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Sustainable development of bioenergy and soil enhancement based on Kemiri Sunan (*Reutealis trisperma*) oil and bioprocessing waste

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Abstract. Kemiri Sunan (*Reutealis trisperma*) presents numerous advantages over other biofuel-producing plants due to its straightforward processing and high oil yields. This makes it a viable solution for reducing fossil fuel consumption by producing sustainable biofuels. This study aims to explore the potential of Kemiri Sunan (*Reutealis trisperma*) as a sustainable source of biofuel to reduce fossil fuel consumption. The study employed a bioprocessing method that includes oil extraction and bioprocessing of solid waste into soil enhancers through enzymatic composting fermentation. The results indicate that Kemiri Sunan produces high yields of enzymatically hydrolyzed oil suitable for biofuel production and offers sustainable energy output for up to 50 years. In addition, the solid waste generated during processing can be effectively utilized to enhance soil quality, contributing to sustainable organic fertilizer production. In conclusion, Kemiri Sunan is a promising candidate for bioenergy due to its efficient oil production, minimal environmental impact, and simplified policy framework, as it avoids the food-energy conflicts associated with crops like palm oil. Its cultivation of degraded land ensures sustainability, making it a valuable future resource for green energy.

1 Introduction

Indonesia's biofuel industry heavily depends on palm oil, supported by the nation's extensive plantations and status as the world's top palm oil producer. This dominance has positioned Indonesia as a key player in the global biodiesel market, where palm methyl ester is the primary biofuel. However, this reliance on palm oil has raised concerns about deforestation, biodiversity loss, and food security. To address these challenges, the Indonesian government has introduced sustainable palm oil certification programs to promote environmentally friendly and socially responsible practices within the sector [1,2,3,16].

While palm oil remains the primary feedstock for biofuels, Indonesia is diversifying its production by exploring second-generation biofuels from non-food sources such as jatropha, algae, waste materials, and Kemiri Sunan (KS). These alternatives help reduce competition with food crops and lessen environmental impacts [4,5,17].

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As a high-yield source of non-edible oil, KS offers an effective option for Biodiesel without competing for food resources. In contrast, its Biodiesel is recognized for its high energy content and environmental benefits. Additionally, KS oil shows potential as a natural insecticide, providing an eco-friendly solution for pest control [6,7, 8].

The processing waste of Kemiri Sunan (KS) provides significant advantages. Residual biomass, including shells and press cake, can be transformed into organic fertilizers, enriching soil health and productivity due to nutrient content. Their high lignin and cellulose content makes them suitable for bioethanol production, enhancing KS's sustainability as a bioresource [9,10,11].

The organic waste from KS processing serves multiple purposes. It is rich in nutrients like nitrogen, potassium, and phosphorus. The cellulose in KS shells can be utilized for bioenergy products like biogas or bioethanol, helping to divert organic waste from landfills and reduce environmental impact. These attributes highlight KS's potential as a biofuel source and a contributor to sustainable agriculture and effective waste management [12].

Producing soil-enhancers from Kemiri Sunan (KS) organic waste involves bioactivators containing a consortium of microorganisms that accelerate the decomposition of organic material through fermentation 15].

Bioactivators act as inoculants, introducing a blend of microorganisms, including nitrogen-fixing bacteria, phosphate solubilizers, growth hormone regulators, and substances that neutralize toxins. They are enriched with essential minerals like titanium, potassium, and iron; these components help break down solid waste into organic elements, improve soil structure, boost fertility, and enhance the soil's microbial diversity, ultimately repairing soil damage and increasing crop yields [13,14].

This study aims to evaluate the potential of KS as a sustainable bioenergy source by assessing the environmental, agricultural, and economic benefits of KS oil and its byproducts, as well as the feasibility of using KS processing waste for soil enhancers, contributing to a circular economy and sustainable agricultural practices.

2 Materials and Method

2.1. Preparing Biodiesel using Kemiri Sunan Oil

For each litre of KS oil, approximately 0.2 to 0.3 litres of methanol and about 5 gr of KOH should be used. Dissolve the measured KOH in the methanol thoroughly to form potassium methoxide, which acts as a catalyst. Heat the palm oil to about 55-60°C to enhance the efficiency of the reaction. Gradually introduce the methanol-KOH solution into the warmed palm oil while continuously stirring for 30 to 60 minutes to promote an even reaction. Once mixed, allow the solution to rest in a safe location for several hours (8 to 24 hours). During this time, the Biodiesel will separate from glycerin, a byproduct. Use a separation funnel to remove the glycerin layer, leaving the Biodiesel in the upper container. To eliminate impurities, wash the Biodiesel gently with water. Add a small amount of water, mix well, and then allow it to settle. Finally, gently heat the Biodiesel to evaporate any remaining water [11].

2.2. Preparation of Kemiri Sunan Organic Waste

The production of soil-enhancing fertilizer from Kemiri Sunan organic waste using bio-activators involves a detailed process that leverages a consortium of microorganisms through fermentation and composting, where collection and sorting was conducted by gathering the organic waste material from KS processing, such as shells, press cake, and other residual biomass. If necessary, shred or grind the waste into smaller, uniform pieces to facilitate quicker decomposition and a more consistent fermentation [12,13,21].

2.3. Selection and Preparation of Bio-Activators

The bio-activators should contain a mix of beneficial consortium microorganisms, including nitrogen-fixing bacteria, phosphate-solubilizing bacteria, cellulose-decomposing fungi, and other organic matter decomposers. To enrich the bio-activators, essential minerals like nitrogen, potassium, phosphorus, and trace elements (e.g., magnesium and zinc) that support microbial growth and activity were added [14].

2.4. Mixing and Inoculation

The Inoculation Process was carried out by mixing the prepared Kemiri Sunan organic waste with the bio-activator to ensure an even distribution of microorganisms and promote uniform fermentation and decomposition. Moisture Control was conducted to maintain the optimal moisture content, typically around 50-60%, to facilitate microbial activity without causing anaerobic conditions [14,15,21].

2.5. Fermentation Process and Composting Stage

Initial fermentation was addressed to allow the inoculated waste to ferment in a controlled environment. This stage is crucial for breaking complex organic materials into simpler compounds by the action of microorganisms. Temperature management is needed to monitor and maintain the temperature between 50-60°C, as microbial activity generates heat, which is necessary for efficient decomposition. To provide optimum aeration, it was regularly turn or aerate the composting material to ensure adequate oxygen supply, prevent the buildup of harmful gases, and promote aerobic conditions. After the initial fermentation, the material enters the composting stage, where decomposition continues slower. The microorganisms continue to break down the organic matter, converting it into humus, a nutrient-rich substance beneficial for soil health [22,23,24]. The composting process occurred in 3-5 weeks, depending on environmental conditions and the nature of the organic waste

2.6. Final Curing and Maturation

Once the active composting phase is complete, allow the material to cure or mature. This step ensures that the fertilizer is fully stabilized, free of pathogens, and ready for application to the soil. To test the final product for pH, nutrient content, and the presence of heavy metals to ensure it meets the required standards for soil enhancement, analysis was carried out using a pH meter to measure the pH and proximate analysis to determine the nutrient content, while the content of heavy metals in the final product was determined using Atomic Absorption Spectroscopy (AAS). Since the AAS is a precise and widely used laboratory method for detecting and quantifying heavy metals in soil enhancers [22,23,24, 31].

2.7. Application of Soil-Enhancing Fertilizer

The finished fertilizer can be applied to agricultural fields as a soil enhancer. It improves soil structure, enhances nutrient retention, and supports the growth of beneficial soil microorganisms. By recycling Kemiri Sunan waste into a valuable soil enhancer, the process reduces waste and contributes to sustainable agriculture by promoting soil health and fertility. This detailed process outlines how Kemiri Sunan's organic waste can be transformed into a high-quality, environmentally friendly soil-enhancing fertilizer by using bio-activators and composting techniques. This process yields KS oil that can be used for Biodiesel, natural insecticides, or other applications. This biofertilizer enhances soil fertility and supports sustainable agriculture [24,25].

3 Results and Discussion

3.1. Characteristic of Biodiesel prepared with Kemiri Sunan Oil

The oil content of Kemiri Sunan seeds (Fig. 1) ranges between 50-60% by weight, with the primary fatty acids being oleic acid (40-50%) and linoleic acid (30-40%), making it well-suited for biodiesel production. However, since the oil is non-edible, it avoids competition with food crops, further enhancing its viability for biofuel production (Fig. 2) [1,2].

The biodiesel production process is divided into two stages. In the first stage, 80% of the methoxide solution is mixed with the oil, leading to the initial separation of methyl ester and glycerol after 45 minutes of stirring. In the second stage, the remaining 20% of methoxide is added, and the mixture is heated for 30 minutes, further separating glycerol. The overall biodiesel yield from Kemiri Sunan oil is high, with only minimal glycerol residue reported [7].

Fig 1. Kemiri Sunan fruits and seeds (*sources: Panen News, LPPM UPN "Veteran" Yogyakarta, and Bebeja.com*).

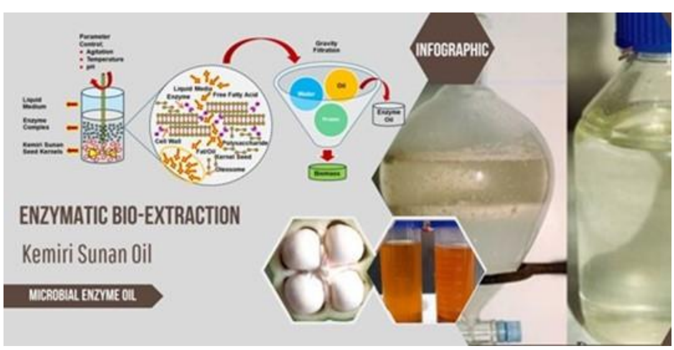

Fig 2. Infographic of Kemiri Sunan Enzymaticlly Bioextraction.

Table 1 presents the characteristics of Kemiri Sunan oil as a biofuel, demonstrating its compliance with the SNI-04-7182-2006 standard, indicating its suitability as an eco-friendly, non-fossil fuel alternative. The production of Biodiesel from this oil involves a transesterification process using methanol. Additional potassium hydroxide (KOH), representing the percentage of the oil's weight, is dissolved in methanol to create methoxide as the reaction catalyst [7,8].

Table 1. Kemiri sunan crude oil composition (*Sources; Konsorsium PT Energy Mineral Resources and PT Bahtera Hijau Lestari Indonesia*).

Parmeters	Unit	SNI-04-7182-2006	Value of KS Oil
Density at 40 °C	KG/m^3	850-890	881.2
Kinematic Viscosity at 40 °C	cSt	2.3-6.0	4.4
Calorific Value	MJ/Kg	-	39.7758
Flash Point "PMCC"	°C	Min.100	129.5
Cetane Number	-	Min 51	53.9
Fog Point °C	Maks 18		12
Base Sediment and Water	%vol Mks 0.05		0
Copper Plate Corrosion at 3/50 °C	No.ASTM	Max No. 3	1b
Sulphated Ash	%wt	Max 0.02	0.02
Sulphur	mg/Kg	Max 100	13
Phosphor	mg/Kg	Max 10	0.98
Acid Number	mg KOH/g	Max 0.8	0.1044
Free Glyserol	%wt	Max 0.02	0.0091
Total Glyserol	%wt	Max 0.24	0.2086
Alkyl Ester Content	%wt	Min 96.5	99.56
Iodine Number	%wt	Max 115	95.24
Halphen's Test	-	Negative	Negative

However, biodiesel production from KS oil also produces byproducts, including glycerol and some organic waste materials. Approximately 10-15% by weight of the oil is converted into glycerol, which can be separated and purified for other uses. Additionally, shells and press cakes, which are high in lignin and cellulose, are suitable for bioethanol production and as organic fertilizers [4,27].

These waste materials can be used to produce biogas and bioethanol, contributing to the circular economy since kemiri sunan trees thrive on marginal lands, reducing the need for deforestation and lowering environmental impact (Fig. 3). Hence, the cultivation of Kemiri Sunan on degraded lands can help restore soil health, promoting sustainability [27,28].

The organic fertilizers derived from KS waste are rich in nitrogen, potassium, phosphorus, and other trace elements, which are beneficial for soil enrichment. Initial research was conducted on a small scale, using 50-liter batches of Kemiri Sunan oil. The process has shown potential for scaling up, with consistent quality and yield observed in larger trials. This data highlights the potential of KS as a sustainable bioresource, offering valuable insights into its use in biodiesel production, environmental sustainability, and economic viability [29, 30].

Fig 3. Infographic of Bioprocessing Kemiri Sunan Waste Materials.

Organic fertilizers refer to any type of organic material derived from waste broken down by decomposer microbes, transforming it into accessible nutrients that enhance soil quality. These fertilizers boost agricultural yields, minimize environmental pollution, and promote sustainable environmental quality. Over time, the consistent use of organic fertilizers can lead to improved land productivity and help prevent soil degradation.

Research on the use of bioactivators has shown that they can be used to create high-quality soil enhancers by using waste from the distillation of eucalyptus leaves as the raw organic material (Fig. 6). This waste comes from the eucalyptus oil refinery in Jatimungul Village, Indramayu Regency. Additional materials like liquid agriminerals and enzyme powders, which serve as bioactivators made from microbial consortia (Fig. 3), are also used. This experiment aims to gather information on the effectiveness of using organic fertilizers and soil conditioners produced by fermentation with bioactivators, particularly in pilot-scale trials. This is part of an effort to develop organic fertilizers and soil conditioners from the bioprocessing of eucalyptus leaf distillation waste in Jatimungul Village, Indramayu Regency [14].

Initially, oxygen and cellulose materials are easily broken down by mesophilic microbes. The temperature during fermentation rises quickly (Fig. 4), causing a corresponding increase in compost pH. The temperature can increase from 35 to 70°C (Fig. 1) within a few days. At this stage, thermophilic microbes, which thrive at higher temperatures, become active. This period sees intense decomposition of organic matter as the microbes rapidly multiply, producing enzymes that break down the organic material into carbon dioxide, water vapour, and heat [14].

As most materials break down, the temperature begins to drop gradually. At this point, the composting process accelerates, resulting in the formation of clay-humus complexes. Throughout composting, there is a noticeable decrease in the volume and biomass of the materials, which can shrink by 20-30% from their original size or weight. The mature bioactivator takes on a dark brown colour, while the surface layer often shows the growth of white fungi that flourish just beneath the surface (Fig. 4).

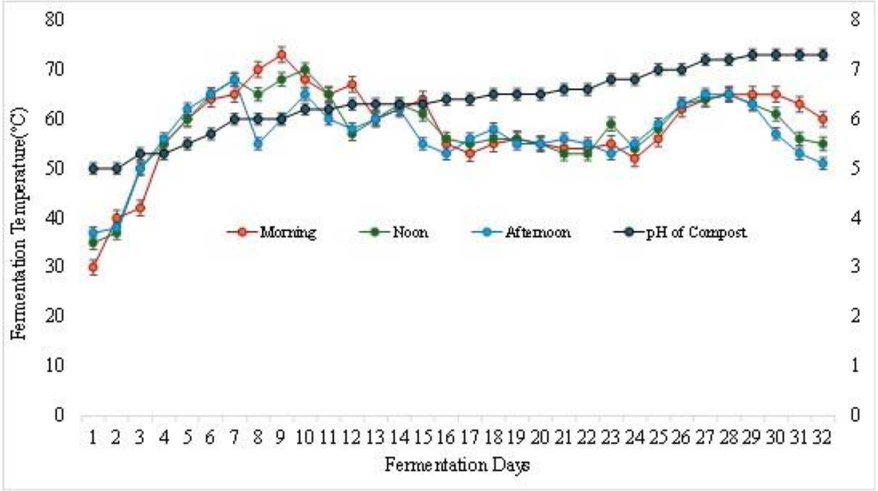

Fig 4. pH and temperature profiles during fermentation of bioactivator.

The bioactivator (Fig. 5), with the composition of types of various microorganisms and enzymes contained therein (Table 2), is subsequently employed to convert eucalyptus leaf distillation waste into organic fertilizer. Using a microbial consortium combined with various enzymes in a starter for composting and soil enhancement offers several benefits. These microorganisms and enzymes work synergistically to accelerate decomposition, improve nutrient availability, and enhance soil health. In summary, a microbial consortium combined with enzymes offers an efficient and sustainable solution for composting and soil enhancement by improving decomposition, nutrient availability, and soil health while minimizing environmental impact.

he microbial diversity in bioactivator ensures the effective breakdown of a wide range of organic materials. Their combined activities to speed up decomposition *(Bacillus, Trichoderma* and *Actinomycetes*), to suppress harmful pathogens (*Trichoderma* and *Penicillium*), to improve nutrient content (*Azotobacter* and *Nitrosomonas*), and to control odors (*Thiorhodaceae* and *Lactobacillus*). This diverse microbial community ensures the production of high-quality, nutrient-rich compost, enhancing soil health and fertility.

In addition, the diversity enzymes collectively break down various organic materials into simpler components that microorganisms can easily consume. Their synergistic activity accelerates the composting process, improves nutrient availability, and ensures the production of high-quality compost.

Since the waste initially appears dry, it is soaked in water containing agriminerals diluted 5000 times to ensure adequate moisture absorption. The material is then subjected to fermentation with the addition of bioactivator (~5%, by weight). This fermentation takes place under facultative aerobic conditions, with the pile covered by a tarp to protect it from rainwater and contaminants in the air. The compost pile is turned weekly to maintain airflow. Aeration is performed if a strong odor develops or the compost becomes overly moist (Fig. 6).

Table 2. Composition of microorganisms and enzymes for bioactivator production.

Types of Microbial Cultures	Role/Function in Composting	Types of Enzymes Produced	Function of Enzymes
Bacillus sp.	Thermophilic bacteria; decomposes proteins and starch	Amylase, Oxidase	Breaks down starch; promotes oxidation
Mucor sp.	Decomposes plant materials (cellulose, fats)	Amylase, Oxidase	Breaks down starch and sugars; oxidizes organic matter
Lactobacillus sp.	Ferments sugars; suppresses pathogens	Protease, Chymase	Breaks down proteins into peptides and amino acids
Trichoderma sp.	Decomposes cellulose; suppresses pathogens	Protease, Chymase	Breaks down proteins and inhibits harmful microbes
Saccharomyces sp.	Ferments sugars; initiates microbial activity	Lipase, Maltase	Decomposes fats; converts maltose into glucose
Actinomycetes	Decomposes tough materials (lignin); produces antibiotics	Lipase, Maltase	Breaks down fats; converts maltose into glucose
Aspergillus sp.	Decomposes starch, fats, and proteins	Cellulase, Urease	Breaks down cellulose; releases nitrogen from urea
Thiorhodaceae sp.	Oxidizes sulfur; reduces odors	Cellulase, Urease	Decomposes cellulose; releases ammonia from urea
Rhizopus sp.	Decomposes carbohydrates in food waste	Invertase, Sucrase	Converts sucrose into glucose and fructose
Azotobacter sp.	Fixes atmospheric nitrogen	Invertase, Sucrase	Converts sucrose into simple sugars for microbes
Penicillium sp.	Produces antibiotics; breaks down cellulose	Catalase, Lactase	Neutralizes hydrogen peroxide; decomposes lactose
Nitrosomonas sp.	Converts ammonia to nitrite (nitrification)	Catalase, Lactase	Protects microbes from oxidative damage; breaks down lactose

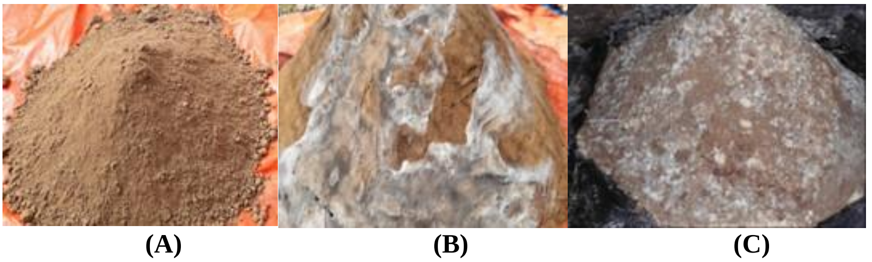

Fig 5. Fermentation using bioactivator of microbial consortium. (A), Raw materials (0-day) for making bioactivators; (B) 3-day-old bioactivators; (C) 5-day-old bioactivators, ready to be used for the production of soil enhncer based on waste from the production of Sunan kemiri biodiesel.

Fig 6. Fermentation of organic materials from eucalyptus oil refining waste used to produce soil enhancers from waste from processing KS oil. (A), Raw materials (0-day) for making soil enhancers; (B) 21-day-old fermented organic materials ready to produce soil enhancers based on waste from KS oil processing.

Figure 7 illustrates the application of bioactivators for creating soil enhancers from waste of KS oil processing as substrate through a 21-day fermentation process. The production of soil enhancers involves treating waste from KS oil processing via a bioprocessing that includes fermenting the waste of KS oil processing as substrate using bioactivators. The substrate was fermented by mixing 3-5% bioactivator with a previously diluted 1-3% mineral solution, followed by incubation for 2-3 weeks. The fermentation results show a notable difference in the waste from KS oil processing before and after the process, as depicted in Fig. 7. Besides functioning as a soil enhancer, the fermented waste from KS oil processing also acts as an organic fertilizer.

Aside from containing mineral nutrients from the breakdown of a consortium of microorganisms, including fermentative bacteria, photosynthetic bacteria, organic matter decomposers, and nitrogen and phosphorus-fixers—the bioactivator microorganisms also produce high levels of primary and secondary metabolites during the fermentation process. This soil enhancer helps activate soil microbiological processes and restore the balance of soil microorganisms by ensuring the soil microflora functions properly (Table 4).

When fertilizing plants, the soil enhancer can be used like a base fertilizer for each planting hole. To apply it, sprinkle 100 grams of the soil enhancer into the prepared hole and then cover it with soil. Before rainfall or if the soil is dry, each hole with the amendment should be watered. Additional watering is not needed during the rainy season if the soil is already sufficiently wet. Seeds or seedlings can be planted after 7 days of incubation with the soil enhancer, provided the soil remains moist from rain or watering.


A) (B) (C)

Fig 7. Soil enhancer prepared from the waste of KS oil processing. (A), Raw materials (0-day) for making soil enhancers based on KS oil processing; (B) 14-day-old fermented soil enhancers; (C) 21-day-old fermented soil enhancers based on KS oil processing ready to be used for soil enhancers.

The use of SBE-based soil enhancers on eucalyptus plants was currently in the trial stage to evaluate how effectively these amendments can maintain and enhance plant quality and productivity. Data on the benefits of these amendments for eucalyptus has not yet been collected. To further this evaluation, testing different application rates beyond the recommended dosage would be beneficial. For instance, experimental designs could be set up to test various dosages of soil enhancers, such as 50, 100, and 150 grams per plant.

Variations in the application of soil enhancers can also be explored by adjusting the distance from the plant stems, such as testing at 10, 20, and 40 cm radii from the stems using recommended dosages. No specific experimental designs are needed for easy implementation.

Field rows and plant blocks can serve as boundaries for different treatments. For example, each row could receive a distinct treatment, ensuring the number of trees in each row is consistent. This approach helps in observing results more quickly. Alternatively, treatments can be based on plant blocks, where each block of eucalyptus plants is treated differently, or a single block can be divided into sections, each receiving a different treatment.

Table 3 indicated that the SBE-based soil enhancer and bio-fertilizer meet the criteria and adhere to the quality standards set by the Minister of Agriculture's Decree No. 261/KPTS/SR.310/M/4/2019, which outlines the minimum technical requirements for organic fertilizers and soil enhancers.

Table 3. Testing of organic fertilizers and soil conditioners based on SBE.

Parameter	**Unit**	**Results**	**Quality Standards**	
			Soil Enhancer	**Biofertilizer**
C-Organic	%	19.83	min 15	min 15
C/N		19.97	≤ 25	≤ 25
Moisture	%	13.50	8-20	8 – 20
As	ppm	0.10	max 10	max 10
Hg	ppm	< LoD	max 1	max 1
Pb	ppm	15.30	maks 50	max 50
Cd	ppm	1.07	max 2	max 2
Cr	ppm	52.06	max 180	max 180
Ni	ppm	9.25	max 50	max 50
pH		7.5	4-9	4-9
E. coli	ml MPN/g	<30	$< 1 \times 10^2$	$< 1 \times 10^2$
Salmonella sp	ml MPN/g	<30	$< 1 \times 10^2$	$< 1 \times 10^2$
Fe total	ppm	1432.25	max 15.000	max 15.000
Fe available	ppm	286.24	max 500	max 500
Zn	ppm	61.72	max 5.000	max 5.000
Total Na	ppm	639.24	max 2.000	max 2.000
Total Cl	ppm	t.a	max 5.000	max 2.000
Macro nutrient (N+P2O5+K)	%	3.95	-	min 2

4 Conclusion

Kemiri Sunan (KS) oil demonstrates significant potential for sustainable biodiesel production due to its high oil content and favorable fatty acid profile. The production process yields high-quality Biodiesel with minimal glycerol residue, complying with eco-friendly fuel standards. Furthermore, the byproducts, including glycerol, shells, and press cake, contribute to a circular economy by being repurposed for bioethanol, biogas, and organic fertilizer production. Using bioactivators to compost KS waste transforms it into nutrient-rich organic fertilizers, promoting soil health and sustainable agriculture. The integration of microbial consortia accelerates decomposition and enhances soil quality, supporting eucalyptus and other crop cultivation. KS-based fertilizers and soil enhancers meet regulatory standards, offering environmentally friendly solutions to improve productivity on degraded lands. With scalable production potential, KS oil and its derivatives provide a sustainable approach to biofuel development and land restoration.

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