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Economic Analysis of Red Tilapia (*Oreochromis* sp.) Production Under Different Solar Energy Alternatives in a Commercial Biofloc System in Colombia †

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Abstract: The study investigates the economic aspects of red tilapia (*Oreochromis* sp.) production using biofloc technology under different electrical energy sources. Conducted at the El Vergel Fish Farming Association in Arauca, Colombia, the study examines four energy treatments: conventional energy (CE), combined conventional and photovoltaic energy (CPVE), full photovoltaic energy (PVE), and simulation of photovoltaic energy generating surplus for nighttime use (PVES). The water quality and zootechnical performance met the species requirements, with dissolved oxygen decreasing as fish size increased. The PVE treatment had the highest initial investment due to solar panels and battery costs, but it also had the lowest operating energy costs. However, the overall costs of the PVE treatment increased due to depreciation and maintenance. Feed was the largest production cost, followed by labor in most treatments, while depreciation was a major cost for the PVE treatment. The total operating cost (TOC) of the photovoltaic energy systems (PVE and PVES) was lower compared to that of conventional energy (CE), with PVES showing the highest cost savings. The reduction in energy costs highlights the potential for solar energy systems to enhance the economic viability of aquaculture production, making these systems a favorable option for sustainable production in the long term.

Keywords: photovoltaic energy; BFT; solar panels; aquaculture; selling price

Key Contribution: This study demonstrates that incorporating solar energy into red tilapia biofloc systems reduces operating energy costs but increases initial and depreciation expenses. Economic viability depends on enhancing sales prices to offset higher production costs. The research underscores the need to align sustainable energy adoption with market strategies in aquaculture.

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1. Introduction

In recent decades, aquaculture has become the best option for providing aquatic-derived protein [1]. The FAO has reported the aquaculture production of 466 individual species worldwide, including tilapia [2]. By 2030, tilapia production is expected to double that of 2010 [3]. Efficient use of resources [4], development of sustainable and environment friendly aquaculture systems [5], and building systems that provide an equitable cost/benefit ratio to support economic and social sustainability are required to improve production [4]. According to Crab et al. (2012), biofloc technology (BFT) meets these requirements for the sustainable development of aquaculture [6].

BFT is an aquaculture production system based on efficiently using nutrients with minimum or zero water exchange [7]. It involves food waste and toxic organic and inorganic compounds recycled by microorganisms present in the water, thus providing favorable conditions for chemoautotrophic, autotrophic, and heterotrophic bacteria to reduce the saturation of nutrients, making them available for reuse by fish [4]. Further, this technology depends on factors that are not considered in other systems, such as carbon sources to stimulate the growth of heterotrophic communities [8] and electrical energy for the operation of aerators [9] used to maintain dissolved oxygen levels and turbulence.

The BFT system was originally used to produce different Penaeid species such as *Penaeus monodon*, *Fenneropenaeus merguiensis*, and *Litopenaeus vannamei* [10]. The BFT system is extensively studied in white shrimp (*L. vannamei*) production [11], including the analysis of bioeconomy indicators to assess the system's economic viability in shrimp production [12], and productive integration studies of white shrimp and Nile tilapia [13]. However, further studies are required to prove the technical and economic viability of the BFT system for red tilapia in monoculture.

Fuel and electricity are the main power sources used to produce aquatic organisms [14]. They are used for pumping water, cooling, processing, and aeration [15–17]. Power costs depend on the regional location of the system. Electrical power consumption is directly proportional to the intensification of production and the technology used [18], and it contributes to the environmental impact of aquaculture [17]. Electrical power use can put the viability of production systems at financial risk because of the increase and instability of power prices [19,20].

Electricity bills account for 10–25% production costs in systems with electricity-intensive load [18,21], especially in the recirculating aquaculture system (RAS). Oxygenation equipment in RAS consumes 20% of the total power used [22] and adds 5% to the final product cost per kilogram [15]. Kubitza (2011) reported that the cost of electrical power in BFT systems in Brazil could account for up to 15% of the production costs [23]. Another study conducted in Brazil has reported that the power used for aeration represents 11.96% of the production costs for Nile tilapia (*Oreochromis niloticus*) production in a BFT system with 1000 L tanks [24]. In Mexico, although the government provides a subsidy to a part of the electricity used for aquaculture production, implementation of the BFT system is limited by the cost of electricity bills [25]. Experimental projects with *Piaractus brachypomus* and *O. niloticus* using BFT in Colombia have reported that electrical power represents between 10% and 14% of the production costs [26].

In aquaculture, different energy sources have been proposed for use according to the availability of resources in each country and the technologies developed [15]. An example of this is the use of geothermal power in systems for catfish production in countries such as Iceland [27] and Egypt [28]. The residual heat from thermoelectric or hydroelectric energy is used for aquatic organisms [15,29]. In addition, biogas is recommended for useful power in this activity [30]. There are limited studies on the use of biomass, wind, or tidal power in fish farming [31]. Photovoltaic power is proposed as an alternative in aquacultures [18,30,32], and is studied in tilapia hatcheries [33], recirculation systems [34], and marine fish production [35].

Collazos-Lasso and Arias-Castellanos have suggested that studies on the BFT system should be conducted under specific conditions of each country, and the production costs, especially the costs of electricity, should be calculated in detail [36]. Thus, from an economic standpoint, this study aimed to analyze red tilapia production in a BFT system using conventional electrical (hydroelectric) energy and to determine whether photovoltaic energy, with its variations, can improve the economic viability of the activity.

This study proposes three alternatives to conventional electrical (CE) energy: combined conventional and photovoltaic energy (CPVE), full photovoltaic energy (PVE), and photovoltaic energy generating surplus for night-time use (PVES). CPVE utilizes photovoltaic energy during the day and conventional electricity at night, reducing costs by 40% but still relying on the grid at night. PVE is fully independent, relying on solar panels and batteries, eliminating electricity costs but requiring high upfront investment and ongoing maintenance due to battery depreciation. PVES generates enough photovoltaic energy for both day and night, selling the surplus during the day to cover nighttime usage, avoiding the need for batteries but still depending on the grid during outages.

2. Materials and Methods

2.1. Production System

The study was conducted under field conditions, without disturbing the production process, at the facilities of El Vergel Fish Farming Association (ASOVERGEL, for its name in Spanish) located in the municipality of Arauquita, Vereda la Arenosa, Colombia, at 6°58′ north latitude and 71°07′ longitude, at 143 m above mean sea level.

The production system included nine circular tanks (143 m^3), each with an independent supply and aeration system (Figure 1). Each year, 1.7 production cycles are performed with an average density of 6500 fish per tank (45.4 fish/m^3). The red tilapia (*Oreochromis* sp.) used weighed 5 ± 0.2 g each and were previously masculinized with 17 alpha methyltestosterone. Aeration was constant during the study that was provided by radial splash aerators (1.5 hp) connected to the electrical power sources under study, the tanks were independently equipped with an aerator. For pH maintenance, 25 g/m^3/day1 calcium hydroxide was added when the values fell below 6.5 [24]. For the maintenance and control of nitrogen compound levels, liquid molasses (50% carbon) was used at a C:N ratio of 6:1 when ammonium values exceeded 1 mg/L [37].

Figure 1. Image of the production system, high-density polyethylene (HDPE) geomembrane tanks, and photovoltaic system.

Feeding was performed according to the feed manufacturer's instructions, starting with 40% protein powdered feed and ending with 20% protein pelleted feed. The food management is described as follows: During the first 6 weeks, tilapia weighing 20–28 g were fed a diet containing 40% crude protein (CP) at 7.1% of their body weight, with nine daily feedings. In weeks 7–13, as the fish grew to 100–120 g, the protein content was reduced to 34% CP, with a feeding rate of 3.6% and six feedings per day. From weeks 14–19, when the fish weighed 220–245 g, the protein content decreased to 30% CP, with 2.3% of their body weight fed five times daily. During weeks 20–25, at a weight of 370–395 g, the feed contained 24% CP, with a 1.5% feeding rate and four daily feedings. Finally, in weeks 25–30, fish weighing 370–470 g received 20% CP feed at 1.3% of their body weight, with four feedings per day (Table 1).

Table 1. Feed management during red tilapia production cycles.

Weeks	Weight Range (g)	CP * %	Avg. Feeding Rate %	Times
1–6	20–28	40	7.1	9
7–13	100–120	34	3.6	6
14–19	220–245	30	2.3	5
20–25	370–395	24	1.5	4
25–30	370–470	20	1.3	4

* CP = crude protein.

Key elements of publications, such as year, authors, institutions, journals, and most cited articles, were evaluated through a performance analysis, and the data collected from Scopus were processed using Microsoft Excel® to generate charts. The performance analysis allows for defining the main contribution and the significant impacts of these elements in the research field.

2.2. Experimental Design

The following treatments were included in the production cycle under evaluation: tanks with conventional energy (CE), tanks with combined conventional energy/night + photovoltaic energy/day (CPVE), tanks with full photovoltaic energy and batteries (PVE), and a simulation with tanks with energy that generate surplus energy for use at night without batteries (PVES).

1. CE: The source of energy was conventional electricity, 24 h a day throughout the production, provided by the public services company of the Department of Arauca. A fuel generator was used during power outages.
2. CPVE: The source of energy was combined (conventional and photovoltaic). No accumulator batteries were used in this system; therefore, electrical energy consumption was necessary at night. A fuel generator was used during power outages.
3. PVE: A photovoltaic energy source with infrastructure and accumulator batteries was used, thus making the system independent of conventional electric power or fuel generators.
4. PVES: This simulation system used photovoltaic energy connected to a conventional electrical network (on-grid). Solar panels were used to produce sufficient energy to run the system 24 h a day. No accumulator batteries were used; therefore, fuel generators were used during power outages, which are common in the rural areas where the study was conducted.

2.3. Water Quality

Water quality parameters were assessed on a daily basis. Temperature and dissolved oxygen concentration and saturation were measured using an YSI EcoSense® DO200A instrument of the company Xylem Analytics Inc. Yellow Springs, EE. UU. (Yellow Springs, OH, USA) and pH was determined using a Hanna Instruments® meter (Model 991300) of the company Hanna Instruments, Limena, Italy. Ammonium, nitrite, nitrate, and alkalinity were monitored weekly using an HI83300 photometer of the company Hanna Instruments, Limena, Italy, and the specific reagents for each parameter from HANNA Instruments® of the company Hanna Instruments, Limena, Italy. The volume of settleable solids (SS) was measured weekly by filling an Imhoff cone with a water sample and allowing the sample to settle for 15–30 min. After the settling period, the volume of settled solids was recorded in milliliter per liter, providing an assessment of the solids concentration in the sample.

2.4. Performance

The performance was analyzed in biometrics conducted at the beginning and harvest. All animals were weighed in groups, counted to calculate the survival, and final biomass was also calculated. Food intake by each group was recorded. The following equations were used for the zootechnical performance analysis:

Survival (S)%: The percentage of individuals who survived until the end of each evaluation period.

$$(S)\% = \frac{FNI}{INI} \times 100$$

where FNI is the final number of individuals in a given period and INI the initial number of individuals stocked in the tank.

Average weight gain (AWG) (g) in fish refers to the mean increase in body mass over a specific period. This performance indicator is evaluated with the following equation:

$$AWG = FAW\ g - IAW\ g$$

where FAW is the final average weight and IAW is the initial average weight.

Average food intake (AFI) g/day represents the mean quantity of feed consumed by an individual or group of fish over a set period, usually measured in grams per day.

$$AFI = \frac{TFI\ g}{NI}$$

where TFI is the total food intake (g) and NI is the number of individuals.

Apparent feed conversion ratio (FCR) between AFI and AWG is the ratio of feed consumed to the weight gained, used to assess the efficiency of feed utilization in aquaculture production. The equation used to calculate the FCR is:

$$FCR = \frac{AFI\ kg}{AWG\ kg}$$

where AFI is average food intake and AWG is average weight gain.

Final biomass (B) (kg) refers to the total weight of a population of fish at the end of a rearing or production period, and is calculated with the following equation:

$$B = FNI \times FAW$$

where FNI is the final number of individuals and FAW is final average weight.

2.5. Economic Analysis

For the economic analysis, the production data obtained from the production cycles evaluated and the production models of the ASOVERGEL fish farm were used. Each treatment included three tanks, for a total of nine tanks of 143 m^3, each equipped with radial splash aerators (1.5 hp). After obtaining the results, a financial projection and economic analysis was carried out for 6 tanks per treatment, each equipped with radial splash aerators (1.5 hp). The farm had a water use permit; the water resource came from the Matapalito River. Conventional electricity was provided by the public services company of the Department of Arauca. In addition, the fish farm had a 48 kVA fuel generator. Commonly used infrastructure included a 20 m^2 warehouse, a 9.5 m^2 office, and a 10 m^2 bedroom.

The production data used for the economic analysis were obtained from three production cycles of monosex red tilapia. To obtain the fixed capital needed to start the activities, an inventory of the fish farm was made including tanks, aerators, support equipment, common use infrastructure, and an electrical power system. The ratio of the capital invested in the tanks to the other investment items as well as the investment per m^3 was determined. The hiring of two specialized professionals and two field technicians responsible for the daily tasks was also included in the analysis. The final product was marketed directly to the distributor, with no intermediaries for the sale of the fish.

With the performance parameters, costs of production factors and prices of fresh fish marketed, production costs and profitability indexes were calculated. The costs were obtained based on the Total Operating Cost (TOC) structure [38], by adding the Effective Operating Cost (EOC) with depreciation. In the EOC, the costs of fry, feed, hired labor, maintenance of fixed capital, electrical power in cases where electrical power was used, fuel and inputs for the development of the BFT system were added. For this study, the value of Kw/h of 0.17 was considered, as were the monthly billing reports from the electrical energy service provider. The depreciation of infrastructure, equipment, and utensils was calculated using the linear method [39].

The economic indicators were determined using the method proposed by Martin et al. and Costa et al. Implementation investment, TOC, unit costs or average costs, gross revenue, operating profit = gross revenue − TOC and profit index = operating profit/gross profit × 100 [39,40].

To determine profitability, operating profit, and profit index, the percentage of fresh fish destined for wholesale trade was considered. The investment values were corrected by the general price index (exchange rate: 3924 Colombian pesos = 1.00 US dollar in January 2024, reference month for all prices).

The cash flow was elaborated over a 10-year horizon using fixed capital and outflows. The minimum attractiveness rate of return (MARR) was 5% and was determined by the highest value of a certificate of deposit offered by banks in Colombia. The outflows considered were investment in fixed capital to start the process, reinvestments in fixed capital over the horizon, operating cost, and working capital. The inflows included were gross profit on the sale of fresh fish, residual value, and working capital. The implementation of the project was considered as the initial time. Economic viability indicators such as net present value, internal rate of return, and simple and economic payback period were calculated from the cash flow [12,41].

The net present value (NPV) is calculated to assess the viability of investment projects [42]. The NPV corresponds to the present value of future payments, discounted at an appropriate interest rate, minus the cost of the initial investment. Fundamentally, it is the calculation of the current worth of future payments minus the initial cost [12]. If the NPV is positive, the investment in the project is favorable; on the contrary, if the result is negative, the investment is unviable and this indicates a profitability below the minimum required rate [43].

The NPV was calculated using the following equation:

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{\mathrm{Rt} - \mathrm{Dt}}{(1+\mathrm{i})} + \frac{\mathrm{St}}{(1+\mathrm{i})^{t}} - \mathrm{I}_0$$

where R_t is the revenue for a period $_t$; D_t is the expense for a period $_t$; S_t is the project residual value in the last period; I_0 is the initial investment; i is the MARR.

In addition to the NPV, the internal rate of return (IRR) is one of the most important factors in the calculation of a capital budget [12]. It functions as a tool to evaluate the viability of the investment, allowing to reflect the rate of return of the project [44]. If the IRR is greater than or equal to the minimum attractive rate of return (MARR), the project may be attractive for investment. The IRR has a close relationship with NPV and is a discount rate that makes the NPV equal to 0.

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{\mathrm{Rt} - \mathrm{Dt}}{(1+\mathrm{IRR})^{t}} + \frac{\mathrm{St}}{(1+\mathrm{IRR})^{t}} - \mathrm{I}_0 = 0$$

where R_t is the revenue for a period $_t$; Dt is the expense for a period $_t$, St is the project residual value in the last period; I_0 is the initial investment; IRR is the internal rate of return.

The internal rate of return (IRR) is the discount rate that equates the price of entry to the outlet box. Thus, a project or investment is considered attractive when presenting an IRR greater or equal to "i" (discount rate). It was given by the formula:

$$\sum_{t}^{n} \frac{NCF_t}{(1+i)^t} = 0$$

Payback (PB) is a return period that can be defined as the time needed to recover the amount of initial investment [12]. Entrepreneurs seek profitability in the shortest possible time, increasing profitability and reducing risk [44]. The PB is used as a tool to evaluate the recovery period of the investment [45]. Simple payback as an indicator does not consider that money has "time value", and economical payback is based on a discounted flow and considers that money has "time value".

When cash flow for each period is equal, i.e., effective net inflows are constant, PB can be calculated as follows:

$$\text{Payback} = \frac{I_0}{CF}$$

where I_0 is the initial investment and CF is the cash flow.

PB is not an indicator of project profitability because the PB method is closely aligned with the liquidity that the project represents. The advantages of using the PB method are that it is simple to apply, is easy to understand, adjusts for uncertainty of later cash flow, and is biased towards liquidity [12].

In this case, production, harvest, and commercialization were based on animals with an average weight of 450 g, which was the weight associated with the highest market price for the producer. Fish was sold in its natural state, immediately after harvest and slaughter, and was directly delivered to buyers at the production facilities.

3. Results

3.1. Water Quality

The water quality parameters (Table 2) remained within the normal ranges for the cultivated species and for the BFT system.

Table 2. Water quality parameters during red tilapia production using the biofloc technology (BFT) system under different solar energy alternatives.

Parameter	Treatment		
	CE	**CPVE**	**PVE**
Temperature (°C)	28 ± 2.3	29 ± 1.9	28 ± 2.1
Dissolved oxygen ($mg \cdot L^{-1}$)	5.3 ± 1.5	5.1 ± 2.1	5 ± 1.3
pH	6.4 ± 1	6.2 ± 0.5	6.7 ± 0.5
NH_4-N ($mg \cdot L^{-1}$)	1 ± 0.5	1 ± 0.1	1 ± 0.1
NO_2-N ($mg \cdot L^{-1}$)	0	0.01	0.01
NO_3-N ($mg \cdot L^{-1}$)	0.6 ± 0.1	0.5 ± 0.1	0.5 ± 0.1
Alkalinity (ppm)	139 ± 23	141 ± 19	137 ± 21
SS ($mL \cdot L^{-1}$)	39 ± 9	38 ± 10	39 ± 11

BFT, biofloc technology; CE, tanks with conventional energy; CPVE, tanks with combined conventional energy + photovoltaic energy; PVE, tanks with full photovoltaic energy and batteries; NH_4-N, ammonium; NO_2-N, nitrite; NO_3-N, nitrate; SS, settleable solids.

3.2. Productive Performance

The electrical system implemented in the production of red tilapia in the BFT system did not affect the zootechnical performance (Table 3) as well as the production factors. Nevertheless, to avoid compromising fish survival, electrical support equipment was necessary to generate energy to operate the aerators in the CE, CPVE, and PVES systems.

Table 3. Performance of red tilapia cultivated in BFT with different solar energy alternatives.

Treatment	Zootechnical Performance Parameters				
	S%	AWG (g)	AFI (kg)	FCR	TB (kg)
CE	94 ± 1.0	0.430 ± 0.02	0.647 ± 0.002	1.46 ± 0.05	2627
CPVE	94 ± 0.5	0.428 ± 0.02	0.648 ± 0.002	1.51 ± 0.07	2615
PVE	93 ± 0.5	0.435 ± 0.01	0.649 ± 0.005	1.51 ± 0.05	2629.5

BFT, biofloc technology; S, survival; AWG, average weight gain; AFI, average food intake; FCR, apparent feed conversion ratio; and B, total biomass of whole fish (TB). CE, tanks with conventional energy; CPVE, tanks with combined conventional energy + photovoltaic energy; PVE, tanks with full photovoltaic energy and batteries.

3.3. Economic Analysis

The investment costs (Figure 2) for the CE, CPVE, and PVE systems were USD 45,831.39, USD 58,035.91, and USD 147,219.67, respectively. For the simulation PVES system, the investment could reach up to USD 100,690.39. Commonly used infrastructure was the item with the highest percentage share of investment costs for CE and CPVE, 52.29% and 41.29%, respectively. The highest investment for PVE and PVES was in the purchase of photovoltaic electric power systems, USD 103,507.90 and USD 56,978.62, respectively. Moreover, the investment cost in the purchase of splash aerators was between 12.17% and 3.79% in different systems (Table 4).

Table 4. Investment in dollars (USD) for red tilapia production in BFT with different sources of electrical energy.

Item	Useful Life	CE	CPVE	PVE	PVES
Infrastructure	-	11,601.88	11,601.88	19,363.52	11,601.88
Tank	10	10,065.10	10,065.10	10,065.10	10,065.10
Aerators	20	4506.76	4506.76	4506.76	4506.76
Electrical installations	-	9474.21	19,335	110,614.67	53,798.20
Cable	5	210.32	210.32	1156.74	1156.74
Elec.consoles	20	1502.25	1502.25	1502.25	7511.27
Solar panels	20	-	4102.15	9858.54	18,590.39
Inverter	15	-	3004.51	3004.51	6259.39
Frame	20	-	2754.13	9764.65	6259.39
Batteries	5	-		75,112.67	
Regulator	15	-		10,215.32	
Transformer	25	-			6259.39
Fuel generator	20	7761.64	7761.64		7761.64
Others	-	1382.07	1382.07	1382.07	1382.07
Total		37,030.02	46,890.81	145,932.13	81,354

Trading date: 20 January 2024; exchange rate: 3994 Colombian pesos = 1.00 US dollar. BFT, biofloc technology; CE, tanks with conventional energy; CPVE, tanks with combined conventional energy + photovoltaic energy; PVE, tanks with full photovoltaic energy and batteries; PVES, a simulation with tanks with energy that generate surplus energy for use at night without batteries.

The investment value varied depending on the energy system used. Photovoltaic energy storage batteries increased the total investment cost threefold compared to that of production with conventional energy or a partial photovoltaic system. The investment in electrical installations for the PVE system doubled that of the PVES system, although the number of panels purchased for PVES was greater than that for PVE. The batteries cost thrice as much as the panels.

The photovoltaic system reduced the production costs (Table 5). The use of energy storage batteries in the PVE system decreased the total EOC by approximately 7.7% compared to that of the PVES system and by 27.4% compared to that of the CE system (Figure 2).

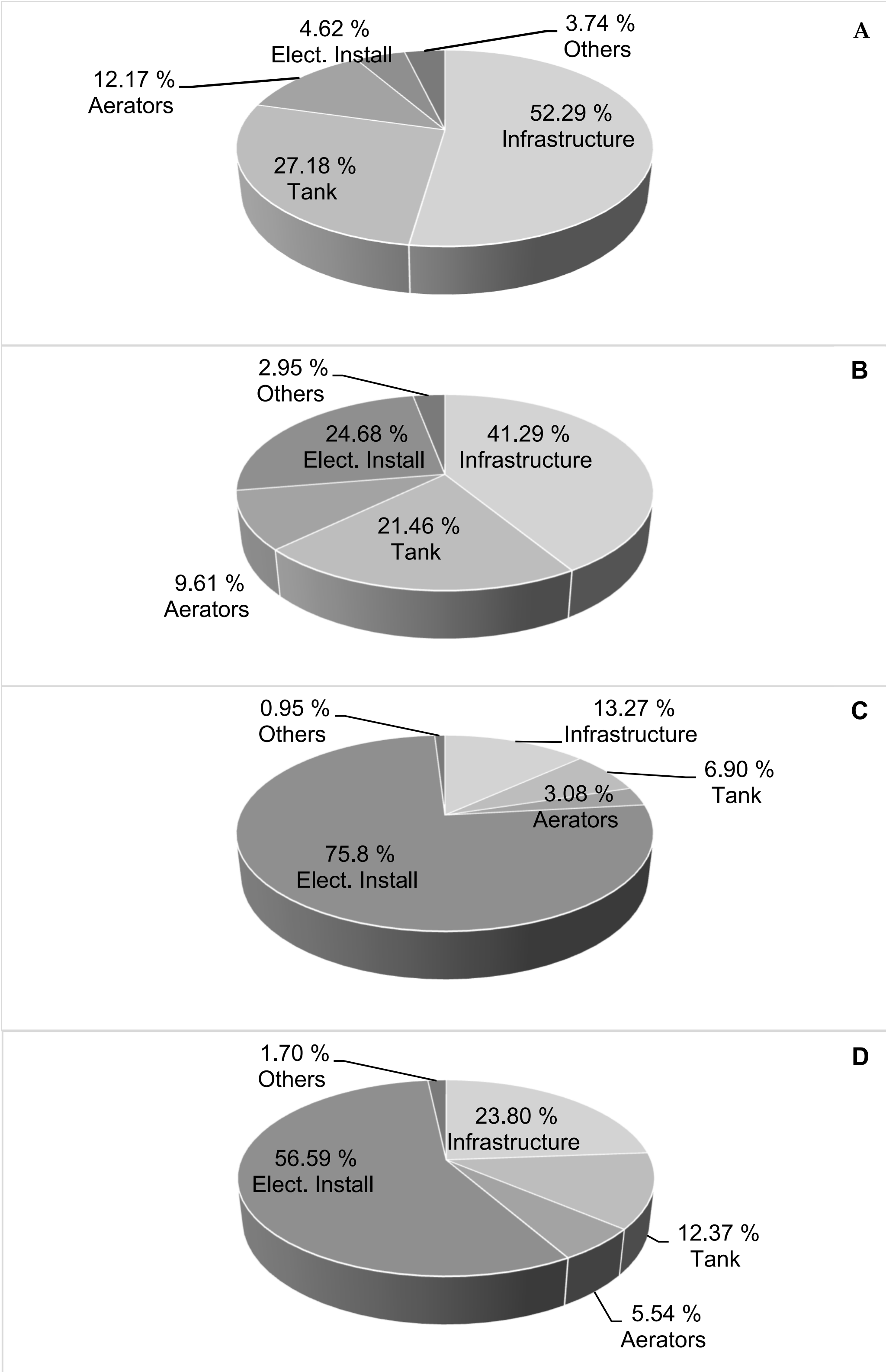

Figure 2. Percentage share of initial investment costs for fish farming in BFT with different sources of electrical energy in the eastern region of Colombia. (**A**) CE, (**B**) CPVE, (**C**) PVE, (**D**) PVES. BFT, biofloc technology; CE, tanks with conventional energy; CPVE, tanks with combined conventional energy + photovoltaic energy; PVE, tanks with full photovoltaic energy and batteries; PVES, a simulation with tanks with energy that generate surplus energy for use at night without batteries.

Table 5. Total operating cost and production indices obtained from the production of red tilapia in BFT with different sources of electrical energy.

Costs	Treatments			
	CE	**CPVE**	**PVE**	**PVES**
Inputs	18,218.68	18,175.37	15,991.76	18,023.20
Food	12,595.66	12,567.20	12,506.00	12,506.00
Cane molasses	1381.65	1351.49	1355.51	1355.51
Calcium hydroxide	713.28	728.61	633.61	633.61
Hypochlorite	71.36	71.36	71.36	71.36
Urea	7.03	7.03	7.03	7.03
Fingerlings	1171.76	1171.76	1171.76	1171.76
H_2O quality reagents	246.50	246.50	246.50	246.50
Fuel	2031.44	2031.44	-	2031.44
Labor	5225.01	5225.01	5225.01	5225.01
Utilities	4908.50	3028.06	210.32	210.32
Power	4698.18	2817.74	-	-
Water	210.32	210.32	210.32	210.32
Maintenance	216.01	273.53	851.27	474.57
EOC	28,568.20	31,926.98	22,278.36	23,933.1
Depreciation	1815.94	2132.76	7336.87	3588.31
Total operating cost	30,384.14	34,059.74	29,615.23	27,521.40
Production (kg·cycle^{-1})	14,229.24	13,767.98	13,673.56	13,673.56
Sales price (USD·kg^{-1})	2.30	2.30	2.30	2.30
Gross income	32,776.42	31,713.94	31,496.42	31,496.42
Gross profit	2392.27	2345.81	1881.19	3975.02
Breakeven point (USD·kg^{-1})	2.14	2.47	2.17	2.01
Breakeven point (K)	13,190.68	14,786.37	12,856.87	11,947.88

BFT, biofloc technology; CE, tanks with conventional energy; CPVE, tanks with combined conventional energy + photovoltaic energy; PVE, tanks with full photovoltaic energy and batteries; PVES, a simulation with tanks with energy that generate surplus energy for use at night without batteries.

The cost of food was 41% for CPVE and 39% for CE and PVE (Figure 3). The highest cost of food in the entire study was observed for the PVES simulation with a 43% share in the production costs. The values were not affected by the energy system implemented for the operation of the aerators.

The specialized labor to implement the BFT system was the second item with the highest share in the production costs, with 20%, on average, for all the electrical energy systems studied.

The cost of water supply was the same for all systems. Electricity billing costs decreased with the implementation of photovoltaic systems. In PVE, the costs of power or fuel were not considered because of the storage batteries. Conversely, those systems without batteries consumed between 6% and 8% of fuel costs due to the use of electric generators during a power outage. This represented 9% and 14% in the CE and CPVE systems, respectively. The maintenance costs were USD 587.36 for PVES and USD 858.78 for PVE. This can be attributed to the equipment installed, whose cost was higher than that of conventional electrical installations. The battery life (5 years) and equipment necessary for PVE represented 26% of the TOC in depreciation, making this system the one with the highest depreciation.

The cash flow, NPV, IRR, and PB results (Table 6) are shown below.

The economic analysis of red tilapia production under different energy systems, as shown in Table 6, demonstrates that the photovoltaic energy system with surplus generation for nighttime use (PVES) offers the most favorable financial outcomes. The PVES system shows a net present value (NPV) of USD 31,735.32, a positive indicator of project viability, as compared to negative NPV in the other systems, particularly the PVE system which suffered a considerable loss with an NPV of USD −79,970.69. The internal rate of return (IRR) for PVES is 9.88%, significantly higher than other systems, particularly CE at 2.06%.

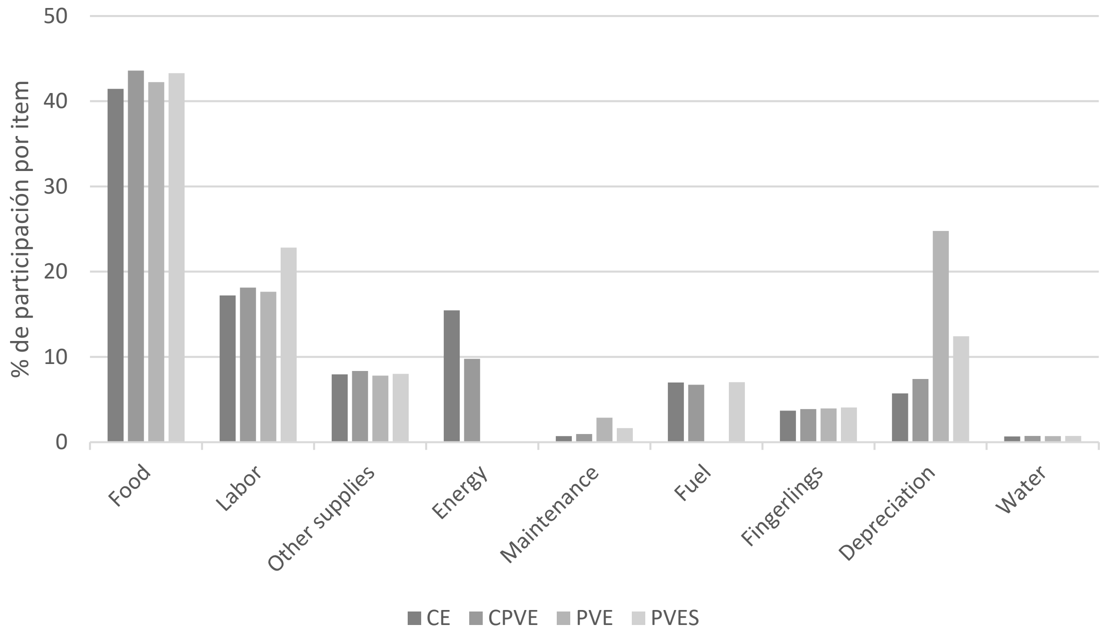

Figure 3. Percentage share of production costs for red tilapia production in BFT with different sources of electrical energy in the eastern region of Colombia. BFT, biofloc technology.

Table 6. Financial analysis summary: NPV, PB, IRR, and reinvestment results.

Indicator	Treatments			
	CE	CPVE	PVE	PVES
Reinvestment USD	3635.45	3635.45	3635.45	3635.45
PB simple	-	-	-	7.44
PB economic	-	-	-	9.13
NPV	−12,153.28	−394,99	−79,970.69	31,735.32
IRR %	2.06	4.91	5.79	9.88

PB = payback; NPV = net present value; IRR = internal rate of return.

The payback period (PB), another critical financial metric, also favors PVES with an economic payback of 9.13 years, demonstrating a shorter recovery time compared to other systems. Notably, the simple payback for PVES stands at 7.44 years, reflecting quick cost recovery. This contrasts sharply with the PVE system, which, despite offering complete independence from conventional energy, presents long-term financial challenges due to its high initial costs and significant depreciation expenses related to battery usage.

4. Discussion

The BFT system is proposed to be a substitute for aquaculture production systems that use large quantities of water [6]. Collazos-Lasso and Arias-Castellanos stated that BFT is a good alternative for fish farming in Colombia because it reduces the contamination of tributaries also because of prolonged droughts in some regions of the country [36]. However, they recommended making detailed calculations of the production costs, especially those related to electricity. In commercial aquaculture, it is important to consider the economic performance [46] because it provides vital support for the sustainability and continuity of an aquaculture farm [47].

The performance results of this study on red tilapia production using BFT in Colombia showed favorable survival rates and feed conversion ratios, with final biomass reaching 370–470 g over 30 weeks, but profitability depended on reducing energy costs and optimizing sales prices. Similarly, a BFT study on Nile tilapia in Brazil found that intermediate stocking densities (33 fish/m^3) provided the best growth and profitability, with fish reaching an average weight of 842.26 g [24]. In Mexico, a comparison of BFT and green water technologies (GWT) showed that while BFT had reduced feed costs due to biofloc, it required more energy, especially during the dry season, and GWT was more cost-effective under certain conditions, achieving a feed conversion ratio of 1.27 and market size in 145 days [48].

In aquaculture, the use and dependence on energy increases as the production increases. In turn, this increases the cost per kg of fish produced, making the sector vulnerable due to the energy costs and instability of prices [19]. The product cost increases by 5% in the production systems that include aeration [15]. In the present study, based on the total EOC, the product cost was 23% higher under conventional energy than that in the system using PVE. but the TOC result shows that the difference in the cost of the product is 2.5% higher in conventional energy, this will depend on the useful life of the batteries and panels, because the shorter the useful life, the greater the depreciation that will be reflected in the TOC of the product. Energy is mainly used for mechanical support processes, such as aeration to maintain oxygen levels as well as to maintain particles or flocs in suspension, and represents one of the main drawbacks of the BFT systems [12,26,49]. According to Almeida (2021) the cost of energy is the second fixed cost with the highest effect on the TOC of shrimp production in the BFT system with a value of 10.7% [12]. In the present study, energy represented 15.46% and 8.27% in the CE and CPVE systems, respectively. In contrast, PVE and PVES systems had no costs of energy because of the use of batteries and surplus energy production.

In Egypt, intensive fish farming systems have increased energy use by 25% [50]. Power requirements in the biofloc system are approximately 22.4 kW per kg of fish, whereas the production in RAS requires 11.2 kW per kg of fish [51]. In the present study, 2.3 kW were necessary for the production of 1 kg of red tilapia, considering only the energy consumption of the aerator, i.e., excluding any other energy consumption in the farm. In Brazil, electricity represents 15% of the production costs for tilapia production in BFT systems [23]. In Mexico, energy costs affected profitability, increasing the costs by 6% to 15% for the production of Nile tilapia in BFT systems compared to green water systems [48]. Although 50% of the total cost of energy is subsidized in that country, it is still a constraint for the implementation of the BFT system. Studies conducted in Colombia have concluded that the energy cost to produce *Piaractus brachypomus* and Nile tilapia in polyculture with the BFT system is 14% [26]. The above confirms the results of 15% of energy costs obtained in the present work, specifically in the TEC treatments.

Therefore, developing aquaculture production systems based on alternative energy sources has become a topic of general interest [52]. Solar energy is proposed as a substitute for conventional energy sources for the production of aquatic organisms in intensive systems that depend on an energy source for the operation of equipment [15].

Photovoltaic systems used exclusively during daytime (daylight hours) reduce the consumption of conventional electricity by 34% in in-ground ponds for tilapia production [53]. In Korea, energy savings of approximately 19.9% were observed after the implementation of solar panels in aquaculture farms. In the present study, partial implementation of photovoltaic energy decreased 40% of the energy cost, and the implementation of photovoltaic energy along with storage batteries decreased energy costs in the EOC by 100%.

The use of solar panels in a recirculation system for the production of Nile tilapia fingerlings in Kenya, Africa, reduced energy costs by USD 120 per month. Pereira (2020) stated that the BFT system is viable for *Colossoma macropomum* production only if solar panels are used to generate energy [54]. Although there are proprietary photovoltaic energy systems for the BFT system [55], there are no studies comparing the strategies and models that implement solar panels for the production of aquatic organisms in the BFT system.

The different strategies and energy source models assessed in the present study showed a variety of investments. The systems that include batteries to store energy and keep the equipment running without depending on conventional energy, represented the largest investment and tripled the investment required for systems that use conventional energy. Costa et al. stated that the cost of cages is the largest investment in the production of Nile tilapia; however, the use of new technologies reduces the share of cages in the total investment [40]. Similarly, in the present study, the share of geomembrane tanks was higher in the initial investment costs for those systems that used less technological equipment.

The greenhouse structure represented 75% of the initial investment in the production of white shrimp (*L. vannamei*) in the BFT system. Among the components included were galvanized arches, polyethylene sheets, geomembrane-lined wooden boxes, pipes, aerators, and air diffusion pipes [12]. In this study, the initial investment in production infrastructure was lower because greenhouses were not considered.

The energy sources and systems implemented in red tilapia production did not affect the total quantity of supplies used; however, they affected the costs of energy, fuel, maintenance, and depreciation. Fish farming systems that use batteries to keep the equipment running during hours when there is no sunlight have reported a 5-year lifetime for the batteries [56], requiring replacement twice during the lifetime of the photovoltaic panels [57]. In our work we used lithium batteries, which despite having a higher cost, have a useful life of 10 years, thus reducing reinvestment costs and depreciation costs. According to Yuan et al., aerators used in tilapia production in China have a 5-year lifetime under production conditions [58]. However, the current equipment for aquaculture aeration has UV protection and is made of high-density polyethylene, which can extend the lifetime by 15–20 years. Therefore, the depreciation of aerators did not represent an important share of costs in this study.

The integration of photovoltaic energy systems in aquaculture, such as the production of red tilapia in biofloc systems, demonstrates a promising shift toward sustainable and economically viable aquaculture. However, the high initial investment costs associated with solar panels and battery systems present a significant barrier, particularly for small-scale producers. These systems often require substantial upfront capital, leading to long payback periods that may deter adoption without external support [59]. While the operating costs of photovoltaic systems are notably lower compared to conventional energy systems, depreciation and maintenance costs remain critical considerations. Addressing these economic challenges requires robust financial models and policy interventions, such as government subsidies, tax incentives, or feed-in tariffs, to reduce the financial burden on small-scale producers [60,61]. For instance, the implementation of indirect incentives like tax reductions has proven to lower the levelized cost of electricity in similar contexts, enhancing economic feasibility [60]. A combined approach that includes direct incentives, such as subsidies or grants, alongside existing policies, could accelerate the diffusion of renewable energy technologies in aquaculture. This would not only promote economic sustainability but also align with broader environmental goals [61]. Therefore, fostering public-private collaborations and designing tailored financial mechanisms will be pivotal in making photovoltaic energy systems accessible and attractive to small-scale aquaculture operations [25].

Labor is essential in the BFT system for technical management and high densities allow for efficient use of the facilities [62]. Moreover, the implementation of smaller areas translates into hiring fewer but more specialized personnel. According to Almeida et al. (2021), specialized labor accounted for 17% in the production of marine shrimp using the BFT system, and it was not always hired to avoid increasing labor costs [12]. Labor represented more than 20% of the costs for tilapia production in the BFT system; however, a larger fish farm could be managed with the same labor considered in the present study for the production using six tanks. Less intensive systems and less specialized management usually involve family labor, and the professional visits for technical assistance are paid for by several producers jointly. Therefore, labor costs would not represent a significant percentage of production costs [63].

Tilapia sales costs in Colombia are steady even when farmed in systems that use fewer liters of water per kg of fish produced. Red tilapia has a higher sales price than Nile tilapia. However, as reported by Yuan et al., the lack of knowledge and lack of commercial organization of producers prevents them from getting competitive prices for their product [58]. This situation forces fish farmers to depend on wholesale buyers who set the price for 300–500 g tilapia. Similarly, in the present study, the price was set by intermediaries. Although the prices reported at the main supply centers are higher, the producers are paid 22% less. Buyers do not pay more for larger fish [58], and fish are sold from 350 g [25]. It is therefore imperative to search for strategic markets by assessing the value chains for red tilapia that will allow higher gross profit. This is observed in the commercialization of shrimp wherein the average final weight and sales price represent the most relevant factors in maximizing financial return. This occurred because better prices were obtained for larger shrimp, with the lowest commercialization price reported at USD 7.20 [12]. In contrast, in the present study, the sales price for whole tilapia was USD 2.3, and did not vary depending on the size. Further, the sales value directly affects the return on investment and the TOC. Despite the fact that tilapia has a lower cost of sale, it was observed that the economic viability is positive, and this viability improves depending on the energy source used.

Gross profit is important while analyzing cash flow, which in turn is an indicator of the financial viability of production projects [64]. In this study, the NPV, IRR, PB show that photovoltaic energy systems, although requiring higher initial capital due to solar panel and battery costs, can lead to substantial long-term savings in operating costs, especially energy costs. The highest NPV was recorded for the PVES system, as it generated surplus energy for nighttime use, reflecting a more favorable payback period compared to other models that rely solely on CE. Comparatively, a similar analysis of biofloc technology in shrimp farming in Brazil demonstrated that while the BFT system resulted in a higher NPV, compared to conventional systems, the IRR was considerably lower, highlighting the intensive technological support required for BFT [49].

The PVES system presented the best economic indicators, with a NPV and an IRR. These values suggest that PVES provides a more sustainable and profitable option in the long term, which aligns with similar findings in the literature. For instance, a study on shrimp production using BFT also reported significant energy cost reductions when using solar power, demonstrating that renewable energy can enhance the economic viability of aquaculture production [12].

In contrast, the PVE system, which relies entirely on photovoltaic energy with battery storage, showed poor financial performance, with a significantly negative NPV and a high depreciation rate due to battery costs. This is consistent with findings from studies conducted in Egypt and Brazil, which highlight the challenges of using battery-dependent systems due to their high upfront and maintenance costs [23,49]. Despite the lower operational energy costs, the depreciation and replacement expenses associated with battery use render the PVE system economically unviable without substantial financial support or subsidies. These results underline the importance of carefully evaluating the long-term financial implications of different renewable energy strategies in aquaculture.

The economic viability of red tilapia production using photovoltaic energy systems can be significantly influenced by market variables such as feed prices, labor costs, and selling expenses. A sensitivity analysis was conducted to evaluate the effects of a 10% reduction in these costs on the total operating cost (TOC) and profitability metrics. Feed, which constitutes the largest proportion of production costs (up to 41% in this study), was analyzed under a reduced-price scenario. A 10% reduction in feed costs would lower the TOC by approximately 4%, improving the gross profit margins, particularly in energy-intensive systems like CE and CPVE [49]. This is particularly relevant given the dependency on high-protein diets in biofloc systems [24].

Labor costs, representing around 20% of production costs across systems, were similarly analyzed for a 10% reduction. Such a decrease would reduce TOC by 2%, offering greater financial flexibility for small-scale producers [62]. Strategies to achieve this could include the adoption of labor-efficient practices or scaling up production to maximize the use of existing personnel without compromising operational efficiency [12].

Selling costs, which are influenced by intermediary pricing and logistical expenses, also play a crucial role in determining profitability. A 10% reduction in selling costs, achieved through direct-to-consumer marketing strategies or improved supply chain efficiencies, could further reduce TOC by approximately 1–2%, amplifying net revenue [58]. These reductions collectively highlight the importance of optimizing production inputs and sales strategies to buffer against market uncertainties and enhance the economic feasibility of aquaculture systems [12,25].

By integrating these adjustments, the financial performance of PVES systems in particular becomes increasingly attractive, with improved payback periods and higher net present value (NPV). This analysis underscores the potential for targeted interventions in cost reduction to improve the sustainability and profitability of aquaculture operations, particularly for small-scale producers who are more vulnerable to market fluctuations.

5. Conclusions

The economic analysis suggests that the PVES strategy shows promising results. With a lower initial investment compared to the PVE system, the PVES strategy eliminates the need for batteries by selling surplus energy during the day to offset nighttime consumption. This reduces dependency on costly energy storage systems while maintaining efficient production. Consequently, the PVES treatment lowers total operating costs and increases gross profit margins, making it an economically attractive option for sustainable aquaculture in sun-rich regions.

Further studies should be conducted to evaluate the value chain of red tilapia, thus improving economic results. Research should be conducted on energy sources for the biofloc system and tools should be sought that allow more efficient use of specialized labor, e.g., increase the productive units and calculate the number of workers needed for the units, without negatively affecting the production costs.

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