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Enhancing Global Food Security through Sustainable Fisheries and Aquaculture: A Comprehensive Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

As the global population rises, addressing food security becomes more critical, particularly in developing regions struggling with hunger and malnutrition. Fisheries and aquaculture provide a vital solution by offering essential nutrition, employment, and economic benefits to millions worldwide. This study conducts an in-depth review of how capture fisheries and aquaculture contribute to global food security, emphasizing ten key areas: sustainable fisheries management, aquaculture growth, nutritional advantages, economic empowerment, climate adaptability, post-harvest loss reduction, policy and governance, technological advancements, biodiversity preservation, and global market access. The review evaluates the strength and consistency of

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evidence regarding the positive impact of these sectors on food security and poverty alleviation. The findings highlight the importance of cohesive policy and governance, technological improvements, and broader market access to fully leverage the role of fisheries and aquaculture in addressing global food challenges. Additionally, this review identifies research gaps that need to be addressed to maximize the sectors' potential for economic growth and environmental sustainability

Keywords: Sustainable fisheries; food security; aquaculture; global; nutrition; climate.

1. INTRODUCTION

The global population, currently estimated at 7.8 billion, is projected to reach approximately 9 billion by 2050, primarily due to rapid growth in developing countries [1]. This demographic surge is exacerbating global hunger, with nearly 821 million people suffering from food insecurity [2] and about 14% of the population experiencing deficiencies in protein and energy [3]. Addressing these challenges is crucial for ensuring global food security, particularly as traditional food sources struggle to keep pace with rising demands.

Fish, as a vital source of protein, fatty acids, and essential vitamins, plays a significant role in global nutrition and economic stability. The contribution of fisheries to human livelihoods, especially in developing nations, is substantial. Approximately 60 million people depend on inland fisheries, which support around 12% of the global population. Furthermore, nearly 93-97 million individuals are involved in various aspects of the fish industry, including cultivation, capture, processing, marketing, and retail [4]. Notably, women frequently engage in small-scale fish processing and local market retail, providing critical income for their families [5].

In 2020, developing countries were responsible for producing 79% of global fish, reflecting their significant role in the industry. With over 29,000 fish species worldwide, of which 1,500 are commercially recognized, the sector continues to expand. Fish farming, particularly through innovative techniques like bio-floc technology, offers an efficient alternative to traditional methods, requiring less space and benefiting regions with limited land [6,7]. Commonly cultured species include *Tilapia species*, *Clarias gariepinus* and *Cyprinus carpio* [8].

Fish provides a cost-effective source of high-quality protein, vitamins, and micronutrients compared to beef or mutton, especially in developing countries [9]. Regular fish consumption addresses deficiencies in essential nutrients and omega-3 fatty acids, contributing to improved health and diet quality [10,11]. With the rise in per capita fish consumption from 9.9 kg in 1960 to 18.4 kg in 2009, fish farming is increasingly meeting both local and export demands [5].

Moreover, by-products from fish processing, such as fish oil and fishmeal, are vital for livestock and aquaculture feeds [12]. The United Nations' Sustainable Development Goals (2018) emphasize the importance of fisheries and aquaculture in combating poverty and hunger, aligning with goals of no poverty, zero hunger, and sustainable production [7,13]. However, while food security and poverty reduction are central to global development, the focus has evolved with population growth, technological advancements, and environmental changes [14, 15].

The role of fisheries and aquaculture in food security and poverty alleviation is multifaceted, encompassing nutrition, supply sustainability, demand, access, and the involvement of small-scale workers. Despite their importance, past research has often concentrated on ecological, conservation, and economic efficiency issues, with insufficient emphasis on the sectors' contributions to food security and poverty reduction [3].

This paper aims to evaluate the current evidence on how capture fisheries and aquaculture contribute to global food security and poverty reduction. It assesses the scientific quality and consistency of existing research across various development themes, including sustainable fisheries management, aquaculture expansion, nutritional benefits, economic empowerment, climate resilience, reduction of post-harvest losses, policy and governance, technological innovation, biodiversity conservation, and global market integration. By providing a comprehensive review, this paper seeks to clarify the impact of these sectors on food security and economic development and to identify areas where further research and policy action are needed.

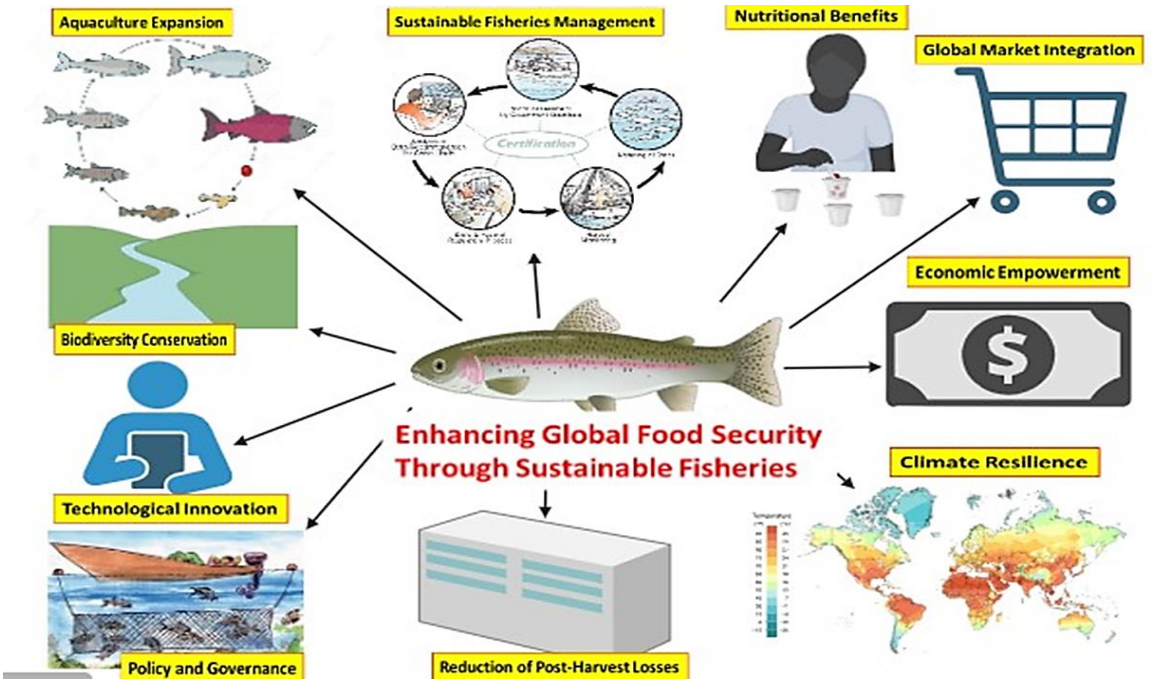

Fig. 1. Enhancing global food security through sustainable fisheries and aquaculture

Enhancing food security through fisheries for the global population can be approached by focusing on several key highlights:

1. Sustainable Fisheries Management
2. Aquaculture Expansion
3. Nutritional Benefits
4. Economic empowerment
5. Climate resilience
6. Reduction of post-harvest losses
7. Policy and governance
8. Technological innovation
9. Biodiversity conservation
10. Global market integration

1. Sustainable Fisheries Management: Sustainable fisheries management plays a crucial role in ensuring long-term food security by maintaining healthy fish stocks and supporting overall ecosystem health [16]. One key aspect of sustainable management is maintaining fish populations through scientifically determined catch limits, which help prevent overfishing and allow natural replenishment of fish stocks [17, 18]. This ensures fish remain a reliable and renewable food source for future generations. Additionally, the establishment of Marine Protected Areas (MPAs) is instrumental in safeguarding marine ecosystems. MPAs restrict certain human activities, promoting ecosystem recovery and leading to healthier fish populations that often "spill over" into surrounding fishing areas, thereby enhancing overall productivity [19, 20].

Addressing the pervasive issue of Illegal, Unreported, and Unregulated (IUU) fishing is another critical component. Through improved monitoring, control, and international collaboration, measures aimed at combating IUU fishing protect legal fishers while ensuring the sustainability of fish populations [21]. In tandem, the Ecosystem-Based Fisheries Management (EBFM) approach takes into account the broader marine ecosystem by balancing species needs, reducing bycatch, and conserving biodiversity, which collectively support essential ecosystem services [22]. Lastly, sustainable fisheries management must remain adaptable in the face of climate change. By regularly assessing fish populations, adopting resilient fishing practices, and protecting vulnerable coastal ecosystems, fisheries can continue to contribute to food security despite the challenges posed by environmental shifts [23].

2. Aquaculture Expansion: Aquaculture Expansion is critical to addressing global food security by providing a sustainable source of fish [24]. As global populations grow and wild fish stocks face pressure, aquaculture meets rising demand by producing fish in controlled environments [25]. Currently, aquaculture supplies over 50% of global fish consumption,

ensuring a stable food source, particularly in regions where fish is essential.

Aquaculture is also resource-efficient, requiring less feed per kilogram of fish compared to land-based livestock [26]. By utilizing agricultural and fishery byproducts for feed, the industry minimizes environmental impact. Advances such as selective breeding and sustainable practices like Integrated Multi-Trophic Aquaculture (IMTA) and Recirculating Aquaculture Systems (RAS) have further boosted productivity and reduced waste [27].

Additionally, aquaculture promotes species diversification, offering both high-value and affordable fish options [28]. This diversity enhances dietary options and contributes to nutritional security. Economically, aquaculture provides jobs and supports local economies, particularly in developing countries where alternative livelihoods are limited [29]. Its resilience against climate change impacts, such as extreme weather and shifting fish distributions, further reinforces its role in ensuring a stable food supply [30].

3. Nutritional Benefits: Nutritional Benefits are essential for enhancing food security, as fish are nutrient-dense and provide vital vitamins, minerals, and high-quality protein. Expanding fisheries and aquaculture can significantly improve global nutrition, especially in areas with high malnutrition rates and limited food diversity [31].

Fish serve as a high-quality protein source, providing all essential amino acids crucial for muscle mass, immune function, and overall health. For low-income populations with limited access to meat or dairy, fish offers an affordable and sustainable protein option, particularly beneficial for children, pregnant women, and the elderly [32]. Additionally, fatty fish such as salmon and mackerel are rich in omega-3 fatty acids, which are vital for brain function, heart health, and reducing inflammation. Omega-3s lower cardiovascular risks and support fetal brain development, making fish consumption important for public health, particularly in regions with low omega-3 intake [33].

Fish also provide essential micronutrients like vitamin D, which supports bone health and immune function, and vitamin A, necessary for vision and immune health. Minerals like iodine, iron, zinc, and calcium are critical for thyroid function and anemia prevention [32,34]. In low-income countries, fish help combat malnutrition by supplying concentrated nutrients that address undernutrition and micronutrient deficiencies, particularly in coastal and riverine communities [35]. Incorporating fish into diets improves both quality and diversity, which is crucial for overall health. For regions heavily dependent on staple crops, fish can fill nutritional gaps, promoting better health outcomes and greater resilience against disease

4. Economic empowerment: Economic empowerment is essential for improving food security, particularly in developing countries where fisheries and aquaculture serve as vital sources of income and livelihoods. Over 120 million people globally rely on these sectors, not only for fishing but also for jobs in processing, marketing, and transportation, which help reduce poverty and unemployment in coastal and rural areas [36,37]. Empowering small-scale fisheries through community-based management promotes sustainable practices and preserves traditional methods, while securing access rights for fishers prevents industrial encroachment [38]. Economic inclusion of marginalized groups, such as women and indigenous communities, provides access to resources and training, helping to alleviate poverty and boost social inclusion. Infrastructure improvements, such as cold storage and transport, reduce post-harvest losses, while fair trade systems ensure equitable pricing for fishers, enhancing profitability [39]. Access to financial services, like microcredit and insurance, allows fishers to invest in better equipment and recover from risks, ensuring stable livelihoods. Empowering women in fisheries strengthens productivity, as gender equality and economic independence lead to better family health, nutrition, and education [40]. Economically empowered communities are also more likely to invest in sustainable practices, protecting ecosystems and ensuring long-term fish stock viability. In times of economic or environmental shocks, these communities are more resilient, able to adapt to changing conditions and maintain food security. Income from fisheries fosters broader economic growth, supporting local development projects, while government policies and global trade agreements further enhance the sector's potential for growth and sustainability [41,42]**.**

5. Climate resilience: Climate resilience is essential for maintaining food security in the face of climate change, with fisheries and aquaculture

playing a key role in enhancing adaptability and stability [43]. Many fish species and aquaculture systems can adjust to environmental changes like temperature fluctuations and salinity shifts, ensuring food availability even during extreme weather events such as droughts or floods [33]. Healthy aquatic ecosystems, such as mangroves and coral reefs, not only support fish habitats but also protect coastal areas from erosion, benefiting both fisheries and local communities. Adaptive management practices, including adjusting fishing quotas and integrating fish farming with seaweed or shellfish cultivation, bolster system resilience and sustainability [23]. Fisheries are particularly vital for food security in vulnerable coastal and island communities, providing a reliable food source amidst climate change disruptions [43]. By offering diversified income opportunities, fisheries reduce economic vulnerability and enhance local food systems' resilience, making them less dependent on global supply chains [44]. Research into climate-resilient fish species and innovations in aquaculture technology, such as improved water filtration, further strengthen the sector's capacity to withstand climate impacts. Additionally, healthy ecosystems provide crucial services like coastal protection and nutrient cycling, sustaining fish populations and overall ecosystem productivity. Engaging local communities in fisheries management and climate adaptation strategies ensures tailored, effective responses to climate challenges. Finally, climate-responsive policies and international cooperation support the integration of climate considerations into fisheries management, enhancing collective resilience across regions.

6. Reduction of post-harvest losses: Reduction of post-harvest losses is essential for enhancing food security through fisheries by addressing inefficiencies and waste that occur between harvest and consumption [45,46]. Advanced processing techniques, such as vacuum packing, freezing, and canning, extend the shelf life and quality of fish, with methods like high-pressure processing (HPP) and pasteurization preserving freshness without compromising nutritional value [47]. Value addition through processing fish into products like fillets and fishmeal broadens market reach and reduces waste [48]. Efficient storage solutions, including cold storage facilities and innovative packaging like modified atmosphere packaging (MAP), are crucial for maintaining fish freshness and reducing spoilage [45,46]. Enhancing distribution networks through cold chain management and improved logistics ensures that fish remains at optimal temperatures throughout the supply chain. Improved handling practices, supported by training and standard operating procedures (SOPs), minimize physical damage and contamination, which are major causes of post-harvest losses [48]. Technological innovations, such as RFID tags and automation in processing, increase efficiency and reduce waste by monitoring fish quality and optimizing storage conditions. Investing in infrastructure development and supporting small-scale fishers with modern facilities help minimize post-harvest losses through improved practices and technologies [48]. Government support through policies and regulations that encourage investment in post-harvest infrastructure, along with the enforcement of industry standards, further reduces losses. Ongoing research and collaboration with international organizations drive innovation and the development of new preservation methods, ensuring continued progress in reducing post-harvest losses [45,46].

7. Policy and governance: Policy and governance are crucial for enhancing food security through fisheries by ensuring sustainable management and equitable distribution of benefits. Strengthening international fisheries agreements, such as the United Nations Convention on the Law of the Sea (UNCLOS) and the United Nations Fish Stocks Agreement (UNFSA), establishes a robust framework for managing shared fish stocks and marine resources, promoting sustainable practices and conservation measures [49,50]. Improving the effectiveness of Regional Fisheries Management Organizations (RFMOs), which manage transboundary fish stocks, is essential for enforcing regulations, setting quotas, and monitoring compliance to ensure fair resource sharing [51]. At the national level, implementing policies that promote sustainable fisheries, such as setting quotas and regulating gear, is vital for safeguarding fish habitats and stock recovery [19,20,52]. Policies should be adaptive to environmental changes and new scientific data, allowing adjustments based on emerging challenges like climate change. Robust monitoring systems, including satellite tracking and electronic reporting, enhance transparency and accountability, while effective enforcement against illegal, unreported, and unregulated (IUU) fishing involves increasing patrols, imposing penalties, and fostering international cooperation. Engaging local

communities, fishers, and industry representatives in decision-making ensures policies reflect diverse perspectives and improve compliance. Raising public awareness and educating stakeholders on sustainable practices supports conservation efforts. Equitably distributing economic benefits from fisheries supports social stability and food security, particularly for small-scale fishers. Providing support for transitioning communities helps them adapt to sustainable practices and mitigate economic disruptions. Regional and international cooperation promotes effective management and conflict resolution over marine resources [53]. Integrating scientific research into policy development ensures evidence-based decisions, while regularly reviewing and adjusting policies based on scientific insights supports timely responses to changing conditions. Addressing climate change through adaptation strategies and supporting international climate agreements like the Paris Agreement helps protect marine ecosystems and ensures long-term sustainability.

8. Technological innovation: Technological innovation is crucial for enhancing food security through fisheries by improving the efficiency, sustainability, and productivity of both wild fisheries and aquaculture [24,54]. Advancements in fishing gear, such as bycatch reduction devices and selective nets, minimize non-target species capture and reduce environmental impact; for instance, circle hooks decrease bycatch of sea turtles, and specialized nets target specific fish sizes or species [55]. Modern materials and designs for fishing gear further enhance efficiency and reduce ecological footprints by extending gear lifespan and lowering greenhouse gas emissions. Monitoring and surveillance technologies, including satellite tracking and Automatic Identification Systems (AIS), provide real-time vessel monitoring to enforce regulations and prevent illegal fishing [56]. Electronic monitoring systems with onboard cameras capture detailed data on fishing practices and bycatch rates, while integrated fishery management software aids in effective decision-making [57]. In aquaculture, Recirculating Aquaculture Systems (RAS) promote sustainability by recycling water and reducing pollution [58]. Advances in genetics and breeding improve aquaculture species, and Integrated Multi-Trophic Aquaculture (IMTA) systems enhance resource efficiency by mimicking natural ecosystems. Sustainable feed innovations, such as alternative feeds and nutrient optimization, reduce reliance on fishmeal and lower environmental impacts. Data and Artificial Intelligence (AI) applications, including big data analytics and machine learning algorithms, enable accurate forecasting and improved fisheries management [59]. Environmental monitoring through remote sensing technologies and advanced oceanographic tools enhances our understanding of marine ecosystems and climate change impacts [60,61]. Smart aquaculture systems, leveraging IoT technologies and automated feeding systems, further optimize management and productivity by monitoring water quality and improving feed efficiency [62]**.**

9. Biodiversity conservation: Biodiversity conservation is essential for enhancing food security through fisheries by maintaining the health and resilience of marine ecosystems, which support sustainable fish populations and the communities' dependent on them [16,63]. Marine ecosystems, including coral reefs, seagrass beds, and mangroves, provide critical habitats for numerous fish species, serving as breeding grounds, nurseries, and feeding zones that are vital for fish life cycles. Healthy ecosystems facilitate fish reproduction and growth, leading to stable and productive fisheries. Additionally, these ecosystems offer vital services such as nutrient cycling, carbon sequestration, and coastal protection, which are crucial for maintaining overall ecosystem health and resilience, thus supporting food security and community well-being.

Ecosystem-based management, which considers the interconnectedness of marine species and their habitats, ensures the long-term sustainability of fish populations by addressing predator-prey dynamics, habitat quality, and environmental changes [22,23]. Protecting key species that play essential roles in marine ecosystems, such as predator and herbivorous fish, helps maintain ecological balance and supports sustainable fisheries. Marine Protected Areas (MPAs), where human activities are restricted, play a significant role in replenishing fish stocks, preserving vital habitats, and enhancing ecosystem health. Properly designed and managed MPAs, which involve local communities in decision-making, often lead to the recovery of fish populations and can benefit adjacent fishing areas [19].

Addressing threats to biodiversity is crucial for conservation efforts [64]. Overfishing depletes fish stocks and disrupts ecosystems; therefore, sustainable fishing practices, including catch

limits and gear restrictions, are essential to prevent overfishing and protect marine species [65]. Climate change, which impacts marine ecosystems through rising temperatures, ocean acidification, and sea level rise, affects fish distributions and habitat conditions. Effective conservation must include monitoring climate impacts and adapting management strategies. Pollution from land-based sources, such as plastics, chemicals, and nutrients, also harms marine ecosystems; reducing pollution through improved waste management and cleanup efforts is necessary to protect marine biodiversity [66].

Community involvement and education are key to successful biodiversity conservation. Engaging local communities in conservation fosters stewardship and aligns efforts with local needs through community-based management approaches, such as co-management and participatory planning. Raising awareness about marine biodiversity and conservation benefits encourages positive behavioural changes and policy support, with educational programs for fishers, coastal communities, and the public promoting sustainable practices**.**

10. Global market integration: Global market integration is crucial for enhancing food security through fisheries by improving trade and market access for fish products, particularly benefiting developing countries with abundant fish resources [67]. Facilitating access to international markets enables these countries to tap into higher-demand markets with better prices, boosting revenue for fish producers and supporting local economies [68,69]. Moreover, integration helps diversify export destinations, reducing reliance on local markets and mitigating risks associated with market fluctuations or economic downturns, [70] providing greater stability for producers [70, 71].

Successful global market integration often involves upgrading processing and quality standards to meet international requirements, which can lead to improvements in local facilities, enhance product value, and reduce post-harvest losses [72]. Building infrastructure such as cold storage, transportation, and logistics is also crucial for supporting efficient distribution, reducing spoilage, and ensuring that fish products reach international markets in optimal condition [73].

Access to global markets creates incentives for adopting sustainable fishing practices as international buyers increasingly demand sustainably sourced products. This drives producers to comply with sustainability certifications and international regulations promoting responsible fisheries management, which helps prevent overfishing, protect ecosystems, and ensure the long-term sustainability of fish resources [74].

Economic development is further supported through income generation and employment opportunities, as access to global markets can increase export revenue for fishers, processors, and related businesses, contributing to poverty reduction [75]. Integration into global markets also provides economic stability by offering new revenue streams and reducing reliance on domestic markets, which is particularly important for developing countries facing economic challenges and seeking to strengthen food security and livelihoods.

Addressing trade barriers, such as high tariffs and export restrictions, is essential for facilitating smoother trade flows and improving market access [76]. Strengthening bilateral and multilateral trade agreements can enhance market access by negotiating favourable trade terms and reducing barriers, offering better opportunities for fish exporters [77].

Regional cooperation among fish-producing countries can improve market integration by harmonizing regulations, sharing best practices, and collaboratively addressing trade challenges, thus enhancing regional competitiveness [78]. Capacity building through technical assistance and training programs helps fish producers and exporters in developing countries meet international standards, improving skills and competitiveness in global markets [48]**.**

2. CONCLUSION

Fisheries and aquaculture are crucial in tackling global food security challenges by offering essential nutrition, economic opportunities, climate resilience, and sustainable development for millions of people worldwide. By focusing on sustainable fisheries management, expanding aquaculture, and incorporating technological innovations, these sectors can address the rising demand for food while protecting marine biodiversity and reducing the strain on wild fish stocks. Additionally, the nutritional benefits of fish, combined with strategies to minimize post-harvest losses and improve market access,

highlight the importance of these sectors in enhancing health outcomes and alleviating poverty, especially in vulnerable communities.

Empowering small-scale fisheries economically, alongside strengthening policy and governance frameworks, promotes sustainable practices and helps communities better cope with environmental and economic challenges. Integrating climate resilience into fisheries management and aquaculture ensures that these food systems can adapt to the changing climate, safeguarding local and global food security. Conserving biodiversity is essential for maintaining the ecosystems that sustain fisheries, supporting the long-term sustainability of fisheries and marine environments.

In conclusion, through advancements in technology, improved governance, and market integration, fisheries and aquaculture can significantly contribute to feeding the world's growing population while ensuring environmental sustainability. However, continued research and policy efforts are necessary to address current gaps and fully realize the potential of these sectors in securing global food supplies for future generations.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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