aquaculture journal

Article

Economic Feasibility and Risk Analysis of Nile Tilapia Juveniles Reared in a Biofloc Technology System

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Abstract: To meet the growing demand for sustainable aquaculture, the biofloc technology (BFT) system has emerged as a promising solution, offering high productivity, improved water use efficiency, and enhanced environmental and biosecurity performance. Economic and risk analyses are essential tools for identifying the key technical and economic factors that determine the profitability and long-term sustainability of aquaculture systems. This study aimed to evaluate the economic feasibility and the risk associated with Nile tilapia juvenile production in a BFT system. Economic viability indicators were calculated using real data on capital investment, operational costs, and zootechnical performance from a production cycle. Scenario analyses were conducted to assess the effects of fluctuations in input prices and survival rates on overall economic outcomes. Stochastic simulations were also conducted to determine the probabilities of economic results. The items with the greatest impact on costs were the acquisition of the greenhouse and fingerlings, representing 27.64% of the initial investment and 33.24% of the operating cost, respectively. The BFT system showed a positive net margin and profitability per production cycle, with the exception of the pessimistic scenario. The risk analysis demonstrated that in 87.29% of the simulations resulted in a positive profit. Thus, the production of tilapia juveniles in a BFT system is an economically viable investment. However, its success is contingent upon specific technical and market conditions, underscoring the need for careful management and context-specific planning.

Keywords: fish farming; *Oreochromis niloticus*; profit; stochastic simulation

Academic Editor: Aires Oliva-Teles

Received: 2 April 2025
Revised: 21 May 2025
Accepted: 13 June 2025
Published: 17 June 2025

Citation: Bezerra, G.A.; Pires, D.C.; Watanabe, A.L.; Buglione Neto, C.C.; Cardoso, A.J.d.S.; Simões, A.R.P.; Hisano, H. Economic Feasibility and Risk Analysis of Nile Tilapia Juveniles Reared in a Biofloc Technology System. *Aquac. J.* **2025**, *5*, 9. https://doi.org/10.3390/aquacj5020009

1. Introduction

According to the Food and Agriculture Organization of the United Nations, global aquaculture production reached approximately 130.9 million tons in 2022, with an economic value of USD 312.8 billion, and represented 59% of global fisheries and aquaculture production [1]. Due to the stagnation of fisheries caused by the overexploitation of natural stocks, aquaculture has assumed an important role in meeting the growing worldwide demand for aquatic animals, achieving an average growth rate of 5.0% per year from 2000 to 2022, highlighting its significance in food and nutritional security [1].

Nile tilapia *Oreochromis niloticus* is a highly valuable species and one of the most cultured in the tropical and subtropical regions, prized for its notable rusticity, ease of management and reproduction, rapid growth, adaptation to various environments and high stocking densities, and good market acceptance due to the high nutritional and organoleptic quality of its filet [2,3]. Tilapia was highlighted as the fourth most cultivated species in global aquaculture in 2022, with a production of 5.3 million tons [1]. In Brazil, Nile tilapia accounted for 68.36% of the total farmed fish production in 2024, exceeding 662 thousand tons, with the highest production concentrated in the southern region of the country [4].

To meet the increasing demand for safe and high-quality fish, aquaculture must adopt production systems that allow higher densities, maintain water quality at acceptable levels, ensure optimal zootechnical performance, and address biosecurity and environmental concerns [5]. The biofloc technology system (BFT) meets these requirements due to its high water efficiency, reducing water consumption by more than 90% and significantly decreasing effluent discharge into the environment [6–8]. Moreover, BFT also maintains water quality at adequate levels, and can achieve high productivity (30 kg/m^3) and survival rates approaching 100% [9–11].

The use of tilapia juveniles for initial stocking, especially in net cages, is a growing trend in Brazil. The production of tilapia juveniles represents an underexplored market segment that offers several advantages, including the possibility of early vaccination, a shortened production cycle, reduced mortality rates, and improved population uniformity [12]. Additionally, early-stage tilapia uses natural food sources, particularly beneficial in BFT systems, where microbial biomass can contain up to 40% crude protein, serving as a supplementary feed source and potentially reducing feed costs [13].

Economic analysis is essential for fish farmers to assess risks and compare the viability of different production systems [14]. However, few studies assess the economic aspects and associated risks of activity, complicating decision-making for fish farmers. Market volatility and environmental unpredictability further exacerbate investment uncertainties, particularly when adopting new technologies. Therefore, it is essential to consider the risks of the main variables that may affect the project and their probability of occurrence [15], identifying them and creating strategies to minimize risks [16]. Risk analysis using the Monte Carlo method addresses these uncertainties by quantifying risks through stochastic modeling [17]. This approach generates pseudo-random numbers based on predefined probability distributions derived from historical data, allowing for a more accurate and comprehensive risk assessment by simultaneously evaluating multiple economic indicators [18].

Despite advances in the use of the BFT system, there is still a lack of studies specifically assessing the economic viability of juvenile production, particularly when combined with risk analysis. Most existing research focuses on the grow-out phase or adopts simplified approaches that do not adequately account for the uncertainties inherent to aquaculture activities. Evaluating the economic feasibility and associated risks of BFT systems is essential, not only to support informed decision-making by local fish farmers, but also to guide global strategies aimed at promoting sustainable food systems, enhancing aquaculture resilience, and advancing responsible aquatic resource management. Given these considerations, this study aimed to evaluate the economic viability and associated risks of Nile tilapia juvenile production in a biofloc technology (BFT) system.

2. Materials and Methods

The values related to the initial investment, production costs, and zootechnical performance data were provided by Itaipu Binacional, located in Foz do Iguaçu, Paraná State, southern Brazil, where the study was conducted. Sixty thousand male Nile tilapia fingerlings, with an average initial weight of 5 g and a density of 750 fish/m^3, were cultivated in the BFT system. The BFT module consisted of an 80 m^3 circular tank housed under a 144 m^2

greenhouse, equipped with an aeration system powered by a 0.38 hp radial compressor, 2000 L solids settling filter, and an energy generator system.

Each day, temperature and dissolved oxygen were monitored using a multiparameter probe (YSI Professional Plus®, Yellow Springs, OH, USA); total ammonia, nitrite, nitrate, and alkalinity levels were monitored using a spectrophotometer and commercial kit (Hanna Instruments®, Woonsocket, RI, USA); pH was measured with a benchtop pH meter (Digimed®, São Paulo, SP, Brazil); and the volume of settleable solids was analyzed using an Imhoff cone. These water quality variables remained at adequate levels for Nile tilapia cultivation in the BFT system [6,10,12,13], with the following mean values ± standard deviations observed during the production period: temperature, 24.39 ± 2.32 °C; dissolved oxygen, 4.65 ± 1.11 mg/L; total ammonia, 0.91 ± 1.17 mg/L; nitrite, 9.73 ± 5.90 mg/L; nitrate, 16.83 ± 15.59 mg/L; pH, 7.33 ± 0.42; alkalinity, 185.98 ± 88.53 mg/L; and settleable solids, 40.27 ± 11.19 mL/L. During the cycle, there was no water renewal, only the replacement of water lost through evaporation.

A 60-day production cycle was performed during July and August 2018. A stabilized biofloc was utilized, with cane sugar serving as the carbon source, applied as necessary based on the total ammonia content analyzed [19]. A commercial diet containing 40% crude protein, 8% ether extract, 14% ash, and 6% crude fiber (Guabi Nutrição e Saúde Animal S.A., Campinas, Brazil) was used for fish feeding. The feeding frequency was set at four times daily at a rate of 2–3% of biomass. Biweekly, biometrics were performed to adjust the feeding rate. Harvesting was carried out when the fish reached an average commercial weight of 27 g.

The economic viability indicators were determined [20] to characterize the economic profile of the activity. The following cost and revenue items were determined and evaluated:

Total Revenue (TR): composed of all monetary entries from the sale of animals;

Effective Operating Cost (EOC): corresponds to direct expenses for the purchase of inputs and the interest rate on working capital;

Total Operating Cost (TOC): adding to the EOC, depreciation, and pro labore;

Total Cost (TC): determined by adding the remuneration of the average invested capital (capital opportunity cost) to the TOC.

Based on these cost and revenue structures, the following indicators for economic evaluation were used:

Gross Margin (GM): TC−EOC;

Net Margin (NM): TR−TOC;

Profit (P): TR−TC.

Labor costs were based on a permanent employee responsible for all operational activities, with a proportional remuneration of USD 478.44 per month (working eight hours a day; USD 1 = 5.35 Brazilian Real—BRL, quote for 10 June 2024). The pro labore remuneration was defined as 5% of the total monthly gross revenue.

Depreciation was determined by the durability of equipment and materials recommended by the manufacturer, using the linear method with a residual value equal to zero. Interest on working capital and the opportunity cost of fixed capital were set at 6% per year based on the basic interest rate in Brazil.

In addition to the observed results (realistic scenario), alternative scenarios (pessimistic and optimistic) were generated based on the economic viability indicators, considering variations in the prices of the most relevant inputs of the production system [14,21]. Scenario analysis is essential for capturing the variability in input prices, animal survival rates, and sale prices—factors influenced by market fluctuations and production risks. This approach enables the assessment of the biofloc system's resilience under different conditions, providing an estimate of the potential range of financial outcomes. Thus, calculating the pessimistic and optimistic scenarios is important to evaluate the economic robustness and potential variability of the BFT system under different production and market conditions. The pessimistic scenario was characterized by a 20% increase in costs for the acquisition of animals and feed, a 20% reduction in the sale price, and a survival rate of 60%. The optimistic scenario was characterized by a 20% reduction in costs for the acquisition of animals and feed, a 20% increase in the sale price, and a survival rate of 100%.

For the risk analysis, two thousand iterations were simulated using the Monte Carlo method [22], implemented in the free software R version 4.4.0 [23]. Due to the absence of a historical time series of prices of input variables, the coefficient of variation of 20% and the uniform distribution of probability was used. The input variables used were fish acquisition costs, feed, and selling price, and a survival rate variation of between 60% and 100%, based on the previous literature [14,21]. Profit was the variable used to assess the risk analysis, with regard to direct and indirect costs.

3. Results

The initial investment for the production system of tilapia juveniles in a BFT was estimated at USD 9632.55, with the largest expense being the greenhouse implementation, accounting for 27.64% of the total cost (Table 1). The zootechnical performance variables are presented in Table 2.

Table 1. Initial investments for the juvenile tilapia culture in biofloc technology system.

Items	Value (USD)	(%)	Life Cycle (Years)
Structures			
Land (144 m^2)	425.00	4.41	-
Greenhouse (12 × 12 m; 144 m^2)	2662.06	27.64	10
Circular tank (80 m^3)	1373.83	14.26	5
Equipment			
Cleaning system [a]	1198.88	12.45	10
Power generator (6 kva three-phase)	1444.67	15.00	10
Submersible pump	171.21	1.78	10
Aeration system [b]	735.14	7.63	10
Digital oximeter	333.44	3.46	5
PPE [c]	75.85	0.79	1
Balance	46.73	0.49	10
Fishing tackle [d]	204.45	2.13	2
Documentation			
Licensing [e]	961.29	9.98	-
Total	9632.55	100.00	

[a] Filter 2000 L, tubular drainage system, and solids settling tank; [b] 0.38 hp radial compressor and 1.5 hp three-phase fountain aerator; [c] Personal Protective Equipment: Two waterproof fishing suits and two pairs of PVC boots; [d] 2 units of fishing nets (10 m length and 12 mm mesh), and 2 units of biometric nets (2.5 m length and 8 mm mesh); [e] Environmental licensing and granting of water use. Currency conversion: USD 1 = BRL 5.35.

Table 2. Zootechnical indicators of production of juvenile tilapia in biofloc technology system.

Indicators	Unit	Value
Initial number of fish	fish	60,000
Starting average weight	g	5
Final average weight	g	27
Density	fish/m^3	750

Table 2. *Cont.*

Indicators	Unit	Value
Initial productivity	kg/m^3	3.75
Final productivity	kg/m^3	16.18
Survival	%	80
Average weight gain	g	22
Gain in biomass	kg	994.38
Feed consumption	kg	1124
Feed conversion rate	-	1.13

The production of tilapia juveniles in a BFT system proved to be economically viable (Table 3). In terms of activity costs, the acquisition of fingerlings represented one-third of the expenses per cycle. Furthermore, the production cycle demonstrated short-term viability (GM > 0), long-term viability (NM > 0), and economically attractive values ($p > 0$) when compared to the opportunity cost of 6% per year.

Table 3. Economic evaluation of the production of juvenile tilapia in a biofloc technology.

	Unit	Quantity	Value (USD)	(%)
Fingerlings	Fish	60,000	2242.99	33.24
Feed	kg	1124	1512.67	22.42
Energy	kWh	1.49	100.63	1.49
Agricultural lime	kg	112.40	18.91	0.28
Labor	Employee	1	478.44	7.09
Source of carbon (Sugar)	kg	56.2	25.31	0.38
Sea salt	kg	240	50.22	0.74
Water analysis	Kit	1	50.45	0.75
Technical assistance	Month	2	299.07	4.43
Interest (working capital)			28.97	0.43
EOC			4807.67	-
Depreciation			190.90	2.83
Pro labore	Month	2	1702.54	25.23
TOC			6701.11	-
Opportunity cost			47.12	0.70
TC			6748.24	100.00
Final production	kg		241.94	-
Sale price	USD/kg		6.58	-
Total revenue	USD/cycle		8512.71	-
Gross margin (GM)			3705.04	-
Net margin (NM)			1811.60	-
Profit (P)			1764.47	-

EOC, Effective Operating Cost; TOC, Total Operating Cost; TC, Total Cost. Currency conversion: USD 1 = BRL 5.35.

The reduction in total revenue and survival rate, combined with increased costs, rendered the activity unviable under the pessimistic scenario due to the negative net margin and profit (Table 4). However, the optimistic scenario showed that the increased productivity resulting from higher survival rates and total revenue, along with reduced total costs, led to a 284.74% increase in profit compared to the deterministic results (Table 4).

Table 4. Different scenarios in the production of juvenile tilapia in a biofloc technology system.

	Pessimistic	Realistic	Optimistic
		USD	
Total Revenue (TR)	5114.02	8590.44	12,785.05
Effective Operating Cost (EOC)	5106.71	4798.15	4056.54
Total Operating Cost (TOC)	7000.15	6691.59	5949.98
Total Cost (TC)	7047.27	6738.71	5997.10
Gross Margin (GM)	7.31	3792.29	8728.51
Net Margin (NM)	−1886.13	1898.85	6835.07
Profit (P)	−1933.25	1851.73	6787.94

Currency conversion: USD 1 = BRL 5.35.

The probability of negative profit was 12.71% based on the 2000 iterations performed by the Monte Carlo simulation (Figure 1).

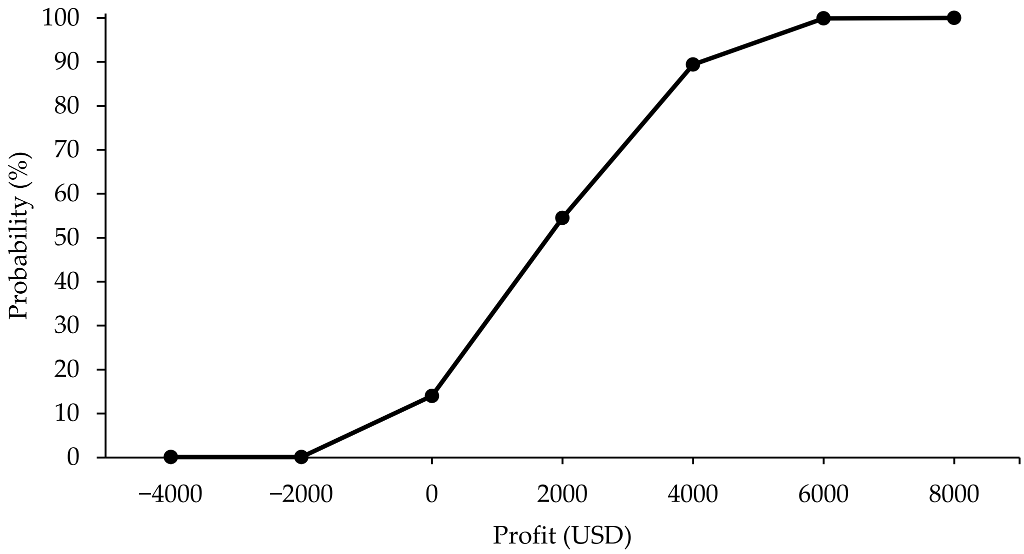

Figure 1. Accumulated probability distribution of profit for the production of juvenile tilapia in a biofloc technology. Currency conversion: USD 1 = BRL 5.35.

4. Discussion

To the best of our knowledge, this is one of the first studies to assess the economic viability and risk analysis of Nile tilapia juvenile production in biofloc systems, offering relevant practical insights. By quantifying costs, risks, and profits across different scenarios, the study demonstrates the economic feasibility of the activity and identifies the main factors influencing profitability, contributing to reduced uncertainty and improved production planning.

The climatic conditions of Foz do Iguaçu, Paraná State, Brazil, where the study was conducted, feature an annual average temperature of 21.29 °C, dropping to 16.93 °C during autumn and winter (Brazilian National Institute of Meteorology). These conditions justify the use of greenhouses for maintaining water temperature, ensuring uninterrupted production during colder months. However, the high implementation cost of greenhouses may limit new investments, particularly for small-scale farmers.

In tropical climates, greenhouse structures are not strictly required, but their absence may prolong production cycles, necessitating a cost–benefit risk assessment by farmers. Conversely, in regions with mean annual temperatures exceeding 25 °C, greenhouse use is unnecessary, substantially reducing initial investments and operational costs for juvenile production in biofloc technology (BFT) systems.

The most significant operating cost was fingerlings acquisition (33.24% of total expenses), followed by feed (22.42%). These findings corroborate [24], who reported fingerling costs as the primary expense (46.13%) in milkfish (*Chanos chanos*) production, while feed and carbon sources accounted for 6.37% and 3.72%, respectively. Similarly, fingerlings and feed contributed 42% and 38.2% of costs in the economic viability study of tilapia juvenile production in earthen ponds [25].

The activity demonstrated short-term economic viability, covering all operational costs and yielding a positive gross margin per cycle. The net margin indicated that the activity provided a monetary return capable of covering depreciation expenses and the opportunity cost of labor, showing long-term viability as well. The production profit of tilapia juveniles in a BFT was positive, indicating economic attractiveness since the income covered all costs and provided a return on invested capital at a rate higher than the opportunity cost. Enterprises with larger production scales can achieve higher net margins and profits [26], as these indicators improve with increased physical structure and labor. This pattern is commonly observed in large-scale aquaculture enterprises in major fish-producing countries, which benefit from economies of scale. This highlights the importance of expansion strategies to enhance the sector's competitiveness.

Scenario analysis revealed an economic break-even point, with risk assessment indicating only a 12.71% probability of financial loss, suggesting a high likelihood of profitability. These results are consistent with [18], who reported a 13.6% risk of loss in cage-based tilapia farming, and [27], who observed a 10% loss probability in BFT shrimp production. This type of risk modeling is particularly useful for investors and producers operating in regions with high variability in input prices or commercial instability, as it enables the evaluation of scenarios and the adoption of more resilient strategies.

Survival rates are critical for aquaculture success, particularly in BFT systems, where continuous aeration is essential. In a BFT system, fish survival depends mainly on constant aeration provided by electric aerators, and a power outage coupled with improper generator operation could lead to fish mortality. Although this event was not tested in our simulations, it would likely affect the systems, following an exponential probability distribution. Therefore, future studies are needed to incorporate contingency scenarios using advanced risk modeling techniques to better capture the full range of vulnerabilities in intensive systems. Outside of these exceptional cases, studies using BFT show that high survival rates are achievable, reducing one of the most significant risks. The survival rate proposed in the optimistic scenario corroborates the results of the study by [10] with juvenile tilapia in BFT with a survival rate of 100% in 60 days. Conversely, stochastic simulation is essential for data interpretation, as it enables fish farmers to make informed decisions while minimizing risk [28].

The results showed the activity's viability in both the real situation and in the optimistic scenarios. Fish farmers should be aware of this and assess market conditions and their production systems to achieve greater profitability and efficiency. On the other hand, it may be considered that the results obtained in this study were conservative since the production cycle occurred from July to August (winter), which slowed fish growth due to lower temperatures and reduced metabolism and feed consumption. In warmer temperatures (spring–summer), the life cycle period to reach the same weight would be shorter.

Variations in feed prices, marketing prices, and other important inputs might cause abrupt economic fluctuations, resulting in financial instability, and potentially making the activity unfeasible in the long run [29]. This is consistent with the data observed in this study through the pessimistic scenario and the Monte Carlo simulation.

Furthermore, studies conducted under laboratory conditions indicate that it is feasible to produce tilapia juveniles in a BFT at an initial density of 1250 fish/m^3 with a 96% survival rate and final biomass from 15.12 kg/m^3 [8] up to 37 kg/m^3 [9]. Due to the use of a biofloc as a complementary food, it is possible to reduce dietary crude protein from 36% to 28% without losses in growth performance [30]. The cost reduction with the use of lower protein levels is also relevant, since feed is one of the most representative items for defining the total cost. If fish farmers breed tilapia on their farms, they might be able to supply the demand for fingerlings and reduce expenses, as fingerling acquisition is the most significant cost. There is potential for improvement in productivity, shorter cycles, and cost reduction for juveniles reared in a BFT, further enhancing the economic indices.

It is recommended for fish farming to adopt systems that enable higher productivity and sustainability [5]. The BFT system offers a solution to some of modern aquaculture's main problems, such as water consumption, land use, and feed costs [24]. Tilapia juveniles cultured in ponds can generate a consumption of 35,000 L of water per kilogram produced [31,32]. Conversely, tilapia reared in a BFT reduces this demand by up to 12 times [8], making it a viable option in regions with limited water use.

Another significant advantage of BFT is the smaller area required compared to traditional pond systems due to higher productivity. Furthermore, this allows their installation in various modules, providing greater convenience and proximity to urban centers. In comparative terms, the present study used 50 m^2 of water surface to produce 60,000 tilapia juveniles whereas [25] used 1250 m^2 to produce 30,000 juveniles.

The results of the present study provide valuable information, demonstrating that management and decision-making processes can be significantly improved with accurate and contextualized information through scenario simulation techniques and risk determination. It is important to emphasize that BFT enables a reduction in water and land use, contributing to the sustainable development of aquaculture.

One of the major demands for conducting our study was the scarcity of economic analyses focused on tilapia production in BFT systems. Although this study was focused on a local context, the data generated can serve as an initial reference for similar analyses and are largely applicable to other production settings worldwide with different climatic and culture conditions, contributing to a broader understanding of the economic viability of BFT in tilapia farming. Furthermore, the economic variable definitions were based on a commercial-scale production cycle, ensuring realism over idealized laboratory models.

The scenario analysis highlighted the potential financial risks associated with input costs and zootechnical performance, while stochastic modeling indicated an 87.29% probability of profitability. These results suggest that Nile tilapia juvenile production in a BFT system is economically viable, offering advantages in resource-use efficiency, biosecurity, and scalability potential. However, as demonstrated in the scenario analysis, system performance is closely linked to factors such as survival rate, feed cost, and the sale price of fingerlings—variables that are influenced by market fluctuations and operational challenges. Furthermore, BFT system success depends on specific technical conditions and market stability, which may not always be guaranteed. Consequently, careful management and context-specific planning are essential to fully realize the potential benefits of the BFT system.

Author Contributions: Conceptualization and methodology: H.H., G.A.B. and A.R.P.S.; data collection and formal analysis: H.H., G.A.B., A.R.P.S., D.C.P. and C.C.B.N.; resources: H.H. and A.L.W.; writing—review and editing: H.H., G.A.B., A.J.d.S.C., A.R.P.S., D.C.P., A.L.W. and C.C.B.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by and Itaipu Binacional and Brazilian Agricultural Research Corporation—EMBRAPA.

Institutional Review Board Statement: Ethical review and approval were waived for this study due to regulations of Brazil's National Council for the Control of Animal Experimentation (CONCEA), zootechnical practices, such as commercial production cycle in livestock and aquaculture are not considered research activities, and therefore do not require ethics committee approval.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors are grateful to *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* (CAPES/Brazil) for granting a scholarship to the first author (Finance Code 001).

Conflicts of Interest: The authors declare no conflicts of interest.

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