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Research Article

Physical and Chemical Properties of Biodiesel Obtained from Amazon Sailfin Catfish (*Pterygoplichthys pardalis*) Biomass Oil

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Amazon sailfin catfish (*Pterygoplichthys pardalis*) is considered one of the greatest threats to the biodiversity of continental aquatic systems, causing serious economic and environmental problems in the regions. In this work, the production of biodiesel from Amazon sailfin catfish biomass oil is studied. The physical and chemical properties of biofuel produced were evaluated under the specifications of the European standard EN-14214 by using gas chromatography-mass spectrometry, infrared spectroscopy, and atomic absorption spectrometry analyses. The results show that the biodiesel complies with all the specifications of the standard, except the content of polyunsaturated methyl esters. The yields obtained from oil and biodiesel were 9.67 and 90.71% (m/m), respectively. The methyl ester concentrations study identified 17 components where 47.003% m/m corresponded to methyl esters with saturated chains, whereas 34.394% m/m was attributed to monosaturated methyl esters and the remaining (18.624% m/m) to polysaturated methyl esters. Finally, mineral analysis by atomic absorption showed the absence of heavy metals Cd, Ni, and Pb, as well as low concentrations of Ni, Fe, Cu, and Zn, demonstrating that the quality of the fuel is not compromised. The study indicates the feasibility of manufacturing biodiesel using Amazon sailfin catfish biomass oil as a low-cost raw material. It represents an environmental option to mitigate a global problem of atmospheric pollution, and at the same time, it shows a commercial alternative to reduce the ecological impact caused by this fish in the diverse ecosystems to which it has spread. In addition, the great adaptability of this fish provides the possibility of a profitable process to have very high rates of reproduction and growth, allowing the generation of large amounts of biomass for the production of biodiesel.

1. Introduction

Atmospheric pollution produced by the combustion of fossil fuels has become a severe environmental and human health problem. According to the International Energy Agency, 25% of greenhouse gases released to the atmosphere are produced by combustion engines [1]. Biodiesel represents a viable fuel substitute to reduce the pollutant emissions produced by the combustion of diesel derived from oil in compression-ignition engines. It has several advantages as compared to diesel fuel oil such as its sustainability, its ability to maintain the balance of the carbon cycle, it is biodegradable, it has a level of lubrication, and it reduces the emission of toxic pollutants that are harmful to human health [2, 3]. Nevertheless, its main disadvantage is the high cost of refined oils used as feedstock for its production, which can represent between 60% and 80% of the final cost of biodiesel production. This limits its economic competitiveness compared to low-cost production of diesel obtained from petroleum [4, 5]. Accordingly, many studies have been conducted in recent years in order to identify low-cost raw oil sources such as used vegetable oil, animal waste fats, unrefined vegetable oils, or fish waste from fishing activities [6–9].

Among the various feedstock options for the biodiesel production, fish oil has been identified as an abundant and cheap source for its manufacture. From total worldwide processed fish, it is estimated that 50% is discarded or sold at very low prices to be used as fertilizer or animal feed [10]. Fish waste can be used as an important source of bio-oil for the production of biodiesel at low cost. The highly unsaturated fatty acids (UFAs) from fish oil can improve the low-temperature fluidity and reduce the cold filter plugging point (CFPP). It makes possible to prevent the adhesion and freezing, and even the stagnation of the vehicles, problems derived from the use of biodiesel at low operating temperatures [11]. In addition, fish oil has demonstrated similar ignition properties and excellent combustion characteristics compared to diesel oil, requiring minimal processing to be used as fuel. Studies carried out on combustion engines and conventional furnaces have shown that the use of biodiesel produced from fish waste generates lower CO, CO_2, and C_xH_y emissions than commercial diesel [12, 13]. Even so, there are some drawbacks due to its high content of polyunsaturated fatty acids (PUFAs) that increase its viscosity and may lead to the formation of insoluble compounds, thus promoting the effects of obstruction [14].

In the last years, properties of industrial fish waste oil have been studied to determine its viability as a raw material for the production of biodiesel [15–19]. Lin and Li [15] compared the fuel properties of the biodiesel produced from the mixture of marine fish under compliance with ASTM No. 2D diesel. The study indicated that marine fish oil biodiesel has a lower gross heating value, cetane index, exhaust gas temperature, equivalence ratio, black smoke opacity, elemental carbon content, and CO emission, as well as a higher fuel consumption rate and elemental oxygen content. Costa et al. [16] evaluated the biodiesel produced from a mixture of fish canning industry waste and olive oil baggage. It was found that the best quality of the biofuel is produced with a mixture of 80% waste olive and 20% waste fish oil (purity of 90.2% w/w). Moreover, the evaluation of the quality parameters shows that the methyl ester content and the kinematic viscosity comply with the European regulations, whereas the acid value has great variations which can damage the engine. Yahyaee et al. [17] presented a study for the potential use of local fish waste in the production of biodiesel for Iran. The results showed congruences of the flash point and kinematic viscosity with the most important regulation standards, leaving the need to evaluate in detail the other fuel characteristics. Fadhil et al. [18] studied the production of methylic and ethylic biodiesels using fish waste from Caspian Sea. Production of biodiesels was conducted by a base-catalyzed transesterification reaction. Fuel properties of biodiesels were in accordance with the ASTM D-6751 standard, achieving a yield of 94.88% w/w and 91.78% w/w for methylic biodiesel and ethylic biodiesel, respectively. Kara et al. [19] used a dual-step esterification-transesterification acid-base to reduce the high free fatty acid (FFA) content in Moroccan waste fish oil and to produce biodiesel, respectively. Fuel characterization by using Fourier transform infrared (FTIR) spectroscopy, nuclear magnetic resonance (NMR) spectroscopy, and the gas chromatography-mass spectrometry (GC/MS) shows that the biodiesel does not contain glycerol trace, and it meets the required international regulations.

Additionally, investigations have been developed to identify the characteristics and technical viability of biodiesel produced from fish species of high consumption or fast growth in farms [20–26]. García-Moreno et al. [20] studied the properties of biodiesel produced from a waste fish oil mainly composed of salmon (90%). The study was conducted evaluating the biodiesel produced under the specifications of the European standard EN 14104. They found a biodiesel FAME greater than 93% and a kinematic viscosity close to the one as established in the standard (6.30 mm^2/s at 60°C). However, oxidative stability of the biodiesel was low due to its high PUFA content, making necessary to improve the fuel through the use of antioxidants. Martins et al. [21] assessed the physicochemical features of biodiesel obtained from tilapia (*Oreochromis niloticus*) oil according to Brazilian mandatory parameters (Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP)) for biodiesel commercialization. The results showed that the biodiesel from tilapia waste is in accordance with the specific mass, kinematic viscosity, water content, acidity level, flash point, and oxidation stability established by the ANP. In the same way, Santos et al. [22] evaluated the biodiesel from tilapia oil produced by ultrasound esterification. The results of the biodiesel quality parameters indicate a kinematic viscosity similar to that of commercial diesel with a yield of 98.2% at low temperature (30°C). Nonetheless, acid values (1.4 mg·KOH/g) greater than the allowable range by the European (EN 14214) and American (ASTM D-6751) standards (0.5 mg·KOH/g) were found, indicating the need to carry out further processing to comply with regulations. Fadhil et al. [23] studied the characteristics of biodiesel produced from *Cyprinus carpio* fish oil performed through base-catalyzed transesterification assisted by a cosolvent. The maximum biodiesel yield achieved was 98.55 ± 1.02%. In addition, the properties of biodiesel are within the values recommended by the standards ASTM D-6751 and EN 14214, where the most remarkable characteristics are the flash point (83°C) and kinematic viscosity (2.90 $mm^2 \cdot s^{-1}$ at 40°C) close to those of petrodiesel (77.0°C and 2.04 $mm^2 \cdot s^{-1}$ at 40°C, respectively). Fadhil and Ali [24] determined the feasibility of using oil obtained from *Silurus triostegus* fish waste in the production of biodiesel. The study assessed the fuel properties of the fish biodiesel produced based on the ASTM standard specification. According to the characteristic results, the produced biodiesel obtained a yield of 96%. The properties of the produced biodiesel showed a higher kinematic viscosity and lower flash point compared with other biodiesel derived from chicken, marine fish oil, lard, and beef fats. Behçet [25] investigated the usability of waste anchovy (*Engraulis encrasicolus*) fish oil in conventional diesel engines. The results indicated that emissions generated by the combustion of biodiesel were lower than those produced by conventional fuels. In addition, high amounts of saturated fatty acids were detected, increasing the number of cetane in biodiesel, which reduces the delay in the ignition and improves the combustion process. The technoecological feasibility of the use of tilapia for industrial biodiesel production was addressed by Braga et al. [26]. Their research determined that although tilapia is a viable alternative to replace oil sources, the levels of oil and grease found in rinse water from tilapia biodiesel oil wash far exceed the limits established by environmental legislation such as Brazilian.

In this work, a study is conducted on the production of biodiesel from Amazon sailfin catfish (*Pterygoplichthys pardalis*). Amazon sailfin catfish is a native fish from the lower, middle, and upper parts of the basin of Amazon River, and it is very adaptable to environmental variability. This species has been introduced in several regions of the world, affecting local ecosystems. In the Asian continent, it has been detected in the countries of the Philippines, Indonesia, Malaysia, and Vietnam [27, 28]; in Europe, it has been detected in Poland [29] and in Italy [30]; there are also reports of its presence in Australia and Bangladesh [31], while in the United States of America, it has been found in rivers, lagoons, and estuaries of Texas and Florida [32]. In Mexico, its presence was identified for the first time in the Mezcala River, Guerrero (basin of the Balsas River), in 1995 and later in the Grijalva River in 2004, and since that date, the species has expanded to other regions of the country, reaching high abundance in the state of Campeche [33]. This species is considered one of the greatest threats to the biodiversity of continental aquatic ecosystems by its negative effects that include alteration of bank structure and erosion, disruption of aquatic food chains, changes in aquatic plant communities, displacing negative fishes by competition, and consuming its eggs that have a commercial importance in their respective regions [34, 35]. Given the absence or few natural predators in the aquifer mantles where this fish has spread [36] and the negative impacts produced on the local fisheries [34], the capture of Amazon sailfin catfish is promoted for its processing and commercial use in various productive sectors [37].

In this sense, the current work presents the production of biodiesel from Amazon sailfin catfish oil as an environmental alternative for the mitigation and exploitation of an invasive species of high diffusion. For this purpose, the physical and chemical properties of the biodiesel were analyzed employing gas chromatography-mass spectrometry, infrared spectroscopy, and atomic absorption spectrometry. The yield and physical-chemical characteristics of biodiesel were evaluated in accordance with international quality control standards in order to determine its feasibility of implementation in combustion engines. The approach presented in this paper establishes a commercial alternative to reduce the ecological impact caused by this species. In addition, the great adaptability of this fish provides the possibility of a profitable process to have very high rates of reproduction and growth, allowing the generation of large amounts of biomass for the production of biodiesel.

2. Materials and Methods

2.1. Materials. The raw material used in the study comprises a total of 100 Amazon sailfin catfishes captured between November and December 2016 and January and July 2017. The fishes were obtained from the river-lagoon-deltaic system (RLDS) of Laguna de Terminos that covers the geographical region of Pom-Atasta and Palizada River (southwest of Laguna de Terminos; 18°19′13″ and 18°29′04″ north latitude and 91°44′36″ and 91°51′31″ west longitude) located in the state of Campeche, Mexico (Figure 1). In order to preserve the specimens, the fishes were frozen at −20°C for storage and transportation. On the contrary, chemical reagents of analytical grade used in this study were hexane, methanol, potassium hydroxide, hydrogen peroxide, and ethanol produced by Fermont; phenolphthalein produced by Merck; and nitric acid and hydrochloric acid obtained from Meyer.

2.2. Experimental Procedure to Obtain the Amazon Sailfin Catfish Biodiesel. The captured fishes were subjected to a series of steps consisting of the generation and refining of fish oil for the manufacturing of biodiesel. Subsequently, gas chromatography-mass spectrometry, infrared spectroscopy, and atomic absorption spectrometry were performed to characterize the properties of the fuel as is illustrated in Figure 2.

2.2.1. Amazon Sailfin Catfish Drying Process. Captured Amazon sailfin catfishes were placed on aluminum trays to be introduced in a DIDATEC Technology dryer (model SDF 010) at 70 ± 1°C for 30 hours. Once the constant weight had been reached (32.445 ± 3.340% w/w), the fishes were cooled until reaching the room temperature. The dried fishes were crushed in a porcelain mortar until a homogeneous powder biomass is obtained in order to facilitate the oil extraction with hexane.

2.2.2. Extraction of Amazon Sailfin Catfish Oil. To extract oil from biomass, 500 g of Amazon sailfin catfish's dry powder and hexane (mass relation 1 : 1) were mixed and introduced into an (2 L) Erlenmeyer flask. The flask was immersed in boiled water and the mixture was heated to its boiling point (69 ± 1°C). The oil extraction was made by duplicate, operating the equipment at a total reflux for 60 minutes.

The oil-hexane mixture was cooled and then filtered using the Whatman paper (No. 40) to remove solid impurities. Afterward, the oil was separated from the solvent (hexane) by vaporization using a Hahnvapor HS-2001NS rotary evaporator (Hahn Shin Scientific, South Korea). The oil obtained was contained in an amber glass bottle and stored in a freezer at −20°C.

2.2.3. Biodiesel Production from Amazon Sailfin Catfish Oil. The production of Amazon sailfin catfish biodiesel (ASC-B) was carried out using a batch reactor (RQ-DT-135/EL) with

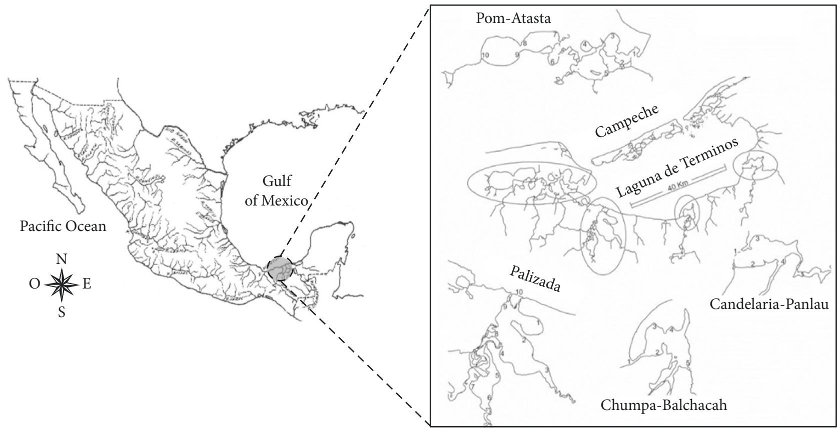

Figure 1: Main estuarine headwaters of Laguna de Terminos, Campeche, including the geographic region of the fish capture [38].

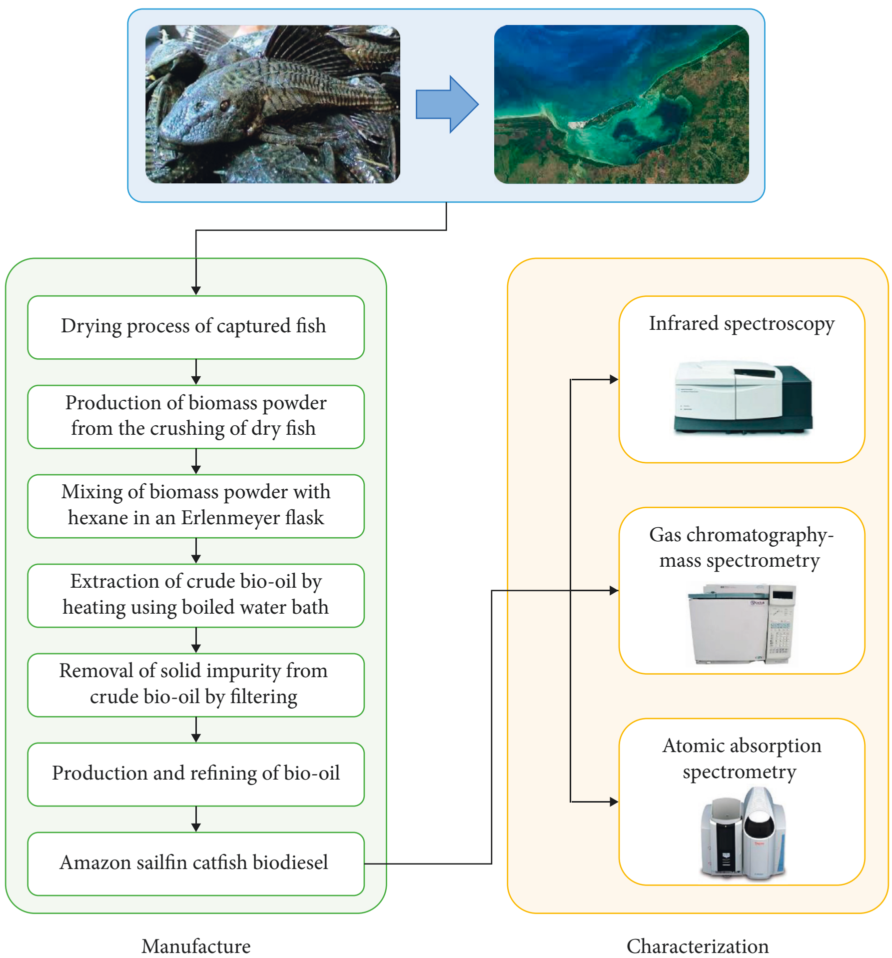

Figure 2: Diagram to obtain the biodiesel and the characterization techniques used in this study.

a capacity of 3 L, made of borosilicate glass, equipped with a control cabinet and data acquisition system (Generatoris, Mexico). For the production of biodiesel, a methanol : oil ratio (6 : 1) and 1% sodium methoxide were used. The preparation of sodium methoxide was carried out by mixing 2.747 g of sodium hydroxide (purity = 99.08%) with 2.88 grams of methanol, in a 1 L Erlenmeyer flask. The mixture was stirred until the complete dissolution of the sodium hydroxide was reached.

Amazon sailfin catfish oil (400 g) was introduced into the reactor together with sodium methoxide; the mixture contained in the reactor was heated at 55°C for 4 hours. Once the reaction was finished, it was cooled until attaining room temperature. The products of the reaction were emptied into a 1 L beaker and placed in a separatory funnel to be washed with distilled water. During the washing, two immiscible phases were formed: the upper phase contains the biodiesel and the lower phase is composed of water, soap, and catalyst residues; the lower phase is decanted by gravity, and its processes were repeated until the presence of soap was no longer observed. Washed biodiesel was transferred from the separating funnel to a ground-glass Erlenmeyer flask (1 L); a straight coolant was added at a 45° angle to remove the water and methanol contained in the biodiesel. Purified biodiesel was left to cool and weighed to calculate the yield of the process. Biodiesel was stored at 3°C in amber glass bottles for infrared spectroscopy, atomic absorption spectrometry, and gas chromatography-mass spectrometry.

2.3. Characterization of the Properties of Amazon Sailfin Catfish Biodiesel (ASC-B). Fuel properties of produced ASC-B were determined according to standards established by the Europe norm EN 14103 [39]. The analysis of the produced biodiesel properties was conducted through studies of infrared spectroscopy (IR), atomic absorption spectrometry, and gas chromatography-mass spectrometry (GC/MS).

2.3.1. Amazon Sailfin Catfish Drying Process. An Agilent Cary 600 infrared spectrometer with Fourier transform (Agilent, United States), equipped with a diamond tip ATR (Gladis) and a KBr-type detector, was used for the characterization of bio-oil and ASC-B. The system was equipped with the software Resolution (Version 4.0) used for the acquisition, processing, and storage of spectroscopic data. The analysis was performed using a volume of 0.1 mL, per sample, placed on the diamond cell. The spectra were collected on a wavelength range comprised between 550 and 4500 cm^{-1} performing eight scans with a resolution of 2 cm^{-1}. All spectra were collected at a temperature of 25°C.

2.3.2. FAME and Fatty Acids Determination by Gas Chromatography-Mass Spectrometry. The percentage content in weight of ASC-B methyl esters was determined using an Agilent 6890 gas chromatograph coupled to an Agilent 5973N mass detector with electron ionization at 70 eV (Agilent, United States). For the sample analysis, an HP-5MS 5% diphenyl-95% dimethylsiloxane chromatography column (25 m × 0.2 mm × 0.33 μm) and a helium gas flow of 1 mL·min^{-1} as a carrier were used. The furnace temperature was increased with a heating rate of 5°C min^{-1} until reaching 250°C in the chromatographic column, which was maintained for 5 min, and the temperature of the injector was at 250°C. The operation of the MS was conducted by setting the filament temperature at 230°C, the quadruple temperature at 130°C, and the detector temperature at 280°C, with a retention time of 4 minutes. To conduct the analysis, 500 μL of dichloromethane was mixed with 2 μL of the sample, injecting 1 μL of the mixture to the chromatograph. The results of the chromatographic spectra were compared with the database of the NIST Library (V 1.7a) for each component identified.

2.3.3. Mineral Determination by Atomic Absorption. To determine the bio-oil and ASC-B mineral composition, 0.5 g of the sample was placed in porcelain crucibles, and they were introduced into a muffle (Fisher Scientific 550-14, United States). In order to transform the samples into the ash form, a digestion process was conducted heating the sample at 250°C for 8 hours, and then the temperature was increased to 600°C for 12 hours. The samples in the form of ash were cooled to room temperature; afterward, 3 mL of concentrated nitric acid (66% v/v) and 3 mL of hydrogen peroxide were added consecutively [40]. The mixture was stirred to homogenize the reagents and then allowed to stand at room temperature for 10 min; finally, 25 mL of deionized water was added.

Solid impurities were eliminated by filtration using Whatman filter paper No. 42. The filtered solutions were combined in a volumetric flask, which was adjusted to 100 mL with deionized water, and stored at a temperature of 3°C for the analysis by atomic absorption. The quantification of metals concentration in the bio-oil and ASC-B was conducted using atomic absorption equipment (Thermo Scientific iCE 3000, United States). Table 1 presents the operating conditions for the quantification of each chemical element.

3. Results and Discussion

3.1. Fuel Properties of Biodiesel. Base on the process illustrated in Figure 2, a yield of 32.445 ± 3.340% w/w was found for the Amazon sailfin catfish dry biomass, obtaining an oil yield of 9.67% (m/m). On the contrary, biodiesel yield was determined as the ratio of biodiesel mass and the weight of oil used, and the yield obtained in our study was 90.71% (m/m). Table 2 shows the physicochemical properties of biodiesel made by Amazon sailfin catfish oil; in order to determine the implementing feasibility of the produced fuel, these values were compared with the European standard EN-14214 [39].

From the results in Table 2, with the exception of the polyunsaturated methyl ester, produced biodiesel complies with the specifications of the international standards [41–45]. The detailed description of properties presented in Table 2 is given in Sections 3.1.1–3.1.10.

3.1.1. Acid Value. This property measures the content of acidic substances in biodiesel, and it is also used to monitor the degree of degradation that may occur during storage. The standard EN-14214 establishes a maximum value of 0.5 mg·kg^{-1}. The analysis indicated that the Amazon sailfin catfish oil had an acid value of 7.45 mg·KOH g^{-1}, while for biodiesel, it was 0.49 mg·KOH g^{-1}, a minor value with respect to that established in the reference standard (Table 2) and lower than that observed for other fuels derived from fish (1.11–1.17 mg·KOH g^{-1}) [46, 47].

3.1.2. Flash Point. According to Table 2, ASC-B presents a flash point temperature of 147°C. The obtained value is higher than the minimum established in the standard EN-14214, and it

Table 1: Atomic absorption equipment operating conditions for determination of the metals concentration in oil and Amazon sailfin catfish biodiesel.

Chemical element	Wavelength (nm)	Grid opening (nm)	Lamp current (mA)	Acetylene flow: air ($L \cdot min^{-1}$)
Cd	228.8	0.5	8	1.2
Cu	324.8	0.5	5	0.9
Fe	246.3	0.2	15	0.9
K	766.5	0.5	Emission	1.1
Na	217	0.5	Emission	1.1
Ni	232	0.2	15	0.9
Mn	279.5	0.2	12	1
Pb	217	0.5	10	1.1
Zn	213.9	0.2	10	1.2

Table 2: Methods used to determine physical and chemical properties of the Amazon sailfin catfish biodiesel.

Properties	Units	Method		Specification	Obtained values
Cloud point	°C	—[a]	—[a]	—[a]	3
Flash point	°C	EN ISO	3679	101 min	147
Kinematic viscosity @ 40°C	$mm^2 \cdot s^{-1}$	EN ISO	3104	3.5–5	3.58
Carbon residue	% w/w	EN ISO	10370	0.3 max	0.023
Water and sediments	$\mu g \cdot g^{-1}$	EN ISO	12937	500 max	108
Density @ 15°C	$kg \cdot m^{-3}$	EN ISO 3675		860–900	867
Acid value	mg·KOH/g biodiesel	EN 14104		0.5 max	0.49
Methanol content	% m/m	EN 14110		0.2 max	0.031
FAME content	% m/m	EN 14103		≥96.5	98.8
Linolenic acid methyl ester	% m/m	EN 14103		12 max	1.68
Saturated methyl ester	% m/m	EN 14103		—	47.003
Monounsaturated methyl ester	% m/m	EN 14103		—	34.394
Polyunsaturated methyl ester	% m/m	EN 14103		—	18.624
Na + K content	$mg \cdot kg^{-1}$	EN 14538		5 $mg \cdot kg^{-1}$	0.361

Not specified.

is within the range of biodiesel obtained from other fish species (103°C–162°C) [12, 17, 21, 46]. Flash point is an important indicator for fuels production that defines the lowest temperature at which the vapors of the material ignite. Therefore, this value indicates the safety of the ASC-B for its transportation, storage, and handling.

3.1.3. Cloud Point. The cloud point is defined as the temperature at which a cloud of wax crystals first appears in a liquid when it is cooled under controlled conditions during standard test [39]. For the produced ASC-B, 3°C of cloud point temperature is reported. In a previous work, similar values (1°C) for biodiesel manufactured from *Cyprinus carpio* oil [24] were obtained.

3.1.4. Density. Analysis of ASC-B reported a density of 867 $kg \cdot m^{-3}$ at a temperature of 15°C. Similar values have been reported by Behçet et al. [25] and Martins et al. [21] for biodiesel manufactured from anchovy (*Engraulis encrasicolus*) oil and tilapia (*Oreochromis niloticus*) oil, respectively. This parameter is important in determining the energy content of biodiesel. According to standard EN-14214 (Table 2), all of them are appropriate for their use in engines.

3.1.5. Kinematic Viscosity. The kinematic viscosity determines the degree of atomization that biodiesel has inside the combustion chamber. The ASC-B obtained a kinematic viscosity of 3.58 $mm^2 \cdot s^{-1}$ at 40°C, and this value falls within the range established in the standard EN-14214 (Table 2). This guarantees a good combustion inside the engine chamber without leaving residual residues that can cause damage. In previous works, similar dynamic viscosities have been reported for biodiesel derived from fishes and their waste (4.2–4.7 $mm^2 \cdot s^{-1}$) [25, 48, 49].

3.1.6. Water and Sediments. The presence of water in the biodiesel can cause corrosion in the engine and/or react with the glycerides producing soap and glycerol. In addition, the presence of water can favor the growth of bacteria that accelerate the degradation of biodiesel generating some undesirable compounds which can cause filter clogging and a poor motor performance. From the chemical analysis of biodiesel, a value lower than that established by the standard was obtained (108 $mg \cdot kg^{-1}$).

3.1.7. Methanol Content. Monitoring residual methanol in biodiesel is a safety issue, and even small amounts of this material can reduce the flash point of biodiesel. Moreover, residual methanol can affect fuel pumps, seals, and elastomers, resulting in poor combustion properties [50]. The ASC-B methanol content was lower than the maximum value established as a reference (0.031% m/m), guaranteeing a high energy content of the biodiesel.

3.1.8. Residual Coal. The ashes analysis of the ASC-B reported a carbon residue percentage of 0.023% m/m, lower than that established by the standard EN-14214 (Table 1). Therefore, the carbon residues generated during the combustion of the developed fuel allow its use without causing an engine wear.

3.1.9. Methyl Ester Content. The results of the gas chromatography-mass spectrometry reported the following saturated and unsaturated ester compositions of the biodiesel produced: 47.003% w/w of methyl ester of saturated chains, 34.394% w/w of methyl ester of monounsaturated chains, and 18.624% w/w of polyunsaturated methyl ester.

3.1.10. Alkaline Metals Content. According to EN-14214, the concentration of alkaline metals (Na + K) in biodiesel must be below $5\,mg{\cdot}kg^{-1}$ (Table 2). Excess of these metals can cause damage to the filters and the engine injectors. The presence of alkaline metals is related to soap and catalyst residues, originating in concentrations higher than $5\,mg{\cdot}kg^{-1}$, so it is important to carry out a proper purification of biodiesel. In our work, the ASC-B presented a value of $0.361\,mg{\cdot}kg^{-1}$.

3.2. Infrared Spectroscopy Analysis. Results of the medium-infrared spectra for the oil and ASC-B show that their absorbance bands are similar, as is illustrated in Figure 3. The absorbance band between 3000 and $3600\,cm^{-1}$ is related to stretching vibrations of the –OH functional group. It can be noted that this band is absent in the fish oil (Figure 3(b)), while for ASC-B, it is notorious due to the presence of small concentrations of moisture (Figure 3(a)). The absorbance peak at $3018\,cm^{-1}$ indicates the presence of unsaturated bonds that correspond to stretching vibrations of *cis* groups (-CH=CH-). The strong absorbance peaks at 2918 and $2854\,cm^{-1}$ are related to symmetric and asymmetric stretching vibrations of methyl ($-CH_3$) and methylene ($-CH_2-$) functional groups, respectively; these are part of the chemical structure of the skeleton of esters and fatty acids. In addition, the intense peak of absorbance at $1740\,cm^{-1}$ is related to vibrations of symmetric stretching of the carbonyl functional group (-C=O). The band between 500 and $1500\,cm^{-1}$ corresponds to a region that presents several peaks of absorbances and where it is possible to distinguish slight differences between both spectra (Table 3).

3.3. Chromatographic Analysis. FAME and fatty acids were determined by a gas chromatography analysis. The peaks of the ASC-B chromatogram were individually analyzed, the mass spectra of each of the components were extracted, and subsequently, their identity was checked with the help of the NIST MS database (Figure 4). From the results obtained for the ASC-B's methyl ester concentrations, 17 components were identified, of which five are present in higher concentration: C16:0, C16:1, C18:0, C18:1, and C20:5 with 24.679, 9.059, 10.844, 16.081, and 9.173% m/m, respectively. In addition, other components with a lower concentration between 0.382 and 5.366% m/m were identified. According to the study, 47.003% m/m corresponded to methyl esters with saturated chains, whereas 34.394% m/m was attributed to monosaturated methyl esters and the remaining (18.624% m/m) to polysaturated methyl esters.

Table 4 enlists and compares the results obtained from the chromatographic study with other biodiesels values reported in the literature derived from marine species (BMFO) and waste cooking oil (WCO). It can be observed that methyl esters concentrations of ASC-B and of BMFO are similar, while biodiesel of vegetable origin shows remarkable differences. This is due to the nature of the oil used in the manufacture of biodiesel. On the contrary, ASC-B presented higher concentration of saturated methyl esters with respect to the other two, as seen in the components C16:0, C17:0, and C18:0. For the monounsaturated esters, it was observed that the biodiesel from vegetable oil has a higher concentration compared to the two biodiesels from the marine species and the Amazon sailfin catfish. Regarding polyunsaturated methyl esters, ASC-B has a lower concentration compared to the other two. A disadvantage of containing high concentrations of polyunsaturated methyl esters in biodiesel is that the chains with more than three unsaturated bonds can react more easily, favoring their deterioration, resulting in the formation of undesired compounds that could damage the engine combustion chambers.

Table 4 also shows a comparison of the physical and chemical properties, as well as the point composition of the methyl esters between the biofuel obtained in this work, and the results reported by Fu et al. [54], Thanh et al. [55], and Maniam et al. [56] for catfish species from other regions. The density and content of FAME reported are very similar to each other. The concentration of methanol and water content were below those established by the standard EN-14214 (in the works cited above). The kinematic viscosity of the biodiesel reported was similar to that obtained by Maniam et al. [56], while the value reported by Fu et al. [54] was much higher. This can be attributed to variations in the chemical composition of the catfish oil that was used for the manufacture of biodiesel. The values of flash point and cloud point were lower than those reported by Maniam et al. [56], and these differences are attributed to the fact that the biodiesel produced presented high concentrations of unsaturated methyl esters (53,018 wt.%).

Additionally, the comparison in the concentration of methyl esters reported in Table 4 indicates similarities in the concentrations of C14:0, C16:0, and C18:0 with respect to those reported by Fu et al. [54]. Nonetheless, significant differences are observed between the concentrations of FAME (C16:1, C18:1, and C18:2), which is attributed to the variation that exists in the composition of the fish oil that occurs in different regions of the world. In this respect, in previous works, Maniam et al. [56], Thanh et al. [55], and Shabani-kakroodi et al. [57] report very similar C18:1 concentrations of 26.8, 27.2, and 28.93 wt.% respectively, while Hemung et al.

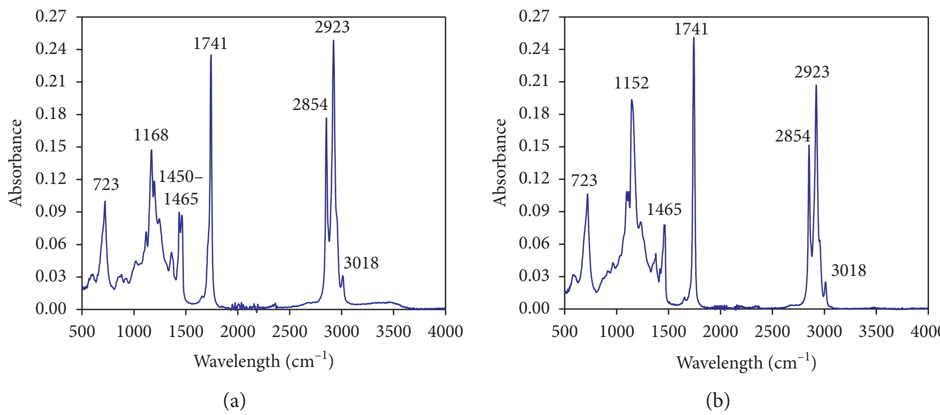

Figure 3: Infrared spectrum of fuels produced: (a) Amazon sailfin catfish biodiesel; (b) Amazon sailfin catfish oil.

Table 3: Differences between produced biodiesel and oil according to analyzed regions of the infrared spectrum.

Absorbance band (cm^{-1})	Assignment	Biodiesel	Oil	Reference
1450–1455	Vibrations of asymmetric flexion of the functional group -CH_3	Present	Absent	[51, 52]
1370–1400	O-CH_2 functional group present in glycerol (TG, DG, and MG)	Absent	Present	[52]
1180–1200	Vibration of asymmetric stretching of O-C-C bonds	Present	Absent	[52, 53]
1050–1120	Vibrations of asymmetric stretching of O-CH_2-C bonds	Absent	Absent	[52, 53]

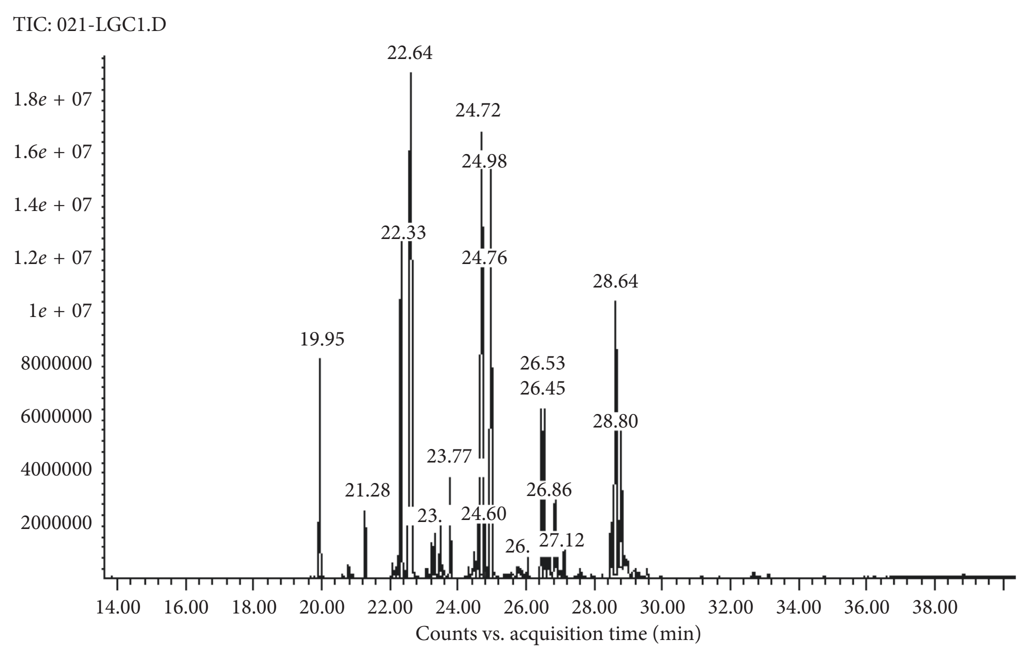

Figure 4: Gas chromatography-mass spectrometry of Amazon sailfin catfish biodiesel.

[58] report a larger value of 37.84 wt.%. Another cause that can be attributed to explain these differences is the type of process used in the manufacture of catfish biodiesel.

3.4. Mineral Analysis by Atomic Absorption. There are several factors that can induce the degradation of biodiesel, among which few mentioned in previous works are (a) moisture content, (b) presence of radiant energy, (c) heat, and (d) the presence of metal ions. These factors induce the decomposition of biodiesel, through the formation of free radicals, generating undesirable chemical products such as organic acids, ketones, alcohols, ethers, aldehydes, and oligomers [59]. In particular, transition metal ions under certain

Table 4: Comparison of the chemical composition of Amazon sailfin catfish biodiesel (ASC-B) with waste cooking oil (BWCO), marine fish oil (BMFO), and previous biodiesel production from catfish works.

Methyl ester profile (% wt.)	Chemical structure	ASC-B	BWCO [46]	BMFO [16]	Previous studies using catfish		
					Fu et al. [54]	Thanh et al. [55]	Maniam et al. [56]
Myristate	C14:0	4.488	0.54	6.6	3.43	—	—
Pentadecanoate	C15:0	1.466	—	—	—	—	—
Palmitate	C16:0	24.679	14.18	21.6	27.89	—	—
Palmitoleate	C16:1	9.059	0.74	8.0	1.67	—	—
Heptadecanoate	C17:0	1.920	0.17	—	—	—	—
Heptadecanoate	C17:1	0.978	—	—	—	—	—
Stearate	C18:0	10.844	3.77	4.1	8.38	—	—
Oleate	C18:1	16.081	47.51	17.3	46.44	—	—
Linoleate	C18:2	1.298	24.83	1.7	10.85	—	—
Linoleate	C18:3	0.382	4.97	2.9	1.33	—	—
Vaccenate	C19:1	5.366	—	—	—	—	—
Arachidate	C20:0	3.606	0.8	—	—	—	—
Eicosenoate	C20:1	2.910	—	4.2	—	—	—
Eicosadienoate	C20:2	0.492	0.17	—	—	—	—
Eicosatetraenoate	C20:4	3.934	0.38	—	—	—	—
Eicosapentaenoate	C20:5	9.173	0.03	13.3	—	—	—
Behenate	C22:0	—	0.1	—	—	—	—
Docosenoate	C22:1	—	0.18	3.8	—	—	—
Docosadienoate	C22:2	—	—	1.7	—	—	—
Docosatetraenoate	C22:4	—	0.14	—	—	—	—
Docosapentaenoate	C22:5	—	0.05	—	—	—	—
Docosahexaenoate	C22:6	3.345	0.04	14.8	—	—	—
Saturated		47.003	19.56	32.3	—	—	39.7
Monounsaturated		34.394	48.43	33.3	—	—	48.11
Polyunsaturated		18.624	30.61	34.4	—	—	12.18
Density (15°C) ($g \cdot cm^{-3}$)		0.867	—	—	0.883	0.887 and 0.873	0.8772
Acid value ($mg \cdot KOH\ g^{-1}$)		0.49	—	—	0.09	0.3	0.12
Methanol (wt.%)		0.031	—	—	<0.01	—	—
Kinematic viscosity at 40°C ($mm^2 \cdot s^{-1}$)		3.58	—	—	—	3.4 and 3.2	4.53
Flash point (°C)		147	—	—	—	174 and 168	—
Cloud point		3	—	—	—	10	—
Water content ($mg \cdot kg^{-1}$)		0.867	—	—	—	300 and 200	—
FAME content (wt.%)		0.49	—	—	97.02	96.6 and 98.2	—

specific conditions accelerate the degradation of biodiesel. For example, the Cu^{2+} and Zn^{2+} ions are shown to have catalytic activity that favors the oxidation of unsaturated bonds [60]. Similar effects have been reported in other works by the presence of other metal ions such as iron, nickel, manganese, and cobalt in the biodiesel decomposition [61, 62]. In this work, the concentration of sodium, potassium, manganese, iron, copper, zinc, nickel, cadmium, and lead ions was determined for the ASC-B. Table 5 shows the concentrations of the metal ions in the ASC-B.

From Table 5, it can be seen that the sum of the sodium and potassium concentrations was 0.361 $mg \cdot kg^{-1}$, a value lower than that established in the European standard (Table 2). The low value obtained from K+ and Na+ is due to the subsequent purification, products of the washing of biodiesel by extraction with an ionic resin (Amberlite Dry 10). The atomic absorption analysis indicates the absence of heavy metals Cd, Ni, and Pb. On the contrary, for the metal ions Mn, Fe, Cu, and Zn, low concentrations were observed (Table 5), so it can be considered that they do not affect the quality of the ASC-B. Finally, similar results for biodiesel obtained from animal fats, canola oil, soybeans, African palm, and castor oil were reported [63–66].

Table 5: Concentration of metals found in the Amazon sailfin catfish biodiesel.

Chemical element	Concentration (mg/kg)
Na	0.237
K	0.124
Mn	0.012
Fe	0.017
Cu	0.029
Zn	0.066
Ni	ND
Cd	ND
Pb	ND

ND: not detected.

4. Conclusions

In this work, the production of biodiesel from Amazon sailfin catfish oil was studied. The chemical and instrumental analyses showed that produced biodiesel complies with the European standard EN-14214 with respect to the physicochemical properties and mineral composition and methyl esters, which guarantees the proper functioning of the engine. According to the results, the biodiesel yield obtained was 90.71% (m/m), the acid value and the kinetic viscosity reported are lower than those observed for other fuels derived from fish waste, and the flash point and density are within the ranges of biodiesel obtained with other fish species. Moreover, a mineral analysis by atomic absorption showed the absence of heavy metals Cd, Ni, and Pb, as well as low concentrations of Ni, Fe, Cu, and Zn, demonstrating that the quality of the fuel is not compromised. However, it is advisable to add an antioxidant agent to the manufactured biodiesel derived from fish to improve its useful life, due to the presence of high concentrations of polyunsaturated methyl esters. The results of this work show that the oil obtained from the biomass of the Amazon sailfin catfish could be an option for the production of biodiesel. This allows to significantly reduce the environmental impact of this species in the subject geographical area. Besides, since it is a species that is not usable for human consumption, it does not conflict with the demand for food production, unlike other raw materials considered for the development of biodiesel. Finally, it is important to note that although the Amazon sailfin catfish contains low fat concentration (7–12% weight), a profitable process may be possible since the reproduction and growth rates (5 to 6 months) of the species are very high, so it can generate a large amount of biomass for the production of biodiesel in a very small space, making it competitive with respect to the raw materials that require large extensions for its production.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

All authors contributed equally to the design and performance of the experiments, the analysis of the data, and the writing and revision of the manuscript.

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