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Review

Fish Waste: A Potential Source of Biodiesel

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Abstract: The continuously increasing energy requirement on one hand and the incessant depletion of non-renewable fossil fuels on the other urge us to focus on alternative renewable energy sources such as biofuels. Biofuels including biodiesel, bioethanol, biobutanol, biohydrogen, etc., are generated from different biological sources, and their waste which stands as the best alternative in the present scenario. Specifically, the utilization of biological wastes as raw materials for the production of biofuels is considered as best waste management practice. To date, most of the biodiesel production research has been carried out with plant, algal, and microbial samples, or their waste. It is a well-known fact that diesel can also be produced from specific oily fish and their waste using different methods. In addition, fish waste constitutes a major quantity compared to other food waste which is a serious concern. Furthermore, the disposal of fish waste shows an impact on both the environment and the economy. Hence, the development of protocols for the efficient production of biodiesel from fish waste is the ultimate goal. However, insufficient knowledge and less effort in the conversion of fish waste to biodiesel impede the achievement of this goal. Therefore, this review intends to summarize the mechanism of biodiesel production from fish waste. Also, various physico-chemical factors involved in biodiesel production from fish waste were discussed. In addition, research on biodiesel generation from various fish wastes or waste fish oil was also emphasized in detail, which will be helpful for commercial practice. Overall, this information will be useful for improvement in biodiesel production from fish waste.

Keywords: renewable fuel; biodiesel; fish waste; transesterification; enhancement; engine

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1. Introduction

Energy is essential for both living and non-living things to carry out different functions. They obtain energy from both non-renewable and renewable resources. Moreover, the ever-increasing population creates a dire necessity for energy sources. To date, a major portion of the global consumption of fuel is met by non-renewable fossil fuels such as coal, petroleum products, and natural gas [1,2]. Specifically, fossil fuels provided more than 80% of global energy between 2013 and 2035 and are the key components for generating energy in the automobile, transport, chemical, material, and other industries [3]. According to the International Energy Outlook (I.E.O.2013) [4] prediction, world energy utilization will grow by 56% between 2010 and 2040. In contrast, the continuous lessening of fossil fuels due to indiscriminate usage shifts our focus towards alternatives. Thus, the gap between the demand and supply of fossil fuels is increasing regularly, which in turn leads to rising fuel prices in most countries [5]. In addition, fossil fuels are responsible for environmental pollution which is one of the major causes of global warming and climate change, thereby imposing severe threats to the health of living organisms [6]. Fossil fuels cannot be regenerated or renewed in a short time and therefore research on alternative renewable energy resources has become a hot topic recently. Furthermore, both governmental and non-governmental organizations are ready to invest in renewable fuels in a number of countries. Hence, there is an urgent need to look into renewable sources of energy that are cost-effective and, cause no threat to the environment [7]. Moreover, the usage of natural resources for various purposes, including energy generation, has been increasing substantially. Specifically, it reached 92.1 billion tons in 2017 and resulting in an increase of 254% from 27 billion in 1970 worldwide (UN 2019) [8,9].

Considering the above facts, researchers are focusing mainly on renewable fuels as a source of energy. Common renewable energy sources in use are solar energy, hydro energy, wind energy, bioenergy, etc. [3]. Biomass-based energy is also an important renewable source which is referred to as biofuel. These are mainly produced from biological organic matters derived mostly from plants, microbial organisms, animals, and their wastes, including dead organisms [10]. The chemical composition of biomass differs amongst different species. In general, biomass constitutes majorly carbohydrates and lipids in plants and lipids together with fatty acids found in animals including fish. Most of the biofuels such as bioethanol, biobutanol, biohydrogen, biodiesel, etc., are generated from different biological sources depending on their chemical composition [11]. In certain cases, after biofuel production, the remaining waste can also be used as manure. Thus, biomass is a significant source of energy and contributes to the global energy supply. Initially, plant and algal species were mainly focused on biodiesel production, and now the focus is shifted towards animals and fish, including their waste. Plants are the key sources of oils and fats which include soybeans, beans, sunflower, canola, cotton, corn, etc. Among all, soybean oil provides more than 70% of the feedstock for the production of biodiesel [9].

Aquaculture production has increased substantially with the successful implementation of advanced practices to meet the global food demand. Particularly fish supply, which had increased enormously due to consumption per capita increasing from 9.0 kg in 1961 to 20.2 kg in 2015 indicates the importance of fisheries (FAO 2020) [12]. Fish is a rich source of animal protein and possesses value-added compounds including enzymes, bioactive peptides, oils, and biopolymers. Specifically, it possesses collagen, peptides, chitin, polyunsaturated fatty acids (PUFAs) such as long-chain omega-3 fatty acids, vitamins (A, B, and D), and minerals including calcium, zinc, iodine, iron, and selenium [13]. Particularly, salmon, herring, mackerel, anchovies, tuna, sardines, etc., are considered as the best oily fish for biodiesel production. Fish waste or their byproducts found in nature or generated through the fish processing industry represent a significant portion of the original fish, and their disposal has both economic and environmental impact. Moreover, fish leftovers/waste released in the environment contribute to a significant quantity of all biological waste, which is a serious topic at the international level [14]. Specifically, 2/3 of the fish is discarded as waste which will be useful for the circular economy with the generation of materials with high added value. Around 250,000 million tons of fish processing waste are generated globally and may increase every year, which will be helpful in order to generate useful products including biodiesel [15]. Furthermore, these natural seashore fish leftovers and fish industrial processing waste can cause serious harm in the form of diseases to the surrounding community. Specifically, waste that has originated through the sea shore or fish industry can alter the oxygen levels, temperature, pH levels, and overall abundance in the environment [10]. The disposal of aquaculture waste, especially fish waste, is a serious concern, urging researchers to give the best solution to implement sustainable waste management practices. Therefore, it is crucial to evaluate the pros and cons of fish waste disposal using waste management methods [16]. Fish waste is generally useful for preparing fish meal and aqua feed, fertilizers, etc. Moreover, fish waste can also be used to generate omega-3 fatty acids, oils, and biodiesel [17]. Particularly, biodiesel can be generated from fish and their waste due to the accumulation of long-chain fatty acid esters. Generally, biodiesel possesses higher biodegradability, inherent lubricant potential, negligible sulfur content, higher flash points, and produces lower polluting emissions than diesel from petroleum [18]. Also, biodiesel can easily be converted into electricity, alongside liberating a huge amount of energy without producing many air pollutants.

Several groups are working to achieve the large-scale production of diesel chemically, and also by using biological organisms and their waste. Specifically, the generation of biodiesel using agricultural, algal, and microbial sources through oil extraction and transesterification has been a regular practice, and only a few research works have been conducted using animal waste. At the initial stages, El-Mashad et al. [19] used salmon oil for biodiesel generation using both esterification and transesterification methods. Santos et al. [20] produced biodiesel through the ultrasound-assisted esterification of *Oreochromis niloticus* (Nile tilapia) oil. The production of biodiesel from the fat of tra catfish was achieved through heterogeneous basic-catalyzed transesterification, along with ultrasonic mixing, by Huong et al. [21]. The generation of biodiesel was achieved using menhaden fish oil through transesterification by Hong et al. [22]. Fadhil et al. [23] generated the maximum yield of biodiesel through the transesterification of *Cyprinus carpio* oil assisted by a co-solvent. Madhu et al. [24] also generated high-quality biodiesel in the process of transesterification using fish feedstock and a CaO catalyst derived from crab wastes. The production of biodiesel was carried out by Kara et al. [25] from waste fish oil, having high free fatty acids in Moroccan fish-processing industries. Fish-waste-based biodiesel production was achieved using both esterification and transesterification methods by Samat et al. [26]. Moreover, the generation of biodiesel was attained from fish processing wastes using in situ transesterification by Zhang et al. [27]. The synthesis of biodiesel from fish waste through transesterification was achieved, along with the assistance of nanomagnetic catalysts, by Smaisim et al. [28]. Overall, less success with fish-waste-based biodiesel production was noticed. Therefore, the production of biodiesel from fish waste by using potential methods which augment the output is one of the targets in the energy sector. Moreover, the conversion of fish waste into energy is a cost-effective and eco-friendly process, which also covers the waste management practice in the seashore or fish industry. The present review focuses mainly on the updated knowledge on biodiesel production from fish waste. Moreover, the prerequisites and advances in technology for the production of biodiesel from fish waste were highlighted in this review for industrial-level generation.

2. Mechanism of Biodiesel Production from Fish Waste

Initially plant, algal, and animal oils and fats were used for biodiesel production [29–31]. Later, fish and their wastes were identified as the best sources for biodiesel production because they are rich in fatty acid esters. The fat and oil contents of the fish and their waste completely depend on the fish's age, sex, nutritional condition, health, and the time of year. Fish oil is found in several parts including the flesh, frames, head, fin, skin, guts, and tail of the fish in different quantities [25]. Mainly fish oil contains triglycerides of fatty acids, with variable amounts of phospholipids, glycerol ethers, and wax esters. In addition, the lipid composition in fish is fairly different from land animal lipids and vegetable oils due to the presence of large quantity long-chain PUFAs including omega-3 [eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA)]. Hence, the global fish oil market size was valued at USD 1905.77 million in 2019 and is estimated to reach USD 2844.12 million by 2027 [9].

In this section, the mechanism of extraction of fats and oils from fish waste in biodiesel production was described. Figure 1 explains the schematic representation of biodiesel production from fish waste. The identification of various fish wastes has been carried out using normal selection methods. Also, fish waste or discarded parts of fish were separated based on the type, organ, and size. Different types of discarded fish wastes, such as internal organs, bones, viscera, trimmings, tails, fins, skin, etc., were generally found on the sea shore and in the fish industry [32]. Furthermore, fats and oil were extracted from specific discarded parts of the fish. Before this, it is mandatory to check the fat and oil contents in fish waste through chemical analysis. The extraction of fish oil was carried out using different procedures and pretreatments with various solvents. Table 1 illustrates the different methods and solvents used for fish oil production from various fish wastes. At the initial stages, researchers preferred to use waste fish oil directly for biodiesel production [19], which is always not economical. Distilled water was also used as a solvent at high temperatures to remove free fatty acids from fish waste to obtain better fish oil for biodiesel production [33]. The incubated content was centrifuged and the supernatant with oil was withdrawn using a micropipette and stored in an amber flask at 4 °C. If there are more fatty acid esters, then the waste is useful for the production of biodiesel. Also, the fish waste was converted into crude oil by squeezing or grinding and it was later mixed with boiling water along with a catalyst [34]. Yahyaee et al. [15] designed a machine to separate oil from fish waste. In some experiments, fish waste was crushed with a solvent such as hexane or n-hexane to obtain the crude oil [32,35]. Furthermore, direct-waste fish oil or prepared crude oil will be pretreated to obtain refined oil. In certain experiments, the pyrolysis or fast pyrolysis will be applied to obtain bio-oil for biodiesel production [36]. In the process of pyrolysis, water of a high temperature is required for bio-oil generation. Fish oil was extracted with the help of boiled water, mechanical expeller, and petroleum ether as the solvent [24]. Waste fish oil was degummed with phosphoric acid and later with water and NaOH for efficient biodiesel production [25]. Zhang et al. [27] and Smaisim et al. [28] used n-hexane and hexane as solvents for fat and oil extraction. Finally, the physico-chemical properties of extracted fish oils were analyzed, which is helpful for biodiesel production.

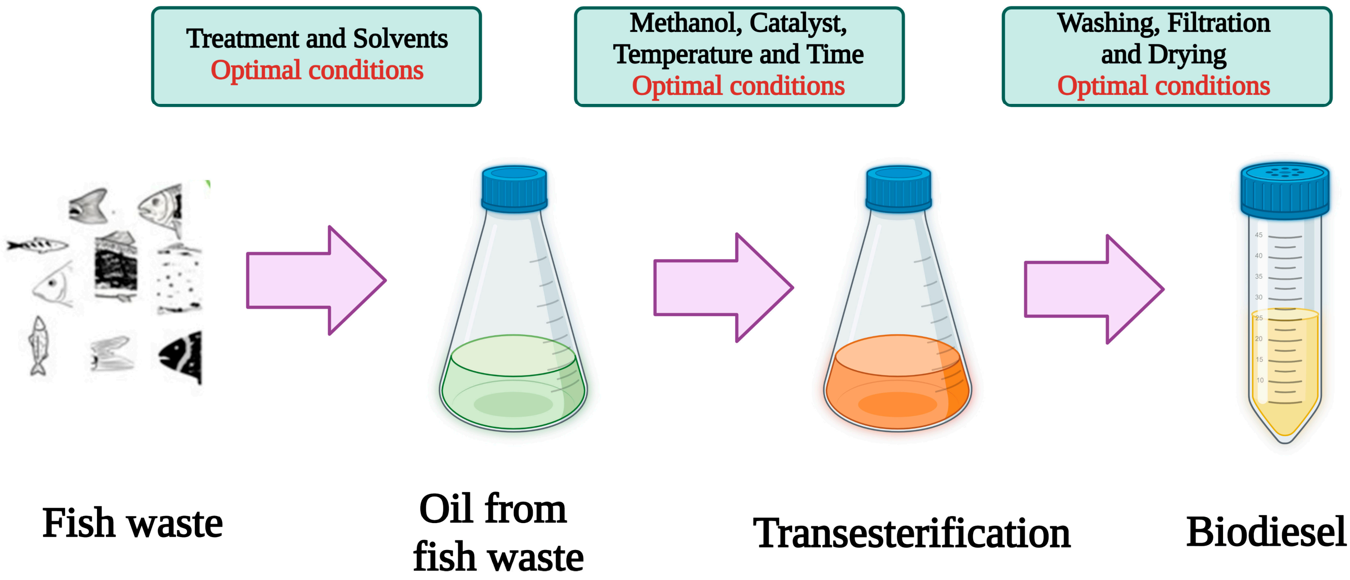

Figure 1. Schematic representation of biodiesel production from fish waste.

Table 1. Extraction of oil from fish waste.

Methods Used	Solvents and Conditions Used	References
Fish waste squeezing, grinding, crushing, mechanical expeller, boiling, pyrolysis or fast pyrolysis, etc.	Water, hexane, n-hexane, petroleum ether, phosphoric acid, NaOH, acid, high temperature, etc.	Yahyaee et al. [15], El-Mashad et al. [19], Madhu et al. [24], Kara et al. [25], Zhang et al. [27], Smaisimet al. [28], Lin and Li [34], Enascuta et al. [32], Sharma et al. [35], Wiggers et al. [36].

In the later stage, extracted and refined oils were used for biodiesel generation. In certain situations, fish oil can also be collected directly from canning industries to conduct biodiesel generation. Before that, it is required to know the nature of the fish oil, and the type of fatty acid, which determines the biodiesel purity [37]. In general, transesterification is a widely used method for biodiesel production [27]. In some experiments, both esterification and transesterification methods were applied to obtain biodiesel. Potent fish oil extraction was achieved from fish waste mixed with the optimum ratio of methanol (CH_3OH) and water. Furthermore, transesterification was carried out for the production of biodiesel from extracted fatty acids and oils.

In transesterification, alcohol (majorly methanol or ethanol) content, i.e., methanol to oil molar ratio, is one of the major concerns. A catalyst is a significant factor for transesterification which may be alkaline or acidic. If it is enzyme-based transesterification, then lipase is added to the mixture and kept at a constant temperature (30–50 °C) in an orbital shaker depending on the conditions. Temperature is another key controlling factor in this reaction, which dictates the yield [25]. Reaction time is also a critical component for efficient biodiesel production. These factors are crucial in transesterification, which dictates the yield levels. Alkaline transesterification, enzyme-based transesterification, thermally-induced transesterification, etc., are some of the transesterification methods. Table 2 illustrates the different transesterification methods and solvents used for biodiesel production. Finally, it is important to know the properties of biodiesel by determining the cetane number, flash point, cloud point, density, kinematic viscosity, etc. [27]. It is also mandatory to know the chemical composition of biodiesel using a standard instrument such as gas chromatography. Finally, the capacity of the biodiesel is checked through the engine testing approach. Several other methods have also been implemented for biodiesel generation worldwide, aside from the conventional wet rendering and dry rendering processes.

Table 2. Extraction of biodiesel from fish waste via different transesterification methods.

S.No.	Reference	Method	Major Solvents and Catalysts	Yield
1.	El-Mashad et al. [19]	Both esterification and transesterification	Methanol and 1% H_2SO_4 as catalyst. Methanol and KOH as catalyst	The two-step process yielded biodiesel from acidified salmon oil
2.	Lin and Li [34]	Transesterification	Methanol and NaOH	Different biodiesel was noticed when compared to waste cooking oil
3.	Huong et al. [21]	Transesterification and ultrasonic mixing	Heterogeneous catalyst like KOH/γ-Al_2O_3 and methanol with ultrasonic mixing	Improvement in biodiesel production was noticed
4.	Patil et al. [38]	Transesterification	Phosphoric acid, sulfuric acid, and methanol	The biodiesel generated was evaluated as per ASTM standards
5.	Garcia-Moreno et al. [39]	Acid-catalyzed pre-treatment to esterify the FFA and alkaline transesterification	Sulfuric acid and methanol. NaOH used as catalyst	Biodiesel was generated using a two-step process
6.	Fadhil et al. [23]	Base-catalyzed transesterification assisted by a co-solvent	Methanol, hexane, and potassium hydroxide	The yield was optimized in this process
7.	Arumugamand Ponnusami [37]	Enzymatic transesterification	Methanol and *Aspergillus niger* lipase as catalyst	Biodiesel obtained and improved the engine efficiency
8.	Girish et al. [33]	Transesterification	Methanol and KOH as catalyst	Generated biodiesel meets the ASTM standards

Table 2. *Cont.*

S.No.	Reference	Method	Major Solvents and Catalysts	Yield
9.	Madhu et al. [24]	Transesterification	Methanol and CaO solid base catalyst was prepared using crab waste	High purity biodiesel was generated
10.	Kara et al. [25]	Esterification and transesterification	FFAs esterification with H_2SO_4 catalyst. Transesterification with methanol and KOH catalyst	Biodiesel generated met the international standards
11.	Enascuta et al. [32]	Esterification and transesterification	Ethanol, $SO^{2-}{}_4/SnO_2$-ZrO_2, and Mg-Al-hydrotalcite loaded with Na_2SiO_3 as base catalysts	Biodiesel production was attained using this method
12.	Samat et al. [26]	Esterification and transesterification	Methanol and sulfuric acid and NaOH	FAME yield is high.
13.	Marin-Suarez et al. [40]	Lipase-catalyzed transesterification	Ethanol and Lipozyme RM IM, Lipozyme TL IM and Novozym 435	Maximum FAEE yield resulted with Novozym 435
14.	Jung et al. [2]	Thermally-induced transesterification	Methanol and Clay	This method proved as promising for biodiesel production.
15.	Ching-Velasquez et al. [18]	Enzymatic transesterification	Lipase from *Thermomyces lanuginosus* and methanol	Biodiesel was produced at 75.3% after 24 h of reaction time.
16.	Smaisim et al. [28]	Transesterification	Nanomagnetic solid base catalyst, methanol, and NaOH	Biodiesel yield is high at 55 °C reaction temperature with catalyst assistance

Most of the popular fish possess oils and fatty acids which, however, depend on the species. Hence, an initial screening of fishes for oils and fatty acid composition through chemical analysis is mandatory [37]. Among the wide variety of fish species, few are famous, such as ahi, albacore, anchovy, monkfish, bonito, bacalao, bass, big eye, black cod, bluefin tuna, Bombay duck, carp, catfish, cod, tilapia, and salmon. Besides strictly balancing food security, it is very important to focus on the waste of these fish for biodiesel production. For instance, *Sardinella longiceps* (Indian oil sardine) waste is one of the best sources for biodiesel production [41]. In addition, *Oreochromis aureus* (tilapia), *Tenualosa ilisha* (Ilish), *Stolephorus indicus* (anchovy), *Eleutheronema tetradactylum* (salmon), etc., are some of the examples of fish whose waste is often used for biodiesel production [42,43]. Choosing a potential candidate fish and their waste for exploring the possibility of improvement in biodiesel production at the industrial level is one of the main targets in the energy sector.

3. Biodiesel Production Using Various Fish Wastes

Biodiesel is one of the clean renewable fuels which causes less pollution when it is combusted. In recent times, increasing demand for renewable energy makes biodiesel an attractive alternative to depleting fossil fuels [5]. The advantage of fish waste is its abundant availability in the seashore and aquaculture industry. In addition, the production of diesel through conventional and chemical methods is expensive and insufficient. So, the evolution of biodiesel from selected fish waste represents a sustainable and environmentally friendly process which is preferable in the present scenario [7]. In the below paragraphs, fish waste used for biodiesel production was emphasized, which will be useful for large-scale generation.

For more than two decades, both the basic and applied science of biodiesel production with different species of fishes and their waste were noticed. In the initial stages, most of the researchers internationally studied fish oil contents in different fishes [44]. Furthermore, few of them focused on fatty acid and oil contents in the fish waste. These works provide the basis for biodiesel production from the oils of fish and their waste. Adebanjo et al. [45] worked on diesel production with animal fat using the method of pyrolysis, which gave the clue that fish oils are useful for diesel generation. Meher et al. [46] illustrated the technical aspects of biodiesel production by transesterification, one of the common methods which is used widely by altering certain stages. Bechtel and Oliveira [47] estimated the lipid contents in cold water fishes. In the same year, Sun et al. [48] worked on the composition of fatty acids in various fishes for diesel production. Preto et al. [49] emphasized the importance of fish oil in biodiesel production. Salmon oil (a by-product of salmon processing) was used as a feedstock for diesel generation by El-Mashad et al. [19]. Both acid-catalyzed (H_2SO_4) esterification and alkaline-catalyzed (KOH) transesterification were followed in this process for biodiesel production and a maximum yield of 99% was attained. Table 3 illustrates the different methods used for biodiesel production from various fish wastes. Alberta et al. [50] estimated the free fatty acid composition using the FTIR technique for biodiesel production. The production of biodiesel was carried out with crude fish oil from the soapstock of marine fish using the transesterification method and by crosschecking the fuel properties [34]. Sodium hydroxide was used as an alkaline catalyst along with methanol in the transesterification process. They noticed that generated biodiesel contains oleic acid (C18:1) and palmitic acid (C16:0) as major components and they also compared the biodiesel with diesel generated through waste cooking oil.

Lin and Li [51] produced the biodiesel from discarded parts of marine fish using the transesterification process. The efficiency of biodiesel generated through discarded parts of marine fish was noticed by testing the engine performance and emission characteristics and also by comparing the biodiesel with biodiesel generated from waste cooking oil. The generation of bio-oil from waste fish oil through a fast pyrolysis method was achieved by Wiggers et al. [36]. The experiment was conducted under steady-state conditions at a high temperature (525 °C) and a bio-oil yield of 72–73% was obtained, which, in turn, is useful as diesel. Wisniewski et al. [52] also used the pyrolysis process at 525 °C for the conversion of fish oil into biofuels. The chemical composition of heavy bio-oil generated through conversion was similar to that of diesel. Andersen and Weinbach [53] proved the potentiality of residues from the fish industry to generate biodiesel in Norway. Santos et al. [20] produced diesel using the oil of *Oreochromis niloticus* (Nile tilapia) through ultrasound-assisted esterification. Initially, the oil was converted into free fatty acids by alcoholic saponification with potassium hydroxide and later acid hydrolysis with sulfuric acid. Furthermore, esterification was carried out with methanol and H_2SO_4 (as catalyst) by applying ultrasound (40kHz) at a 60 W intensity which showed a positive effect. They also applied response surface methodology (RSM) to evaluate the influence of alcohol on oil molar ratio, catalyst concentration, and temperature, and noticed a 98.2% yield after 90 min of reaction. Chakraborty et al. [54] synthesized the biodiesel from vegetable oil using a calcinated scale of *Labeo rohita* as a low-cost heterogeneous catalyst. The response surface methodology was conducted to determine the optimal parameters and a maximum FAME yield of 97.73% was obtained. This work emphasized that different parts of the fish will be useful for biodiesel production. Huong et al. [21] generated biodiesel from the fat of tra catfish through a heterogeneous basic-catalyzed transesterification method using ultrasonic mixing (20kHz). They used $KOH/\gamma\text{-}Al_2O_3$ as a catalyst in this process. The maximum diesel yield was observed in a short reaction time and high amplitude level or a long reaction time and low amplitude level. Additionally, Behcet [43] synthesized the biodiesel from waste anchovy fish oil in the process of transesterification catalyzed by NaOH. Later, biodiesel was blended with diesel in different combinations and the engine capacity was tested. It was concluded that biodiesel is an effective alternative to conventional petroleum diesel.

Biodiesel was generated through the methanolysis of fish oil derived from fish waste using *Carica papaya* lipase [55]. Also, in this study, they tested the molar ratio of oil and methanol, lipase dose, the initial water activity of lipase, temperature, and the effect of various solvents on biodiesel production, and 20% lipase optimized the formation of methyl esters (biodiesel). Zahidah Nurulfitri [56] produced biodiesel using the liquid waste by-products of fish canning industries. Jayasinghe and Hawboldt [57] highlighted biodiesel and other fuel production from fish waste using different methods. The biodiesel production was achieved using fish oil (menhaden oil) through standardizing the optimal conditions [22]. They used the transesterification method by taking methanol and an alkaline catalyst for biodiesel production with standard quality. Generally, the length of the carbon chain in fish oil is greater than in the plant oils, and this larger cetane number improves the diesel engine's performance. Biodiesel production was achieved using oil from fish canning industry wastes [58]. The experiment was performed using the acid esterification pre-treatment method with sulfuric acid as a catalyst and alkaline transesterification. The results showed that 1wt.% H_2SO_4 proved as optimal concentration for a better yield. Yahyaee et al. [15] emphasized biodiesel production using waste fish oil through transesterification method in Iran. Almost 53% of fish waste was in the liquid phase in certain areas in this region. A special machine was designed to separate oil from fish waste and for 1L of fish oil, 0.9 L of biodiesel was produced. Patil et al. [38] synthesized biodiesel through methanolysis using discarded marine fish waste and transesterification methods. Mild and strong acid-catalyzed transesterifications were conducted with phosphoric acid and sulfuric acid along with methanol. They highlighted that the ratio of oil to methanol, catalyst concentration, reaction time, and temperature were crucial for biodiesel production, and obtained the yield as per the ASTM standards. In addition, Ramakrishnan et al. [59] studied the importance and performance of biofuels such as biodiesel through direct engine trials. Garcia-Moreno et al. [39] achieved biodiesel production using fish waste by setting the optimal conditions. They followed a two-step method, including acid-catalyzed pre-treatment, to esterify the FFA and alkali-catalyzed (NaOH) transesterification with methanol and then finally analyzed the fuel properties. High-quality biodiesel was synthesized by Sharma et al. [35] using the single-step transesterification method with methanol (Table 3). Sodium methoxide was used as a homogeneous catalyst in transesterification, and the characterization of diesel was performed through Fourier-transform-nuclear magnetic resonance (FT-NMR). de Almeida et al. [60] used fish oil, palm oil, and waste overfried oil to improve biodiesel production. They followed both acid esterification (H_2SO_4) and alkaline transesterification (NaOH) methods to optimize biodiesel generation. Moreover, they characterized fuel properties such as viscosity, oxidative stability, and COM. The influence of hexane as a co-solvent improved biodiesel production through the transesterification of *Cyprinus carpio* oil, which was studied by Fadhil et al. [23]. The co-solvent reduced the methanol to oil ratio and temperature and optimized the transesterification process. Iastiaque Martins et al. [61,62] proved the biodiesel production capacity of tilapia (*Oreochromis niloticus*) waste and its oil through transesterification. They also characterized the physical and chemical properties of fish-oil-based biodiesel and compared it with diesel for commercial practice. Arumugam and Ponnusami [37] produced biodiesel from waste sardine oil using an enzymatic transesterification process. Generally, sardine oil contains higher free fatty acid contents. The lipase (*Aspergillus niger*) enzyme was immobilized on activated carbon and used as a catalyst for biodiesel production. About a 94.55% yield of methyl ester was noticed under the optimal conditions. Methylic biodiesel generation was achieved by Fadhil et al. [63] through mixing non-edible oils, castor seed oil, and waste fish oil. Gharehghani et al. [64] generated biodiesel from fish waste and compared the capacity with normal diesel by testing the engine. Biodiesel production was carried out with fish waste and later generated fuel was characterized by Girish et al. [33]. Fats were extracted from fish waste using water as a solvent at 80 °C, and saponification was carried out to remove free fatty acids. Transesterification was performed using methanol and potassium hydroxide as catalyst for biodiesel production, which showed the ASTM standards. High-quality biodiesel was generated from fish waste oil [24]. Calcium oxide prepared from crab shells was used as a catalyst in the transesterification process. Saifuddin and Boyce [65] produced biodiesel from *Cyprinus carpio* waste and estimated the performance through engine testing trials. They found less carbon monoxide and hydrocarbon emissions in the engine trials.

Kara et al. [25] produced high-quality biodiesel from waste fish oil by both the esterification of FFAs with H_2SO_4 and transesterification with a KOH catalyst. They observed high free fatty acid contents in waste fish oil obtained from fish-processing industries in Morocco. In this investigation, a high methyl ester group was found in the prepared biodiesel samples. The generated biodiesel did not contain any glycerol and met the international standards. Enascuta et al. [32] designed the simultaneous process of preparing oil with high contents of omega-3 polyunsaturated fatty acid and biodiesel. Hexane was used as a solvent for oil extraction from fish waste. In the process of biodiesel production, the researchers followed both esterification and transesterification methods. An environmentally friendly heterogeneous superacid catalyst (SO_4^{2-}/SnO_2-ZrO_2) was used in the esterification reaction of FFA with ethanol. Also, the saturated content of FAEE was used for biodiesel production and was successful. The capacity of fish waste to generate biodiesel was analyzed by Samat et al. [26] through both esterification and transesterification methods. Marine fish oil generated through the pretreatment method undergoes an esterification process to reduce the free fatty acids. Later, the oil was transesterified with methanol, using NaOH as an alkaline catalyst for diesel production. Ramesh Kumar et al. [66] produced biodiesel using fish waste via the transesterification method and by using KOH as the catalyst. The generated biodiesel performance was analyzed using the specific engine. Lipase-catalyzed transesterification was carried out for biodiesel production using fish waste [40]. Novozyme 435 showed a better performance when compared to lipozyme RMIM and lipozyme TLIM with less loss of activity in lipase-catalyzed transesterification.

Biodiesel was produced by the synthesis of ethyl esters from fish oil waste through an alkaline transesterification method [67]. In the transesterification process, ethanol and NaOH catalyst were used for maximum yield. Jung et al. [2] applied a thermally-induced transesterification method, using clay as a porous material, for biodiesel production from fish waste. Al Azad et al. [10] identified certain fish wastes as potential biodiesel sources which contain high suitable fatty acids. The methylation of the extracted crude fish oil was carried out to obtain FAME, and further transesterification was applied for biodiesel production. Keshri et al. [16] characterized the properties of biodiesel generated from fish waste. Water is used as a solvent for the extraction of fats and later saponified with sodium hydroxide to reduce free fatty acid contents. Transesterification was carried out using potassium hydroxide as a catalyst for biodiesel production. Enzymatic transesterification was carried out for biodiesel production from the oil of viscera fish waste. Lipase from *Thermomyces lanuginosus* was used and finally a 75.3% biodiesel yield was noticed after 24 h of reaction time [18]. Zhang et al. [27] produced biodiesel from fish waste (grass carp, catfish, and sea bass waste) using the transesterification method. Biodiesel with 100% purity was reached with sea bass wastes. In addition, a high protein content was generated from the fish waste, which may be useful as a high-protein feed. Alfio et al. [14] emphasized the usage of biological waste for biodiesel generation, including fish waste. Biodiesel synthesis was carried out via fish waste oil obtained through supercritical methanol and thermodynamic optimization [68]. Smaisim et al. [28] synthesized the biodiesel using a nanomagnetic catalyst via thermodynamic analysis. Biodiesel yield (95 wt%) was high at a 55 °C reaction temperature along with catalyst assistance. Jaiswal et al. [7] highlighted the lipid extraction from fish processing residues for sustainable biodiesel production. Recently, Adhithan and Sachdeva [69] generated biodiesel from freshwater *Labeo catla* waste and blended it with pure diesel using various percentages. Also, they cross-checked the emissions and found HC, CO, and smoke for the FBD-powered CI engine were lesser than those of the diesel-powered engine. Several other workers described the biochemical and molecular basis or reasons for variations in fatty acid contents in fish oil, and ultimately learned more about the various mechanisms. Overall, this information will be useful for the augmentation of biodiesel production using different fish wastes.

Table 3. Biodiesel production from fish waste.

S.No.	Method of Biodiesel Production	Output	References
1.	Biodiesel was produced via a two-step process from salmon oil. Acid-catalyzed esterification and alkaline-catalyzed transesterification were followed in this process.	A maximum biodiesel yield of 99% was obtained using a total methanol/molar ratio of 9.2% and 0.5% (*w/w*) KOH.	El-Mashad et al. [19]
2.	Biodiesel was produced from the discarded parts of marine fish and tested for engine performance and emission characteristics.	Production of different biodiesel was obtained with fish oil compared to waste cooking oil	Lin and Li [34]
3.	Crude oil was produced from the discarded parts of marine fish which in turn used for transesterification and compared with biodiesel from waste cooking oil and ASTM No.2D diesel.	Marine fish-oil biodiesel has different qualities than biodiesel from waste cooking oil.	Lin and Li [51]
4.	Production of biodiesel from fish waste oil through pyrolysis. Pyrolysis resulted in 72.83% of liquid which in turn gives light and heavy bio-oil and oil sludge	Fast pyrolysis resulted in bio-oil which will be used as an energy source.	Wiggers et al. [36]
5.	Biodiesel produced from residual animal fat and fish in Norway.	Almost 100kt of fish fat residue is assumed to be dumped which gives an additional 95 kt biodiesel.	Andersen and Weinbach [53]
6.	Biodiesel was produced through ultrasound-assisted esterification of *Oreochromis niloticus* oil.	More methyl esters (biodiesel) was noticed with ultrasound effect.	Santos et al. [20]
7.	Biodiesel was generated fromoil using the scale of *Labeorohita* as a low-cost heterogeneous catalyst. The main component of fish scale, i.e., HAP (hydroxyapatite), could be transformed into β-tri-calcium phosphate which is useful for the generation of biodiesel from vegetable oil.	Calcinated fish scale was used as a catalyst which is helpful for biodiesel production from vegetable oil.	Chakraborty et al.[54]
8.	Production of biodiesel from the fat of tra catfish was carried out through heterogeneous basic-catalyzed transesterification using ultrasonic mixing. Catalyst like $KOH/\gamma-Al_2O_3$ was used along with ultrasonic mixing.	Biodiesel production was achieved with fat of tra catfish.	Huong et al. [21]
9.	Diesel generation was carried out using anchovy fish waste and the performance and emission were tested in a diesel engine.	Engine performance was enhanced with biodiesel blended with diesel.	Behcet [43]
10.	Production of biodiesel was achieved by methanolysis of fish oil catalyzed by *Carica papaya* lipase.	Maximum methyl ester (biodiesel) production was noticed.	Pinyaphong et al. [55]
11.	Biodiesel was produced using the liquid waste by-product of the fish canning industries.	Successfully, biodiesel was generated.	Zahidah Nurulfitri [56]
12.	Production of biodiesel was achieved using menhaden fish oil through transesterification.	Standard biodiesel production was achieved with menhaden fish oil.	Hong et al. [22]
13.	Production of biodiesel was achieved using oil from fish canning industry wastes using dehydration, acid esterification, and alkaline transesterification.	1 wt.% H_2SO_4 proved as the optimal concentration for better yield.	Costa et al. [58]
14.	Biodiesel generation was carried out using waste fish oil as a source of renewable fuel in Iran. Oil extraction machine was introduced to separate oil and fish waste.	0.9 L of biodiesel was generated for each liter of fish oil.	Yahyaee et al. [15]

Table 3. *Cont.*

S.No.	Method of Biodiesel Production	Output	References
15.	Biodiesel production was achieved through methanolysis of fish oil derived from the discarded parts of marine fish. Both phosphoric acid and sulfuric acids were used.	Optimization of biodiesel was achieved using this method.	Patil et al. [38]
16.	Biodiesel production was achieved with waste fish oil using a two-step method.	Optimized biodiesel production was noticed	Garcia-Moreno et al. [39]
17.	Quick production of high-quality biodiesel was achieved from waste fish oil through single step transesterification.	Standard biodiesel was generated.	Sharma et al. [35]
18.	Biodiesel production from waste fish oil, palm oil, and waste frying oil was achieved.	Various combinations of biodiesel were generated and cross checked for composition.	de Almeida et al. [60]
19.	Influence of co-solvent on biodiesel production through transesterification of *Cyprinus carpio* oil was studied.	Base-catalyzed transesterification assisted by a co-solvent resulted maximum yield.	Fadhil et al. [23]
20.	Biodiesel was produced usingtilapia fish oil and waste.	Highlighted the importance of tilapia oil and waste for biodiesel production.	Iastiaque Martins et al. [61]
21.	Physical and chemical properties were studied for fish oil biodiesel.	Reviewed the physico-chemical properties of biodiesel generated from fish oil.	Iastiaque Martins et al. [62]
22.	Generation of biodiesel through enzymatic transesterification of waste sardine oil and evaluation of its engine performance was carried out. *Aspergillus niger* lipase used as catalyst.	Engine efficiency was enhanced with blend of sardine biodiesel with diesel.	Arumugam and Ponnusami [37]
23.	Production of biodiesel was carried out using mixed non-edible oils, castor seed oil, and waste fish oil.	Optimized biodiesel production was noticed.	Fadhil et al. [63]
24.	Diesel engine combustion characteristics and emission were studies using fish biodiesel.	Generated biodiesel was tested for engine combustion.	Gharehghani et al. [64]
25.	Biodiesel was produced from fish waste by transesterification and characterization of generated biodiesel was performed.	Biodiesel produced meets the ASTM standards.	Girish et al. [33]
26.	High-quality biodiesel was produced using feedstock and catalyst (CaO) derived from crab wastes.	High quality biodiesel was prepared.	Madhu et al. [24]
27.	Using *Cyprinus carpio* waste, biodiesel production was achieved and biodiesel performance was also tested.	The method used for biodiesel is useful for commercial practice and it meets the ASTM standards.	Saifuddin and Boyce [65]
28.	Production of biodiesel was carried out from waste fish oil having high free fatty acids in Moroccan fish-processing industries.	Biodiesel formed through esterification and transesterification which meets the international standards	Kara et al. [25]
29.	Production of oil enriched in omega-3 polyunsaturated fatty acids and biodiesel from fish wastes.	Saturated content of FAEE was used for biodiesel production and was successful.	Enascuta et al. [32]
30.	Fish-waste-based biodiesel production was achieved using both esterification and transesterification methods	Optimal biodiesel production was noticed	Samat et al. [26]
31.	Performance analysis of biodiesel produced from fish waste was carried out.	Biodiesel was tested for engine efficiency.	Ramesh Kumar et al. [66]

Table 3. *Cont.*

S.No.	Method of Biodiesel Production	Output	References
32.	Biodiesel was produced from waste fish oil by reusing immobilized lipases (Lipozyme RM IM, Lipozyme TL IM and Novozym 435) in the process of transesterification.	High FAEE yield was obtained with Novozym 435 and an excess of ethanol.	Marin-Suarez et al. [40]
33.	Biodiesel production was achieved by synthesis and optimization of ethyl esters from fish oil waste.	Optimal ethyl esters were prepared for biodiesel production.	Cardoso et al. [67]
34.	Generation of biodiesel was achieved from fish waste via thermally-induced transesterification using clay as a porous material.	More biodiesel was obtained.	Jung et al. [2]
35.	Source of biodiesel was identified in fish waste feedstock.	Certain fish wastes possess suitable fatty acids for biodiesel production.	Al Azad et al. [10]
36.	Production of biodiesel from fish waste and characterization were performed.	Generated biodiesel was tested for the ASTM standards and found useful for engine combustion.	Keshri et al. [16]
37.	Generation of biodiesel from oil of fish waste by enzymatic catalysis and charaterization were performed	A 75.3% biodiesel yield was obtained after 24 h of reaction time.	Ching-Velasquez et al. [18]
38.	Generation of biodiesel from fish processing wastes was achieved using in situ transesterification. Also, they obtained the high protein feed in this experiment.	Obtained 100% biodiesel purity with sea bass wastes.	Zhang et al. [27]
39.	Production of biodiesel from fish waste oil through synthesis via supercritical methanol and thermodynamic optimization. RSM technology was applied for weight ratio of methanol to fish-waste oil (W), the reaction temperature (T), the pressure (P), and the feed flow rate (F) on yield.	The maximum yield was estimated to be 94.6% (g/g) under optimal conditions.	Espootin et al. [68]
40.	Synthesis of biodiesel with fish waste using nanomagnetic catalysts.	Biodiesel yield (95 wt%) was high at 55 °C reaction temperature along with catalyst assistance.	Smaisim et al. [28]
41.	Biodiesel was generated from *Labeo catla* and tested for gas emissions and performance.	Biodiesel was blended with pure diesel and certain emissions were found to be reduced.	Adhithan and Sachdeva [69]

4. Effect of Physico-Chemical Factors on Biodiesel Production from Fish Waste

Apart from vegetable oils (majorly soybean oil), fish feedstock or its waste is one of the most promising sources to investigate for efficient biodiesel production. But, the yield completely depends on the type of fish waste, the efficient extraction of the fatty acid, and the oil contents and method of biodiesel generation along with various physico-chemical conditions in the production process [54]. In general, a two-phase procedure is followed for the fish waste obtained from the fish industry. The first one is the fish growth phase, and the second includes fish oil extraction and biodiesel production. For naturally available fish waste on the seashore, it is necessary to optimize the conditions during the second phase, i.e., fish oil extraction and biodiesel generation. Fish growth and development completely depend on nutrient availability, temperature, pH, water quality, pathogens, etc. [70]. In the fish industry, feeding them with the best nutrients and avoiding pathogen attack are critical factors. The maintenance of optimal temperature and water quality levels (pollution levels) in fisheries are considered as key issues. In the second phase, optimal conditions for efficient fish oil extraction and biodiesel production require cross-checking the chemical composition of fish leftovers; the pretreatment condition; acid wash; solvents; improvement in fatty acid profiles; catalysts; the temperature, reaction time, and implementation of the best protocols [34–51].

The fresh fish waste sample is most preferable when compared to old dried fish waste. The separation of each discarded part of fish waste is one of the crucial factors for a better yield. The fish oil extraction was performed from fish waste using different solvents, including hexane, n-hexane, water, etc. Moreover, the selection of solvents depends on the type of fish and its waste [25]. The content of the water used as a solvent is also a key factor in extracting a potential fish oil for efficient biodiesel production. The collection of fish oil directly from the canning industry may be helpful to obtain a better output. Methods such as the pyrolysis of fish oil, esterification, transesterification, etc., were proven to be best for biodiesel production [20,52]. Generally, oil or fat reacts with a short-chain alcohol (methanol or ethanol) in the presence of a catalyst which can be acidic, basic, or enzymatic. The optimization of experimental conditions was performed by varying the catalyst concentration and reaction temperature for a better yield [24]. Alkaline catalysts (KOH, NaOH, $NaOCH_3$, etc.) are generally used for biodiesel production. The selection of lipase in transesterification is a valid concern, which, in turn, depends on the fish waste. It is also important to maintain more methanol and less oil in the transesterification process to improve the yield. Overall, the type of fish waste, method of extraction of fats and oils, quality of fish oil, and process of biodiesel production are the key factors to be considered for a better output. Figure 2 explains the key factors involved in biodiesel production from fish waste.

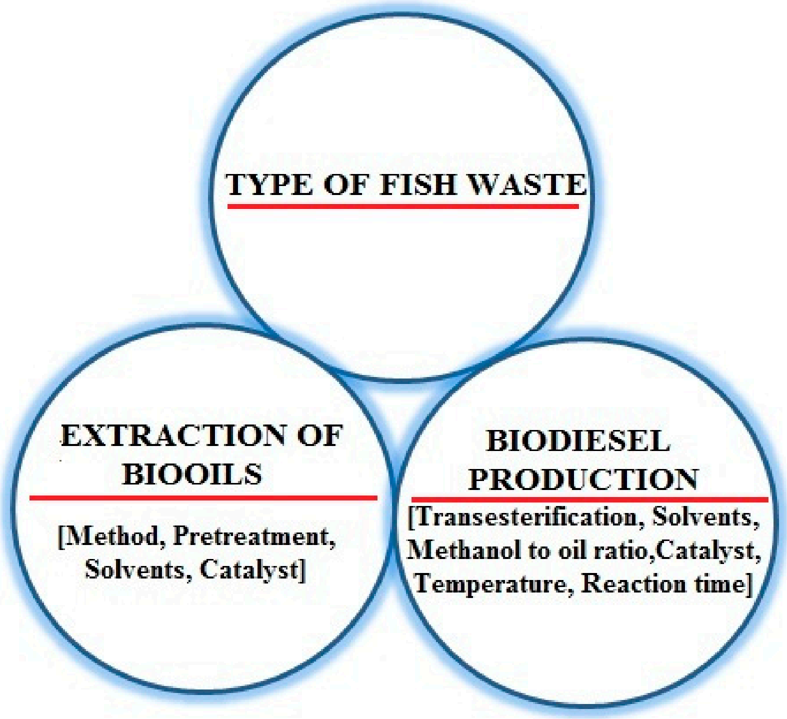

Figure 2. The key factors involved in biodiesel production from fish waste.

5. Future Prospects

Both the modern lifestyle and the industrial revolution are gearing up for a conflict with the energy crisis. Hence, a renewable energy source, such as biodiesel, is one of the best and cost-effective alternatives to fossil fuels. Biodiesel is a form of alternative energy that can be generated from plants, algae, animals, and fish which have oils and long-chain fatty acid esters. Moreover, fish wastes are more available in certain countries, specifically those with coastal areas.

Furthermore, fish waste is a more affordable source of fatty acids particularly in coastal regions. Though the production of biodiesel from fish waste was achieved by a few workers, it still needs more success for use in commercial practice. In addition, a lot of efforts need to be carried out regarding the selection of locally available fish by consulting classical fish biologists. Say, for example, tilapia is the most processed freshwater fish in several places including Brazil. Sardine, tuna, and salmon are popular fishes for biodiesel production in several regions. The distribution of fats and oil in fish parts vary depending on the species, and the selection of discarded parts of the fish is also a valid consideration. Figure 3 displays the variation in oils in different fish waste collected from local markets.

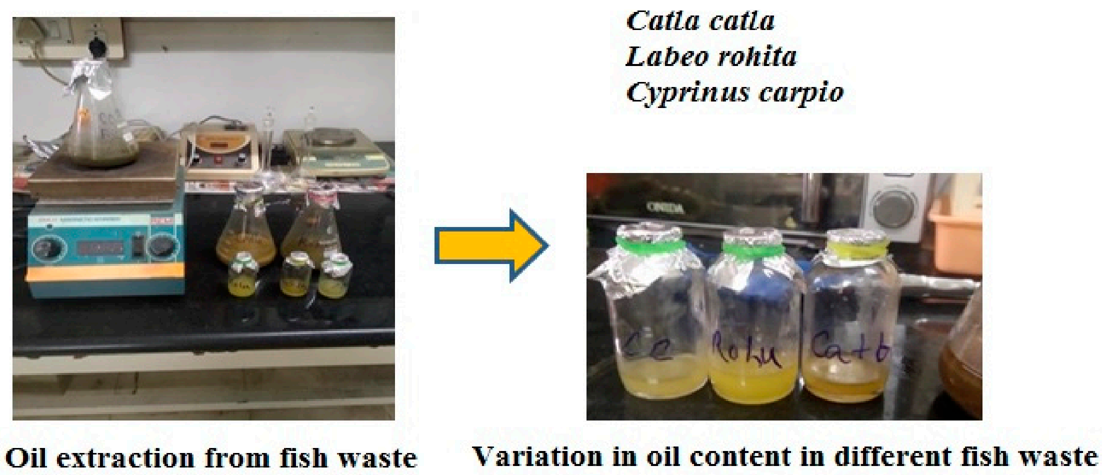

Figure 3. Variation in oil contents with different fish waste. Oil was extracted from fish waste byboiling with water at high temperature, crushing, settling, and filtering.

Along with fish and their parts selection, the content of fish waste needs to be analyzed. A massive screening of the fish and their wastes rich in oils and fatty acid profiles is required, which, in turn, is useful for biodiesel production. To achieve this concept, the identification and separation of fish waste collected from the seashore or fish industry are mandatory. The disposal, collection, and recycling of fish wastes have become challenging issues. Particularly, recycling has been a key issue for several years. It needs to be resolved, and research in this area needs to be expanded enormously. Figure 4 illustrates the different factors that are helpful in augmenting biodiesel production from fish waste.

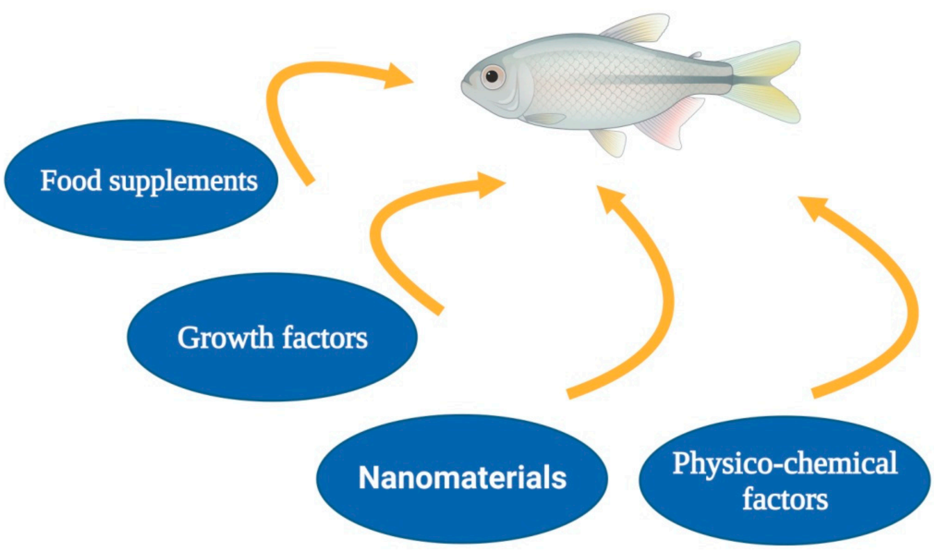

Figure 4. Possible methods to improve biodiesel production using various factors.

The fish waste obtained from the seashore needs assistance only in the fish oil extraction and biodiesel production phase and no need of taking care of the fish growth phase. In contrast, the fish industry needs to improve the food supplements for fish cultures for better growth and development. The lipid content in fish is different from other animal lipids or plant oils which possess large amounts of long-chain PUFAs. Moreover, fish are unable to synthesize certain fatty acids including omega-3, but they obtain them through algae or plankton in their diets. The inclusion of fat-rich algal samples, other food waste, and nutrients in fish cultures may be helpful to improve the biomass in turn fish oil. In addition, it is also suggested to include growth factors, including certain minerals, in the fish culture. In the later phase, optimal conditions need to be established for both fish oil extraction and transesterification to improve biodiesel production. Specifically, oil extraction from fish waste needs to be improved by adding various solvents, depending on the waste. The identification of novel catalysts will also be helpful for enhancing biodiesel. Temperature setting and an incubation period are crucial for maximum yield, which, in turn, depends on the waste. The screening of new processing methods may be useful to improve the fish oil contents in turn biodiesel production. Other factors such as water quality, heavy metal pollution, pH, etc., play major roles in increasing the output.

Nanoparticles are presently in use for biological applications, including in the bioenergy sector, due to their unique physico-chemical factors. The usage of nanomaterials for fish culture in the fisheries will certainly be helpful in improving the useful fatty acid contents in the fish, which, in turn, are useful for enhancing biodiesel. Overall, the whole process requires the optimization of conditions for improving biodiesel production, i.e., the selection of fish, selection of discarded parts of fish waste, chemical analysis of fish waste, extraction of fish fatty acid and oil contents, selection of catalyst and lipase, incubation temperature, reaction time, etc. Moreover, these biofuels tend to provide a higher degree of national energy security in an eco-friendly and sustainable manner by adding conventional energy resources, decreasing the dependence on imported fossil fuels, and fulfilling energy needs. The production of biodiesel from enormous fish waste is also one of the best waste management practices in coastal regions. Furthermore, these studies may bridge the gap between the demand and supply of fossil fuel, as well as improve the environmental situation, thereby improving economic conditions.

6. Conclusions

The population explosion and regular depletion of fossil fuels urge us to concentrate more on renewable fuels. Enhancing biodiesel production using fish waste is one of the best alternatives in the energy sector. In addition, the disposal of fish waste is a pressing issue, urging the novel solutions to implement sustainable waste management practices. Therefore, this review emphasizes the mechanism of biodiesel production from fish waste. Few research groups are working to achieve the large-scale production of biodiesel from fish waste, which is highlighted in this review. The identification of potential fish waste and estimation of fatty acid contents are the initial important steps in biodiesel generation. The collection or purification of waste fish oil and generation of bio-oil from fish waste are the key concerns for biodiesel production. The production of biodiesel from fish waste by using several potential methods and the involvement of various factors which augment the output are also discussed. Specifically, fish waste or waste oil pretreatment, bio-oil production, esterification, transesterification, etc., were emphasized in detail, which will be useful for commercial application. In conclusion, this knowledge may be useful for biotechnological applications with respect to biodiesel production from fish waste.

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Institutional Review Board Statement: All the fish wastes used in the present study were collected from a local market.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is available with corresponding authors upon request.

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

Abbreviations

%—Percentage; ASTM—American Society for Testing and Materials; °C—centigrade; CH_3OH—methanol; C_2H_5OH or EtOH—ethanol; CI Engine—compression ignition engine; CO—carbon monoxide; DHA—docosahexaenoic acid; EPA—eicosapentaenoic acid; FAO—The Food and Agriculture Organization of the United Nations; FAEE—fatty acid ethyl esters; FAME—fatty acid methyl esters; FFA—free fatty acids; HC—Hydro carbons; FTIR—Fourier-transform infrared spectroscope; FTNMR—Fourier-transform nuclear magnetic resonance; H_2SO_4—sulfuric acid; hrs—hours; IEO—International Energy Outlook; kHz—kilohertz; KOH—potassium hydroxide; min—Minutes; NaOH—sodium hydroxide; $NaOCH_3$—sodium methoxide; NPs—nanoparticles; PUFAs—polyunsaturated fatty acids; RSM—response surface methodology; UN—United Nations.

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