notably, fishing gear was consistent across the dams, with all fishers using commercial monofilament nets of 50 m total length and panel sizes of 50 mm, 75 mm, 100 mm, and 125 mm, set overnight for approximately 12 ± 1 h. Fisheries and aquaculture personnel confirmed that Thune dam experiences lower fish exploitation, citing recurring aquatic weed infestations and outbreaks of fish diseases as major constraints to harvesting. These observations highlight the importance of accounting for both fishing effort and environmental challenges when interpreting capture-based aquaculture production data.

Nonetheless, in estimating fish production potential of 20 dams in Botswana, Mosepele and Kolawole (2017) argued that these dams can yield up to 51 tons yr^{-1}. This gap can be addressed through various avenues including devising policies that deliberately support capture-based fisheries in all major dams across Botswana. Besides, stocking new species in large deep dams can enhance fish productivity. We concur with Mosepele and Kolawole (2017) that small pelagic species, such as Kapenta (*Limnothrissa miodon*), could be introduced in selected dams to supplement the existing fish populations. Harnessing such strategies represents a promising approach to sustainably increase fish production in Botswana's dams.

3.2.2.2 Intensive aquaculture strategies: eastern margin

Intensive sustainable aquaculture strategies for the eastern margin must be centered on water cleansing systems, including recirculating aquaculture system (RAS), and aquaponics technologies. Furthermore, integrated aquaculture-agriculture systems (IAAS) may revolutionize aquaculture in the eastern margin. These sustainable revolutionary technologies are discussed hereunder in alignment to the eastern margin of Botswana.

Recirculating Aquaculture System (RAS): Water is a scarce and precious resource in Botswana's eastern margin due to low and irregular rainfall. In this situation, conventional aquaculture techniques, which mostly depend on enormous amounts of water, would not be sustainable. RAS provides a workable alternative for sustainable aquaculture in this area. It is environmentally friendly, sustainable, and infinitely extensible (Timmons et al., 2006). As an innovative aquaculture technology that operate in a closed-loop system, it treats water within the system, significantly reducing the need for fresh water. With its various components including mechanical and biological filters, pumps, and aeration systems, it maintains optimal water quality by removing

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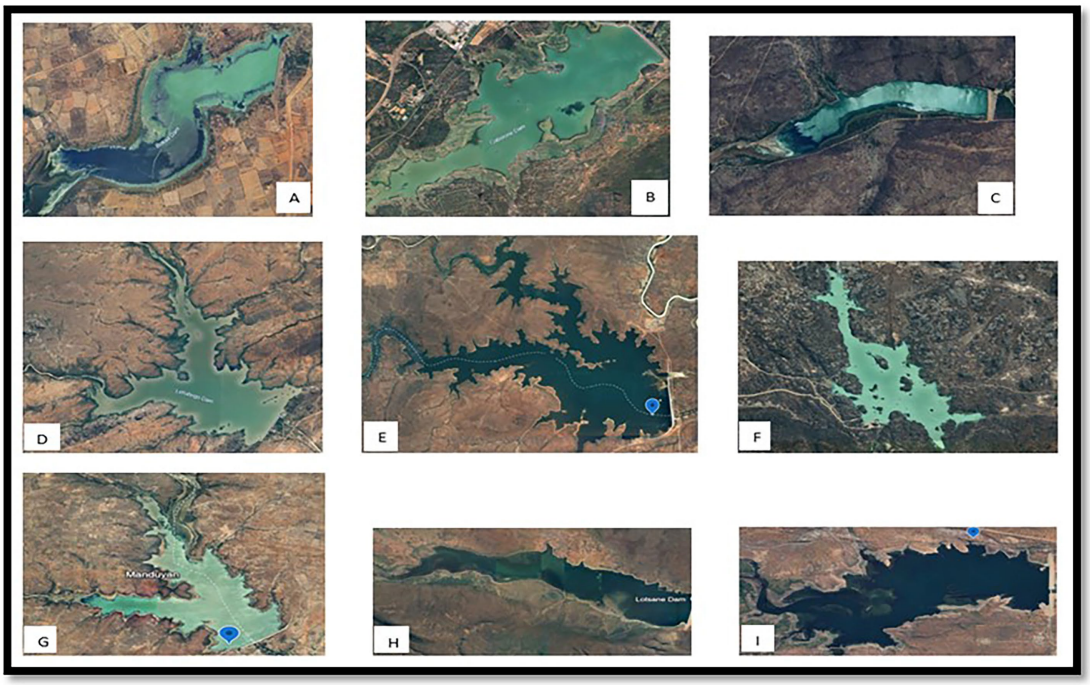


FIGURE 8
Google earth imagery reflecting morphology of the various major dams in Botswana. Source: Google Earth (2025). **(A)** Bokaa dam, **(B)** Gaborone dam, **(C)** Nnywane dam, **(D)** Letsibogo dam, **(E)** Dikgatlhong dam, **(F)** Ntimbale, **(G)** Shashe dam, **(H)** Lotsane dam, and **(I)** Thune dam.

TABLE 3 Checklist of fish species sampled from 6 major dams (Letsibogo, Dikgatlhong, Thune, Lotsane, Shashe and Ntimbale) from 2004 to 2020.

Species	Letsibogo	Dikgatlhong	Thune	Lotsane	Shashe	Ntimbale
Enteromius trimaculatus	✓	✓	✓	✓	✓	✓
Clarias gariepinus	✓	✓	✓	✓	✓	✓
Schilbe intermedius	✓	✓	–	✓	✓	–
Labeo ruddi	✓	–	–	✓	–	–
Enteromius paludinosus	✓	✓	✓	✓	✓	✓
Oreochromis sp.	✓	✓	✓	✓	✓	✓
Oreochromis mossambicus	✓	–	✓	✓	–	✓
Enteromius sp.	✓	–	–	–	✓	✓
Labeo molybdinus	✓	–	–	✓	–	–
Micropterus salmoides	✓	–	–	–	–	–
Labeo sp.	✓	✓	–	✓	–	–
Marcusenius macrolepidotus	–	–	–	✓	–	–
Enteromius unitaeniatus	–	–	–	✓	–	–
Labeo cylindricus	✓	✓	–	–	–	–
Petrocephalus sp.	–	–	–	✓	–	–
Enteromius mattozi	–	–	–	✓	–	–
Sargochromis sp.	–	–	–	–	–	✓

Multi-filament gillnets with 12 different panels (12, 16, 22, 28, 35, 45, 57, 73, 93, 118, 150 and 170 mm) arranged randomly were used to sample during wet and dry seasons across the years. ✓ = Present; – = Absent.

waste products and regulating parameters like oxygen levels, temperature, and pH (Timmons et al., 2006). RAS technology is transforming global aquaculture by facilitating land-based, high-density fish production through this continuous water filtration and reuse factor. As such, it has the potential to substantially enhance commercial fish production in the eastern margin of Botswana. Just like with its adoption in the Okavango-Chobe region, under controlled conditions, it is capable of protecting the products from temperature changes, keep out predators and contaminants, and enable year-round production regardless of the weather. Furthermore, the eastern margin has

TABLE 4 Fish production (Fisher dependent production) from three major dams.

Species	Letsibogo		Dikgatlhong		Thune	
	Number	Weight (kg)	Number	Weight (kg)	Number	Weight (kg)
Bream	23,549	14.34	114,638	85.287	4,701	0.94
Carp	11,734	3.894	0	0	0	0
Catfish	512	0.748	732	1.216	285	0.161
Labeo	375	0.081	46	0.006	0	0
Silver Barbel	0	0	1,052	0.193	0	0
Others	564	0.182	11	0.002	0	0
Total	36,736	19.246	116,479	86.703	4,986	1.102

Reflection of 2017–2020 time-series data.

abundant solar radiation, thus solar panels (e.g., 100–300 W) and solar batteries (24 V) can be adopted to run small pumps and aerators to help the systems reach total off-grid independence (Kulshrestha et al., 2025). This will improve food security, employment, and income generation (Maulu et al., 2024) in the region.

Rainwater harvesting can help collect enough water to operate RAS in the eastern margin. Several strategies can aid water collection including rain water directed toward storage tanks or ponds from roof tops, or pond designed to collect runoff straight from the nearby watershed. The eastern margin is characterized with an array of dams holding water for livestock watering and domestic supply. Most of these dams have proven to hold water until the next raining season. This is a positive move indicating the possibility of rain water harvesting in the region. However, rain water harvesting may present several challenges that RAS adoption. First, it can be challenged by unpredictability of rainfall in the eastern margin, high initial cost, regular maintenance cost, limiting policy issues, limited rainwater harvesting technical expertise, water quality and contamination, and microbial risks (Lepcha et al., 2024; Umukiza et al., 2023). As such, harvested rainwater can have negative impact on fish. For example, there can be toxic accumulation if rainwater is collected from contaminated areas with pollutants like heavy metals. Likewise, fish can be stressed by poor water quality that may come along rainwater harvesting making fish more susceptible to infectious diseases (Oguntimehin et al., 2026). Another alternative is underground water abstraction but similarly it manifests pollution challenges as well (Tafila et al., 2022). As a closed system, intensive feeding is essential for economic sustainability of RAS. Consequently, feed costs account for 60–80% of the production costs (Tanuja et al., 2025b), proliferated by lack of locally produced fish feed. As such, more challenges manifest. Generally, adoption of RAS technology in this case will be challenged by higher initial capital and operational costs compared to traditional systems, the need for skilled personnel, and the need for regular maintenance of system components and strict biosecurity measures (Gupta et al., 2024). These challenges can be addressed through more government support, public-private partnerships and capacity building (Botswana Government, 2021a).

Aquaponics: aquaponics has strong potential for improving food security in eastern margin of Botswana because generally, it is a system associated with reduced water use, recycles fish waste into plant nutrients, can be deployed in urban or peri-urban settings, and aligns with climate adaptation goals in water-stressed regions (Tidwell, 2012; Chen, 2022). The eastern margin of Botswana is characterized by low and variable rainfall, high evapotranspiration (World Bank Group, 2021), recurrent drought stress, and pressure on water resources and agricultural productivity (Matopote et al., 2025). Therefore, aquaponics is a perfect alternative to revolutionize aquaculture in the eastern margin of Botswana because it uses substantially less water than conventional soil-based agriculture, and minimizes nutrient discharge relative to traditional aquaculture (Chen, 2022). As indicated in above sub-section, aquaponics adoption may be capital-intensive initially but offers long-term cost savings by reducing the need for chemical fertilizers, minimizing water usage, and potentially requiring less labor per unit of production (Okomoda et al., 2023). Use of small pumps and aerators that run on solar panels (e.g., 100–300 W) and solar batteries (24 V) for night-time operation (Kulshrestha et al., 2025) may further reduce the associated costs. Its products offer a good market potential as the world shifts toward sustainably-grown food (Thanki et al., 2022). Nevertheless, adopting this technology will provide job opportunities for local communities, and help by providing training opportunities for locals as technical know-how is basic requirement for its operation (Okomoda et al., 2023). As such, access to reliable water sources, for example boreholes and rainwater water harvesting strategies can be perfect enablers to aquaponics adoption in the eastern margin. However, these strategies present several challenges such as high salinity, and microbial contamination (Lepcha et al., 2024; Tafila et al., 2022; Umukiza et al., 2023). Just like RAS, aquaponics is a closed system, and intensive feeding is essential for economic sustainability of RAS and thus more challenges manifest. Successful adoption of aquaponics in the eastern margin will depend on reliable water supply, temperature management, feed availability, technical know-how, and capital investment. More government support, public-private partnerships and capacity building (Botswana Government, 2021a) are therefore key enablers in this case.

Integrated Aquaculture-Agriculture Systems (IAAS): Integrated systems are prised for their multiple sustainability gains such as water-use efficiency, nutrient recycling and circularity, livelihood diversification, climate resilience, and food and nutrition security (Bhattacharyya et al., 2020; Ibrahim et al., 2023). The Eastern margin is a region with more traditional agriculture activities in Botswana (Matopote et al., 2025) and together with the latter, IAAS can be a CSAq system of choice in this region. For example, the Pond-Garden Systems with Fish-Crop Integration, can be used to conserve water for vegetable irrigation during dry seasons in fish ponds (Ibrahim et al., 2023). With this concept, use of inorganic fertilizer is reduced when crops are organically fertilized by pond water that is rich in nutrients. Fish production can be combined with livestock farming and utilize organic fertilizers made from livestock manure for activating primary feed in

the fish pond. This integrated approach offers a resilient and sustainable aquaculture framework that reduces reliance on external inputs and lowers production costs (Hasimuna et al., 2025). Adoption of this technology will play a significant role in mitigating climate change by reducing greenhouse gas emissions associated with synthetic fertilizer production and conventional farming practices, as well as enhancing carbon sequestration in soils and aquatic ecosystems (El Deen and Khairy, 2025). As indicated in the above sub-section, IAAS associates well with gender balance prioritizing women in leadership roles in enterprises (Haque and Mahmud, 2025). This will give women economic independence, and thus strengthening household nutrition. Nevertheless, adoption of this technology in this region is challenged by various factors including limited water resources, lack of knowledge, limited input and services (quality fingerling supply, technical expertise, and extension services), social adoption barriers, and market and institutional barriers. However, government support is required to connect aquaculture with all chains and stakeholders. Research institutions and local universities must fully assume research and capacity building initiatives for successes of this technology (Botswana Government, 2021a).

All fish species that occur in the Limpopo river catchment are favorable species to consider for farming in the eastern margin of Botswana. For example, Mozambique tilapia and Redbreast tilapia are native to the river systems in eastern margin of Botswana (Skelton, 2024) and hence recommended for farming in this region. The African sharptooth catfish exist in the this catchment as well (Skelton, 2024) and thus recommended for farming in this region too. Even though native to northern Botswana Threespot tilapia (Skelton, 2024) has already been introduced to the Limpopo catchment hence recommended for farming in this region. Although it is not native to Botswana (Skelton, 2024), Nile tilapia has already been introduced to the river systems in eastern margin of Botswana. And more importantly, this species has already been phenotypically improved for some desired aquaculture traits, and hence adopted worldwide (El-Sayed and Fitzsimmons, 2023; Prabu et al., 2019). Against this backdrop, this species is recommended for farming in the eastern margin of Botswana.

3.2.3 Arid western-southern region

The most difficult conditions for aquaculture development in Botswana are found in the arid region. Primarily, this region is defined within areas of the Kalahari Desert, Ghanzi District, and southern Kgalagadi. With average annual totals frequently dipping below 250 mm, western-southern region experience the lowest and most unpredictable rainfall in Botswana. Analysis of rainfall from 1991 to 2020 often shows significant inter-annual variability rather than a consistent, linear trend (Figure 9). The annual average temperatures exhibit a steady warming trend. The region is characterized with evapotranspiration rates of more than 2,500 mm yearly (World Bank Group, 2021). Extreme water shortages, temperature extremes (0–45 °C), unpredictable rainfall, and intense sun radiation (Knight and Holmes, 2018) are all problems in this region. Except for brief intervals after rainfall, surface water is virtually non-existent in this region (Mosalagae and Mogotsi, 2013). Groundwater resources are few, deep (typically 80–200 m), and often brackish with chloride and total dissolved solids (TDS) surpassing 1,500 mg/L (Kandjou et al., 2022), and thus unsuited for conventional agriculture or even traditional aquaculture. High salinity (TDS exceeding 500 mg/L), high hardness ($CaCO_3$ exceeding 300 mg/L), fluctuating pH, and heavy metal contamination from natural geological sources are other issues with underground water quality in the region (Kandjou et al., 2022). Notwithstanding these significant obstacles, creative CSAq techniques can facilitate sustainable fish production. This has been the case in various desert regions of countries such as Australia, Egypt, Israel, Mexico, and Central Asia, where challenging conditions include high solar radiation, low rainfall, and high evaporation rates (Khanjani et al., 2024). Therefore, the core CSAq strategies of this region must anchor on water efficient technologies.

3.2.3.1 Intensive aquaculture strategies: arid western-southern region

According to Khanjani et al. (2024), aquaculture development in arid areas is dictated by the use of new technologies based on water saving, such as RAS and aquaponics. Furthermore, Yacout et al. (2025) concurred highlighting sustainable technologies such as aquaponics, desalination, and water recycling as key interventions in addressing aquaculture sector climate challenged areas. From this understanding, we concur that adoption of these aquaculture technologies can help drive CSAq production in this arid region of Botswana.

Recirculating Aquaculture System (RAS): As explained by Khanjani et al. (2024), the central sustainability advantage of RAS is its very low water use in comparison to conventional aquaculture techniques. Of critical importance is that, in a RAS, water is continuously treated and reused, making it well suited to arid western-southern Botswana where water availability is a binding constraint. RAS provides tight control over system parameters such as temperature, dissolved oxygen, ammonia and nitrite, stocking density, feeding, and even pathogen exposure (Khanjani et al., 2024). Compared to open systems, this control increases biosecurity, lowers exposure to climate unpredictability, and promotes more predictable production. This is so important for adoption in this region, where conventional aquaculture may be threatened by heat stress and hydrological uncertainty. Consequently, the strongest limitation of RAS is energy demand, especially for pumping, aeration, filtration, heating or cooling, and system monitoring. Therefore, sustainability of RAS in this region will depend on utilization of solar technology (Tanuja et al., 2025b). RAS is further challenged by high capital expenditure and technical complexity. As such more government support, public-private partnerships and capacity building (Botswana Government, 2021a) are therefore important to aid adoption of this technology in this region. Rainwater harvesting technologies must be harnessed and several strategies can aid water collection including rain water directed toward storage tanks from roof tops. This can provide enough volumes for small systems, or enough water to dilute the underground brackish water for scaled RAS in this region. However, rain water harvesting will be challenged by unpredictability of rainfall, high initial cost, regular maintenance cost, limiting policy issues, limited rainwater harvesting technical expertise, water quality and contamination, and microbial risks (Lepcha et al., 2024; Umukiza et al., 2023). As such, harvested rainwater can have negative impact on fish such as mortality resulting from toxic accumulation if rainwater, further making fish susceptible to infectious diseases (Oguntimehin et al., 2026).

Aquaponics: aquaponics blends well in arid regions because it uses significantly less freshwater compared to conventional agriculture practices, and recycles fish waste nutrients for plant growth, reducing discharge and fertilizer demand (Tidwell, 2012; Chen, 2022). Because the arid western-southern Botswana is constrained by drought,

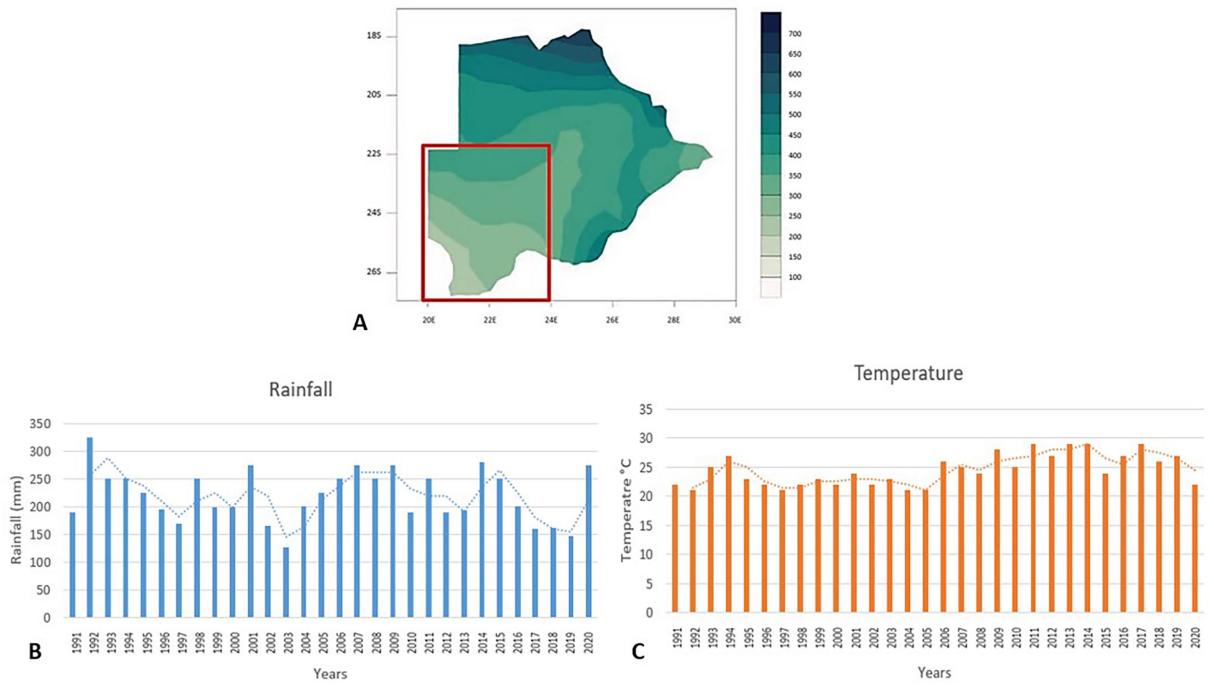


FIGURE 9
The arid western-southern region's (marked in red) spatial variation in rainfall **(A)**, rainfall **(B)** and temperature **(C)** trends from 1991–2020: Adapted from World Bank Group (2021).

rainfall variability, and water scarcity (Matopote et al., 2025), adoption of aquaponics technology can help revolutionize aquaculture in this region. As a double product (fish and plants) production system, aquaponics can boost food security in the region by supplying year-round leafy vegetable production, local fish protein supply, and diversification of diets. The relevance in this region cannot be over justified, because remoteness and climate stress of the region can limit consistent access to fresh produce. However, adoption of aquaponics in this region is constrained by high upfront capital costs, continuous energy demand for pumping and climate control, need for technical skills in fish, plant, and water-quality management, and feed supply. However, it offers long-term cost savings by reducing the need for chemical fertilizers, minimizing water usage, and potentially requiring less labor per unit of production (Okomoda et al., 2023). Using small pumps and aerators operated through solar (Kulshrestha et al., 2025) may further reduce the associated costs. Adopting this technology will create job opportunities, and provide training for locals as technical know-how is basic requirement for its operation (Okomoda et al., 2023). Just like in RAS technology, utilizing rainwater water can help sustain adoption of this technology in this region. As a call from the Botswana Aquaculture Strategy and Action Plan, more support is required from government, private sector, universities and non-governmental organizations (NGO's) to facilitate public-private partnerships and capacity building (Botswana Government, 2021a).

Salt-tolerant fish species can be farmed with the brackish groundwater of the arid western-southern region. Acclimatization of certain hardy fresh water fish species to the brackish water condition can be a game changer. Certain Cichlids have proven hard and tolerant to salt water to some extent. For example, *Oreochromis niloticus* can acclimatize and tolerate up to 20 ppt whereas *Oreochromis mossambicus* can acclimate up to 70 ppt (Uchida et al., 2000; King and Sardella, 2017). Moreover, other species native to or existing in the Limpopo catchment can be adopted for farming in this region. These include species like *Clarius gariepinus*, a species which is hardy tolerating harsh farming conditions (Skelton, 2024).

3.3 Climate-smart aquaculture appraisal for Botswana: evaluating traditional vs. modernized aquaculture technologies

From natural-based systems to intense, technology-driven operations, traditional and modernized aquaculture offer two essentially different approaches to aquaculture production which showcase CSAq feasibility in Botswana. For example, seasonality of Okavango and Chobe Rivers systems dictate formation of floodplains (Mosepele et al., 2022) and traditional systems take advantage of the flood pulse for fish rearing in natural depression wetlands or temporary ponds that can be stocked during high water and harvested during low water. Similarly, reservoirs or dams in the eastern margin of the country are ideal for traditional capture-based aquaculture, where fish are greatly reliant on natural food sources in the water column (Edwards, 2015). This mosaic provide simple sustainable synergies which perfectly define CSAq at a traditional level. However, modern aquaculture systems, such as RAS, biofloc, aquaponics, and IMTA, are important CSAq technologies (Soudah et al., 2025; Tian and Dong, 2023) that can help boost sustainable aquaculture output in Botswana. These techniques open the door to sustainable, scalable, and technologically advanced aquaculture by resolving the inefficiencies and environmental issues of traditional aquaculture. The long-term advantages of lower water use, waste control, and year-round production make modernized systems essential for satisfying the nation's fish demand, even while high initial start-up cost and energy requirements are major obstacles (Tian and Dong,

2023). Table 5 outlines the comparative analysis of traditional and modernized aquaculture, whereas Table 6 describes and tally Botswana's climatic regions against their applicable aquaculture production system and potential fish production species.

4 Challenges to aquaculture adoption in Botswana and mitigation measures

4.1 Challenges

4.1.1 Lack of knowledge and technical capacity

Limited technical capacity in Botswana's aquaculture industry is a significant barrier to adoption of CSAq practices. To start with, there is limited number of government aquaculture extension officers in the country. The Director of the Department of Fisheries and Apiculture confirmed that the department has only 14 aquaculture personnel across all cadres responsible for guiding aquaculture development nationwide. This situation is further exacerbated by a lack of adequately qualified staff in aquaculture technologies within the government extension workforce; of the 14 officers, only 4 possess formal qualifications in fisheries and aquaculture. However, the importance of extension officer's aquaculture technologies adoption cannot be over emphasized. They are essential for boosting output, and promoting rural development through dissemination of technology and knowledge, closing the gap between research and practice (Abiodun and Cookey, 2023; FAO, 2022). Many farmers remain unaware of climate-smart strategies, such as efficient water management systems or sustainable feeding techniques. Even when farmers are informed about new technologies, they often lack the practical skills required for successful adoption, operation, and maintenance, limiting the effectiveness of CSAq interventions in Botswana.

4.1.2 Climate variability and environmental challenges

Because of Botswana's semi-arid climate, aquaculture is extremely susceptible to the effects of climate change. Water scarcity is a major constraint to the adoption of CSAq in the country. The argument follow that from FAO climate-smart sourcebook (Ouda and Zohry, 2022). Limited water availability not only raises operational risks but also intensifies competition among domestic, industrial, and agricultural users. Competition with other home, industrial, and agricultural users increases when water becomes more limited. Shortage and erratic rainfall in Botswana and increased evaporation rates resulting from high temperatures (World Bank Group, 2021), make investing in CSAq technologies more risky. It can bring fish mortality and decreased harvests, affecting viability of enterprises. The country's high temperatures (World Bank Group, 2021) and limited water can concentrate contaminants and aquatic diseases. However, fish are more vulnerable to disease outbreaks, and should this occur, it will necessitate more management work and possibly usage of medications or chemicals, which creates further sustainability issues. The need to remediate low-quality water especially underground water in the arid region, obtaining alternate water sources, like desalination, or constructing larger water storage capacity tanks for water harvesting adds substantial expenses. This will make start-up cost of implementing CSAq practices a significant barrier for ordinary small-holder farmers.

4.1.3 Limited access to credit

In Botswana, the financial needs of aquaculture producers appear to be beyond the reach of financial institutions. Aspiring aquaculture

TABLE 5 Comparative analysis: adoption of traditional and modernized aquaculture as CSAq tools in Botswana.

Aquaculture tool category	Characteristics	Advantages	Disadvantages	System examples	Applicable region
Traditional aquaculture	Involves low-input systems that rely on natural productivity and minimal technological intervention (Edwards, 2015).	-Have lower capital investment and operational costs, and integrate with natural ecosystems, minimizing the ecological footprint (Edwards, 2015).	They are less productive due to limited stocking and are vulnerable to climate change (Edwards, 2015).	Fish production from seasonal pans or lagoons	- Okavango-Chobe region
				Capture-Based Aquaculture	- Eastern margin
Modernized aquaculture	Involves intensive systems that leverage advanced technologies to optimize production and use nutritionally complete diets, aeration, filtration, and advanced disease control measures (Tidwell, 2012; Tian and Dong, 2023).	Have high stocking densities, high production rates, better control over water quality and fish health, reducing mortality rates, and create more employment opportunities (Soudah et al., 2025; Tian and Dong, 2023).	They rely on commercial pellets dictating imported fish feed hence expensive (Maulu et al., 2024), use advanced technologies increasing operational expenses, and farmers will require specialized training to manage modern systems effectively (Soudah et al., 2025; Tian and Dong, 2023).	Intensive pond system	- Okavango-Chobe region
				RAS	- All regions
				Biofloc technology	- Okavango-Chobe region
				Aquaponics	- All regions
				IAAS	- Okavango-Chobe region - Eastern margin
				Integrated Wetland-Aquaculture Systems	- Okavango-Chobe region

TABLE 6 Description of Botswana's climatic regions against their applicable aquaculture production system and potential fish production species.

Climatic region	Climate description	Applicable aquaculture systems	Fish species prioritization
Okavango-Chobe	• Semi-arid with high summer temperature and mild winter temperature (World Bank Group, 2021). • Annual rainfall averages 620 mm (Wolski and Murray-Hudson, 2006, 2008)	• Pond system • Integrated Wetland-Aquaculture Systems • Recirculating Aquaculture system (RAS) • Biofloc-based systems • Aquaponics system • Integrated Aquaculture-Agriculture Systems (IAAS)	• Threespot tilapia (*Oreochromis andersonii*) • Redbreast tilapia (*Coptodon rendalli*) • African sharptooth catfish (*Clarias gariepinus*)
Eastern Margin	• -Semi-arid conditions marked by pleasant, dry winters and warm to hot summers (World Bank Group, 2021). • -Precipitation can reach 650 mm (Statistics Botswana, 2017)	• Recirculating Aquaculture system (RAS) • Biofloc-based systems • Aquaponics system • Integrated Aquaculture-Agriculture Systems (IAAS)	• Nile tilapia (*Oreochromis niloticus*) • Mozambique tilapia (*Oreochromis mossambicus*) • Threespot tilapia (*Oreochromis andersonii*) • Redbreast tilapia (Coptodon rendalli) • African sharptooth catfish (*Clarias gariepinus*)
Southern-Western	• Arid region, presenting driest and cold winters, and hottest summers (World Bank Group, 2021). • Annual rainfall averages 300 mm (Statistics Botswana, 2017.	• Recirculating Aquaculture system (RAS) • Biofloc-based systems • Aquaponics system	• Nile tilapia (*Oreochromis niloticus*) • Mozambique tilapia (*Oreochromis mossambicus*) • Threespot tilapia (*Oreochromis andersonii*) • Redbreast tilapia (Coptodon rendalli) • African sharptooth catfish (*Clarias gariepinus*)

farmers in Botswana frequently lack credit to invest in the infrastructure and inputs like enhanced systems, quality fingerlings, and adequate feed required for CSAq. Financial institutions are reluctant to make loans because they sometimes have little knowledge of the aquaculture industry. However, financial barriers must be removed for aquaculture to grow sustainably (Kleih et al., 2013).

4.2 Mitigation measures

4.2.1 Addressing knowledge and technical capacity

Borrowing from Bhatnagar (2025) concept, key mitigation strategies that can address lack of knowledge and technical capacity include intensive training programs, streamlined production methods, and peer learning networks. Intensive training programs will equip extension officers and farmers with skills and human capital needed to effectively adopt new techniques and adjust to climate threats. It will further increase the possibility of effective adoption of CSAq techniques which are appropriate for their particular situations. Farmers frequently rely on and gain knowledge from their colleague's experiences. Networks can help create a supportive learning environment by facilitating the reciprocal exchange of old and modern information. Additionally, linking farmers offers social support, which can be a crucial coping strategy for handling the pressures and uncertainties associated with climate change.

4.2.2 Addressing climate variability and environmental challenges

Adopting ultra-water efficient technologies like Biofloc Technology (BFT) and Recirculating Aquaculture System (RAS) (Tidwell, 2012) can play a critical role in mitigating water scarcity by drastically lowering water usage in production. By using closed-loop operations, waste recycling, and improved biosecurity, they are able to make aquaculture more climate-resilient (Tidwell, 2012). Another important measure for strengthening community's resistance to water shortage brought on by climate change is diversification into non-water-dependent activities. When traditional aquaculture is endangered by decreased water supply or quality, it helps stabilize lifestyles by offering alternate or supplemental revenue streams. Investing in research, especially studies on the effects of local climate and enhancing indigenous species that are appropriate for various climatic regions in Botswana is key. This will help to create science-based remedies.

4.2.3 Addressing limited access to credit

To address the challenges associated with financing aquaculture enterprises in Botswana, we concur with Kleih et al. (2013) that creative financial solutions for enterprises must be created. A financial model that combine investment funds with business development funds should be adopted to ensure timely loan repayment and economic growth of enterprises. This will then create a win-win situation. Furthermore, creating supportive strategies and policies that encourage adoption of CSAq can address the challenge. For example, devising a tailor made CSAq subsidies that foster a more encouraging environment.

5 Policy and institutional framework for successful climate-smart aquaculture (CSAq) adoption in Botswana

5.1 Conservation compliance

As clearly explained by Mosepele and Kolawole (2017), international, continental, and national conservation obligations must be adhered to by all aquaculture operations. Nationally, aquaculture adoption must be pinned to Botswana Climate Change Policy in order for CSAq implementation to be successfully achieved in the country. Adopting an Ecosystem Approach to Aquaculture (EAA)

(Costa-Pierce, 2021) must form foundation to the envisaged CSAq. The conservation strategy must monitor programs recording ecological impacts and system responses, prohibit the introduction of exotic species that could endanger native biodiversity, and require Environmental Impact Assessments (EIA) for proposed aquaculture sites before start-up (Domínguez and Martín, 2004). Creating multi-sectoral stakeholder structures that include water, food production and energy planning, and empowering farmers on climate-resilient technologies must be priority (Menezes et al., 2024).

5.2 Water resources management policies

Successful CSAq in Botswana requires integrating aquaculture technologies with strict compliance to national policies and environmental regulations, along with other agricultural production streams (Setlhogile and Harvey, 2022). There must be clear rules for water allocating and extraction with sustainable water use and extraction limitations that preserve the integrity of water. Priority must be given to environmental flows that support ecosystem services (Domínguez and Martín, 2004). Limited water resources in Botswana calls for more rainwater harvesting (Siphambe, 2024). We recommend that government must support rainwater harvesting. Subsidies have been adopted elsewhere as water use management strategies (USAID, 2021). As such, we propose government collaborations with Non-Governmental Organizations to secure funding for sound cost-sharing subsidy for water storage infrastructure, designs, and connections.

5.3 Energy and climate policies

CSAq adoption in Botswana must form part of the priority areas and align with the national goal of increasing renewable energy to 50% by 2030 (Botswana Government, 2021b) through encouraging solar-powered operated systems in aquaculture ventures. This endeavor will further reduce carbon footprints which is one key conservation area of the National Climate Change Strategy (Makoba et al., 2024). To foster successful implementation, there must be access to climate finance such as green bonds that finance sustainable aquaculture infrastructure, carbon credit programs for low-emission aquaculture, and climate adaptation funds that support resilient technologies (Olaleru et al., 2021).

5.4 Capacity building

The government of Botswana has developed a National Aquaculture Strategy (2021–2026), which aims to promote sustainable development and management of aquaculture and inland fisheries (Botswana Government, 2021a). As such, successful implementation of CSAq requires strong capacity among stakeholders including farmers, researchers, and extension officers to enhance their abilities to perform functions and sustainably solve problems. Capacity building lessons can be drawn from Advancing Climate-Smart Aquaculture Technologies (ACliSAT) project, aimed to promote climate-resilient aquaculture in arid areas. Through capacitating national aquaculture research institutions and training extension agents, there was increased adoption of sustainable aquaculture technologies with developed guidelines to direct adoption of the technologies, for example (Elewa and Nasr-Allah, 2023; Nasr-Allah et al., 2023). Furthermore, Botswana must leverage on the already designed frameworks like the Aquaculture Adaptation Framework for Climate Change (Aqua-Adapt) (Soto et al., 2025) to design localized capacity-building programs in this manner. Another major challenge to adopting CSAq in Botswana is lack of financial capacity for aquaculture producers. As such, innovative financial mechanisms and targeted investments are required. Producers must be empowered to leverage international public finance initiatives. For example, the Green Climate Fund (GCF) offers financial support under the United Nations Framework Convention on Climate Change (UNFCCC) through grants for projects that enhance resilience and reduce emissions (Gopal et al., 2026). However, national public finance initiatives can be learned from India where, the government has implemented a number of climate finance projects for the fisheries industry, incorporating resilience and sustainability into its policies and programs (Gopal et al., 2026).

6 Conclusion

Climate-smart aquaculture (CSAq) adoption in Botswana requires approaches that work with rather than against the various regional climatic conditions. Success will depend on production systems and infrastructure which will be aligned with environmental conditions of every region. Indigenous fish species and species already introduced to the region must be prioritized for ecological compatibility, biodiversity conservation, and better returns. When properly planned and managed, CSAq can enhance food security and livelihoods while maintaining the ecological functions and biodiversity values of the country significantly. Nevertheless, CSAq adoption in Botswana is challenged by limited technical capacity in aquaculture, climate variability and environmental challenges, and limited access to credit by aspiring aquaculture farmers. Various mitigation strategies have been discussed to address the latter challenges. Intensive training programs, streamlined production methods, and peer learning networks are proposed to address knowledge and technical capacity challenges whereas adopting ultra-efficient technologies like aquaponics and RAS, diversification into non-water-dependent activities, and investing in research for science-based remedies are recommended. Creative financial solutions for enterprises must be created to address the issues of lack of financial resources. It is recommended that policy and institutional framework for successful CSAq adoption in Botswana must be anchored on conservation and compliance, water resources management, green energy technologies and capacity building. By embracing this, CSAq can revolutionize fish production in Botswana. The strongest evidence base supports prioritizing high reuse technologies. For example, intensive ponds can require up to ~45 m^3 of water per kg fish, whereas advanced RAS can reduce new-water inputs to ~0.016 m^3 kg^{-1} (~99.9% lower), and biofloc management has delivered ~45% higher net tilapia production than clear water controls (Gallego-Alarcón et al., 2019). These benchmarks justify policy targets framed around ≥90% reduction in water withdrawal intensity and a realistic pathway to ~10 times national output expansion under water limited conditions, provided energy reliability, skills, and biosecurity are simultaneously addressed.

Recent studies show that Botswana's farmers are already seeing real benefits from adopting climate smart agriculture (CSA), which bodes well for the success of climate-smart aquaculture. A survey of 271 maize growers found that although more than half had heard about climate-smart irrigation, only about half were using it (Jagadeesh et al., 2025). Older age, being female and lack of credit discouraged adoption, while

education and farming experience made adoption more likely (Jagadeesh et al., 2025). Farmers who did invest in these practices saw their crop yields rise, prompting researchers to call for easier credit, more training and efforts to attract younger people to farming (Jagadeesh et al., 2025). Another study that looked at four climate-smart practices (crop rotation, maize-legume diversification, improved seeds and inorganic fertilizer) found that uptake of CSA depends on many factors, including education, farming experience, training, farm size, livestock ownership, membership in farmer groups, extension services, access to markets, secure land tenure and timely climate information (Mpinda et al., 2025). The authors argue that policies need to address these multiple drivers if climate-smart farming is to spread (Mpinda et al., 2025). Further, researchers studying adaptation strategies in Ngamiland East found that most farmers rely on indigenous knowledge and that women and poorer households are less likely to adopt new practices and they urged policy makers to recognize local know-how and community institutions (Mogomotsi et al., 2020). On the ground, these ideas have translated into tangible success. Some farms are even integrating fish and vegetable production through aquaponics, recycling fish waste to feed plants and using far less water than conventional farming (Botswana Ministry of Agriculture, 2023). These experiences show that when farmers have access to credit, training, extension services and supportive local institutions, they can adopt resource-efficient practices and improve their yields. Since CSAq relies on similar tools and support systems, these successes suggest it could also thrive in Botswana.

Author contributions

MM: Writing – original draft, Writing – review & editing, Visualization, Formal analysis, Validation, Methodology, Data curation, Conceptualization. SM: Methodology, Writing – review & editing, Validation, Writing – original draft, Visualization. TB: Visualization, Methodology, Validation, Writing – review & editing, Formal analysis. BM: Resources, Funding acquisition, Project administration, Validation, Writing – review & editing, Supervision. CC: Data curation, Writing – review & editing, Investigation, Writing – original draft. YL: Writing – original draft, Data curation, Investigation, Writing – review & editing. PL: Writing – review & editing, Writing – original draft. ML: Writing – original draft, Writing – review & editing. FK: Writing – original draft, Writing – review & editing. CS: Writing – review & editing, Writing – original draft. TN: Writing – original draft, Writing – review & editing. RT: Writing – review & editing, Visualization, Project administration. KM: Visualization, Validation, Writing – review & editing, Supervision.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declared that Generative AI was not used in the creation of this manuscript.

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