

# From Biodiesel Byproducts to Biogas: A Circular Economy Review of Oilseed Cakes, Glycerol, and Microalgal Biomass

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## ABSTRACT

The global transition toward renewable energy has accelerated biodiesel production, generating substantial quantities of byproducts including oilseed cakes, crude glycerol, and microalgal biomass residues. Conventional disposal of these byproducts poses environmental challenges, yet they represent valuable feedstocks for biogas production through anaerobic digestion. This review synthesizes current knowledge on the valorization of biodiesel byproducts for biogas generation within a circular economy framework. Oilseed cakes—particularly palm kernel, rapeseed, jatropha, and sesame—exhibit significant biogas potential due to their nutrient-rich composition, with methane yields enhanced by 14–226% through co-digestion strategies. Crude glycerol, a major byproduct constituting approximately 10% of biodiesel output, demonstrates remarkable synergy as a co-substrate, improving biogas yields when maintained at concentrations below 8% v/v to avoid inhibition. Microalgal biomass residues, representing 60–70% of total biomass after oil extraction, offer additional energy recovery through anaerobic digestion, with co-digestion of rapeseed oil cake and microalgae achieving methane contents of 62.42% and energy yields of 3.76 kWh·kg<sup>-1</sup> DM. Nigeria's position as a major palm oil producer and emerging biodiesel market presents significant opportunities for integrating biodiesel byproduct valorization into the national energy mix. However, challenges including substrate C/N ratio imbalances, inhibitory compounds, limited technical capacity, and weak policy frameworks must be addressed. This review identifies critical research gaps and proposes a strategic framework for implementing biodiesel byproduct-to-biogas systems in Nigeria, contributing to waste reduction, energy security, and sustainable agricultural practices.

**Keywords:** Biodiesel byproducts, biogas, anaerobic digestion, microalgae, circular economy Nigeria

## 1.0 INTRODUCTION

### 1.1 Global Biodiesel Production and Byproduct Generation

The global imperative to reduce greenhouse gas emissions and transition toward renewable energy has driven exponential growth in biodiesel production. Biodiesel, produced through transesterification of vegetable oils, animal fats, or microalgal lipids, offers a renewable alternative to petroleum-based diesel with reduced carbon emissions (Ben-Iwo et al., 2016). Global biodiesel production exceeded 40 billion liters annually, with projections indicating continued growth driven by policy mandates and increasing environmental awareness (Dickson et al., 2023). However, biodiesel production generates substantial quantities of byproducts that pose environmental challenges if not properly managed. For every 100 kg of biodiesel produced, approximately 10 kg of crude glycerol is generated as a primary byproduct (Tomczak et al., 2025). Additionally, oilseed cakes—the solid residues remaining after oil extraction—represent 60–70% of the original seed mass (Gebreegziabher et al., 2025). In microalgae-based biodiesel systems, 60–70% of the biomass remains as residual waste after oil extraction (Dalal et al., 2026). These by-products, if disposed of improperly, contribute to environmental pollution and represent a loss of valuable organic resources.

### 1.2 The Circular Economy Imperative

The circular economy framework offers a paradigm shift from the traditional linear ‘take-make-dispose’ model to a regenerative system where waste becomes a resource (Gebreegziabher et al., 2025). Within this framework, biodiesel byproducts are not liabilities but opportunities for additional value creation. Anaerobic digestion (AD) emerges as a key technology for converting these organic residues into biogas—a renewable energy source—while producing nutrient-rich digestate for agricultural application (Mata-Alvarez et al., 2014; Weiland, 2010).

The integration of biodiesel production with biogas generation through AD represents a closed-loop system where waste streams from one process become feedstocks for another. This approach aligns with the principles of industrial ecology and sustainable development, reducing waste disposal costs, generating additional revenue streams, and lowering the overall carbon footprint of biofuel production (Gebreegziabher et al., 2025). Studies have demonstrated that biogas generation from biodiesel residues can reduce manufacturing costs by 40–80% (Khuntia et al., 2017).

### 1.3 Nigeria's Context: Palm Oil, Biodiesel, and Energy Poverty

Nigeria occupies a unique position in the global biodiesel landscape. As Africa's largest oil producer and a major palm oil producer, the country possesses significant potential for biodiesel production from palm oil and other feedstocks (Ben-Iwo et al., 2016). The proliferation of cottage oil palm processing industries in Nigeria has increased the availability of palm kernel cake (PKC), a byproduct of palm oil and biodiesel production (Jimoh & Babatola, 2018; Ugheoke et al., 2026).

Simultaneously, Nigeria faces acute energy poverty, with over 85 million citizens lacking access to clean cooking fuel and reliable electricity (Dickson et al., 2023). The country generates substantial agricultural and industrial waste that remains underutilized. The valorization of biodiesel byproducts for biogas production offers a dual solution: managing waste while generating renewable energy for domestic and industrial use (Adeleke, 2023).

## 1.4 Scope and Objectives

This review provides a comprehensive synthesis of literature on the utilization of biodiesel byproducts for biogas production through anaerobic digestion. The specific objectives are:

- i. To characterize the major biodiesel byproducts—oilseed cakes, crude glycerol, and microalgal biomass residues—relevant to biogas production
- ii. To evaluate the performance of anaerobic digestion of these byproducts, including mono-digestion and co-digestion strategies
- iii. To assess the synergistic effects of co-digesting biodiesel byproducts with other organic wastes
- iv. To identify challenges and opportunities for implementing biodiesel byproduct-to-biogas systems in Nigeria
- v. To propose a strategic framework for integrating biodiesel byproduct valorization within Nigeria's circular economy and energy transition

## 2.0 METHODOLOGY OF THE REVIEW

## 2.1 Search Strategy

A systematic literature search was conducted across multiple databases, including Google Scholar, Scopus, ScienceDirect, PubMed, African Journals Online (AJOL), and institutional repositories. The search covered publications from 2000 to 2026, with emphasis on studies published after 2015.

## 2.2 Search Keywords and Combinations

The following keyword combinations were employed:

- i. 'biodiesel byproducts' AND 'biogas' AND ('anaerobic digestion' OR 'AD')
- ii. 'oilseed cake' AND 'biogas' AND ('methane yield' OR 'anaerobic co-digestion')
- iii. 'crude glycerol' AND 'anaerobic digestion' AND 'biogas'

- iv. 'microalgae' AND 'biodiesel' AND 'anaerobic digestion' AND 'biogas', 'palm kernel cake' AND 'biogas' AND 'Nigeria'
- v. 'circular economy' AND 'biodiesel' AND 'biogas'

### 2.3 Inclusion and Exclusion Criteria

**Inclusion criteria:**

- i. Studies reporting biogas or methane yield from biodiesel byproducts
- ii. Studies characterizing feedstock properties of oilseed cakes, glycerol, or microalgae
- iii. Studies on co-digestion involving biodiesel byproducts
- iv. Publications in English

**Exclusion criteria:**

- i. Studies focused exclusively on biodiesel production without byproduct valorization
- ii. Studies on non-biodiesel glycerol sources
- iii. Non-peer-reviewed publications without verifiable data

### 3. BIODIESEL BYPRODUCTS: TYPES, COMPOSITION AND CHARACTERISTICS

### 3.1 Oilseed Cakes

**Oilseed Cakes** Oilseed cakes are the solid residues remaining after mechanical pressing or solvent extraction of oil from seeds. These materials are generated in substantial quantities during biodiesel production from various feedstocks.

### 3.1.1 Palm Kernel Cake (PKC)

**2.1.1 Palm Kernel Cake (PKC)**  
Palm kernel cake is a byproduct of palm oil and palm kernel oil production, abundant in Nigeria and other tropical countries. The increasing number of cottage oil palm processing industries has significantly increased PKC availability (Jimoh & Babatola, 2018). Physicochemical characterization of PKC reveals ash content of  $24.00 \pm 0.01\%$ , total solids of  $89.50 \pm 0.00\%$ , volatile solids of  $65.50 \pm 0.01\%$ , carbon of  $32.57 \pm 0.00\%$ , and nitrogen of  $1.19 \pm 0.04\%$  (Ugheoke et al., 2026). The carbon-to-nitrogen (C/N) ratio of PKC ranges from 30:1 to 35:1, making it an excellent substrate for balancing the low C/N ratios of food waste and other nitrogen-rich feedstocks (Gebreegzabher et al., 2025).

### 3.1.2 Rapeseed Oil Cake

Rapeseed (canola) oil cake is a byproduct of rapeseed biodiesel production, widely available in Europe and increasingly in other regions. Studies have demonstrated that rapeseed oil cake enhances biogas production when co-digested with microalgal biomass, achieving methane contents of 62.42% (Hawrot-Paw & Drzewicka, 2025).

### 3.1.3 Jatropha Seed Cake

*Jatropha curcas* is a non-edible oilseed with high potential for biodiesel production in tropical regions. The pressed cake remaining after oil extraction contains residual oil and inhibitors that can affect anaerobic digestion. Studies have shown that methanolic extraction of inhibitors from *jatropha* seed cake improves biogas yield during continuous anaerobic digestion (Haq et al., 2023).

### 3.1.4 Sesame Oil Cake

Sesame oil cake, a byproduct of sesame oil and biodiesel production, has been investigated for biogas production through two-stage anaerobic co-digestion with sewage sludge (Choi, 2022).

### 3.1.5 Non-Edible Seed Cakes

Non-edible seed cakes, including those from *jatropha*, neem, and karanja, are rich in nutrients and show promise for significant biogas yield (Gebreegziabher et al., 2025). These feedstocks are particularly relevant for biodiesel production from non-edible oils, which do not compete with food supply.

## 3.2 Crude Glycerol

Crude glycerol is the primary byproduct of biodiesel production, generated at approximately 10% of biodiesel output (Tomczak et al., 2025). For every 100 kg of biodiesel produced, approximately 10 kg of crude glycerol is generated. The composition of crude glycerol varies considerably depending on the source of oil, processing technology, reactant ratios, catalyst type, and procedure applied (Tomczak et al., 2025).

### 3.2.1 Composition

Crude glycerol typically contains 40–80% glycerol, along with methanol, water, salts, fatty acids, and other impurities. The variability in composition presents challenges for consistent anaerobic digestion performance but also offers opportunities for process optimization (Tomczak et al., 2025).

### 3.2.2. Biodegradability

Crude glycerol is easily biodegradable and has been identified as a promising co-substrate for anaerobic digestion, aiding in the digestion of recalcitrant substrates (Gebreegziabher et al., 2025). Its high organic content makes it an excellent carbon source for methanogenic microorganisms.

### 3.2.3 Inhibitory Potential

While crude glycerol enhances biogas production at moderate concentrations, high concentrations can inhibit methanogenic activity. Studies indicate that methane content exceeding 60% is typically achieved with crude glycerol content up to 8% v/v in the feedstock (Tomczak et al., 2025). Beyond this threshold, the accumulation of volatile fatty acids and the high chemical oxygen demand can lead to process instability.

## 3.3 Microalgal Biomass Residues

Microalgae have emerged as a promising feedstock for biodiesel production due to their high lipid content, rapid growth rates, and ability to be cultivated on non-arable land using wastewater and CO<sub>2</sub> (Dalal et al., 2026). However, after oil extraction, 60–70% of the microalgal biomass remains as residual waste (Dalal et al., 2026).

### 3.3.1 Composition

Microalgal biomass residues contain carbohydrates, proteins, and residual lipids that can be converted to biogas through anaerobic digestion. The specific composition varies with algal species, cultivation conditions, and extraction methods.

### 3.3.2 Biogas Potential

Anaerobic digestion of microalgal biomass residues offers a simple and low-cost method for recovering additional energy beyond the algal oil itself (Torres et al., 2021). Studies have investigated the anaerobic digestion of various microalgae species and their residues from oil extraction and in situ transesterification processes, using sewage sludge and poultry manure as inocula (Torres et al., 2021).

### 3.3.3 Integration Opportunities

The integration of microalgae cultivation with biogas production creates a closed-loop system. Anaerobic digestion outputs—including nutrients, CO<sub>2</sub>, and water—can be used to cultivate microalgae, which in turn serve as substrates for methane and fertilizer generation (Uggetti et al., 2014).

## 4. ANAEROBIC DIGESTION OF BIODIESEL BYPRODUCTS

### 4.1 Fundamentals of Anaerobic Digestion

Anaerobic digestion is a biological process in which microorganisms decompose organic matter in the absence of oxygen, producing biogas—a mixture primarily of methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>)—and a nutrient-rich digestate (Weiland, 2010; Mao et al., 2015).

The process involves four main stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Angelidaki & Ellegaard, 2003).

#### 4.1.1 Hydrolysis

Complex polymers (carbohydrates, proteins, lipids) are broken down into soluble monomers by hydrolytic enzymes.

#### 4.1.2. Acidogenesis

Soluble monomers are fermented into volatile fatty acids (VFAs), alcohols, hydrogen, and carbon dioxide.

#### 4.1.3. Acetogenesis

VFAs and alcohols are converted into acetate, hydrogen, and carbon dioxide.

#### 4.1.4. Methanogenesis

Acetate and hydrogen/carbon dioxide are converted into methane by methanogenic archaea.

The efficiency of AD depends on several factors, including feedstock composition, C/N ratio, pH, temperature, hydraulic retention time, and organic loading rate (Weiland, 2010; Mao et al., 2015).

### 4.2 Mono-Digestion of Biodiesel Byproducts

**4.2.1 Oilseed Cakes:** Mono-digestion of oilseed cakes has been investigated for various feedstocks. Jimoh and Babatola (2018) investigated the biogas generating capacity of de-oiled palm kernel cake (PKC) in a laboratory anaerobic digestion setup. Laboratory results for de-oiled PKC gave biogas and methane yields of 12.7 ml/g and 4.2 ml/g respectively, with a methane composition of 33%. The theoretical methane estimate was 33.5%, confirming the biogas potential of de-oiled PKC. However, the relatively low methane content (33%) indicates that mono-digestion of PKC alone may be suboptimal.

Studies on jatropha seed cake have shown that the presence of inhibitors—including residual oil, phorbol esters, and other toxic compounds—can reduce biogas yield. Methanolic extraction of these inhibitors improved biogas production in batch experiments (Haq et al., 2023).

#### 4.2.2 Crude Glycerol

Mono-digestion of crude glycerol alone is challenging due to its high organic content and potential for rapid acidification. However, studies have demonstrated that crude glycerol can be effectively digested when properly managed. Tomczak et al. (2025) reviewed the performance of anaerobic co-digestion of crude glycerol with various substrates, demonstrating that adding crude glycerol to feedstock enhanced process performance compared to mono-digestion.

#### 4.2.3 Microalgal Biomass

Anaerobic digestion of microalgal biomass residues offers a simple and low-cost method for energy recovery. Studies have investigated the digestion of microalgae residues from oil extraction and transesterification processes, achieving biogas production with various inocula (Torres et al., 2021).

### 4.3 Co-Digestion: Synergistic Effects

Co-digestion—the simultaneous anaerobic digestion of two or more substrates—has emerged as a superior strategy for valorizing biodiesel byproducts. The synergistic effects of co-digestion address the limitations of mono-digestion, including C/N ratio imbalances, nutrient deficiencies, and inhibitory

compound accumulation (Mata-Alvarez et al., 2014; Angelidaki & Ellegaard, 2003).

#### 4.3.1 Crude Glycerol Co-Digestion

Crude glycerol has been identified as a promising co-substrate for anaerobic digestion, aiding in the digestion of recalcitrant substrates (Gebreegziabher et al., 2025). Tomczak et al. (2025) demonstrated that adding crude glycerol to feedstock caused the enhancement of process performance compared to mono-digestion. Methane content exceeding 60% was typically achieved with crude glycerol content up to 8% v/v in the feedstock.

Empirical data reveals remarkable methane yield boosts, ranging from 14 to 226% when co-digesting with crude glycerol (Gebreegziabher et al., 2025). This wide range reflects the variability in substrates, process conditions, and glycerol composition.

#### 4.3.2 Rapeseed Oil Cake with Microalgae

A study by Hawrot-Paw & Drzewicka (2025), evaluated the potential benefits of co-digesting rapeseed oil cake with microalgal biomass. Anaerobic fermentation was carried out under mesophilic conditions using various doses of press residue as a co-substrate. The results demonstrated that the addition of rapeseed oil cake enhances biogas production. The highest biogas yield was achieved during co-digestion with 1 g VS·L<sup>-1</sup> of microalgal biomass and 0.5 g VS·L<sup>-1</sup> of rapeseed oil cake. The average methane content in the biogas was 62.42%, and the average hydrogen sulfide concentration ranged from 400 to 700 ppm. The maximum energy yield of 3.76 kWh·kg<sup>-1</sup> DM was obtained from co-digesting microalgal and rapeseed oil cake biomass in a 2:1 ratio.

#### 4.3.3 Palm Kernel Cake with Cow Dung

Ugheoke et al. (2026) evaluated the potential of anaerobic co-digestion of palm kernel cake (PKC) and cow dung (CD) as viable feedstock for biogas and bio-fertilizers production. The results showed a cumulative biogas production of 14,005 mL with a methane content of 53.33%. The digestates exhibited acidic pH values and contained essential nutrients, such as nitrogen, potassium, calcium, magnesium, and phosphorus. No heavy metals were detected, suggesting their safe application for agricultural use. This study demonstrates the potential of co-digestion as a sustainable approach for managing agricultural waste while producing biogas and biofertilizers.

#### 4.3.4 Palm Kernel Cake with Sugar Cane Chips

Jimoh and Babatola (2018) investigated the co-digestion of de-oiled PKC with fresh sugar cane chips. The combination yielded **biogas** and methane yields of 3.15 ml/g and 1.25 ml/g respectively, with a measured methane composition of 40% (compared to 33% for PKC alone). The theoretical methane estimate was

41.1%, confirming that the quality of biogas from PKC can be improved by the addition of other biogas-producing wastes.

#### 4.3.5 Sesame Oil Cake with Sewage Sludge

Choi, (2022) investigated the sewage sludge reduction and biogas production using two-stage anaerobic co-digestion of sesame oil cake and sewage sludge.

#### 4.4 Mechanisms of Synergy

The synergistic effects observed in co-digestion of biodiesel byproducts can be attributed to several mechanisms:

#### 4.4.1 Nutrient balance

Oilseed cakes provide carbon-**rich** substrates, while crude glycerol and microalgae contribute readily available carbon sources. Co-digestion balances the C/N ratio, optimizing microbial activity (Gebreegziabher et al., 2025).

#### 4.4.2 Buffering capacity

Co-substrates such as cow dung provide alkalinity that buffers pH fluctuations, preventing acidification (Ugheoke et al., 2026).

#### 4.4.3 Dilution of inhibitors

Co-digestion dilutes the concentration of inhibitory compounds, including residual oils, ammonia, and VFAs (Tomczak et al., 2025).

#### 4.4.4 Microbial diversity

Diverse substrates support a more robust and resilient microbial community, enhancing overall degradation efficiency (Mata-Alvarez et al., 2014).

#### 4.4.5 Complementary degradation kinetics

Fast-degrading substrates (glycerol) provide readily available carbon for methanogens, while slow-degrading substrates (oilseed cakes) sustain long-term biogas production.

## 5.0 PRETREATMENT STRATEGIES FOR BIODIESEL BYPRODUCTS

### 5.1 Rationale for Pretreatment

Many biodiesel byproducts, particularly oilseed cakes, contain lignocellulosic structures and residual oils that resist microbial degradation. Pretreatment aims to disrupt these structures, increase surface area, and enhance biodegradability (Taherzadeh & Karimi, 2008; Hendriks & Zeeman, 2009).

## 5.2 Mechanical Pretreatment

### 5.2.1 Size Reduction

Grinding or milling oilseed cakes reduces particle size, increasing surface area for microbial attachment. This simple pretreatment is widely applicable and low-cost.

### 5.3 Chemical Pretreatment

### 5.3.1 Inhibitor Removal

Studies on jatropha seed cake have demonstrated that methanolic extraction of inhibitors improves biogas yield during continuous anaerobic digestion (Haq et al., 2023). This approach removes toxic compounds including phorbol esters and residual oils.

### 5.3.2 Alkaline Pretreatment

Treatment with sodium hydroxide or calcium hydroxide can break down lignocellulosic structures in oilseed cakes, improving digestibility (Kumar et al., 2009).

## 5.4 Biological Pretreatment

### 5.4.1 Enzyme Addition

Commercial enzymes (cellulases, hemicellulases, proteases) can accelerate hydrolysis of oilseed cakes and microalgal biomass.

### 5.4.2 Microbial Pretreatment

Fungi and bacteria can be used to pre-digest lignocellulosic materials, although this approach is time-consuming.

## 5.5 Thermal Pretreatment

**Heat Treatment:** Heating oilseed cakes and microalgal biomass to 70–100°C can solubilize hemicellulose and partially degrade lignin (Taherzadeh & Karimi, 2008).

## 6.0 CHALLENGE AND INHIBITION IN ANAEROBIC DIGESTION BYPRODUCT

### 6.1 Substrate C/N Ratio Imbalance

Biodiesel byproducts exhibit diverse C/N ratios. Oilseed cakes typically have C/N ratios of 20:1–35:1, while crude glycerol has a very high carbon content and microalgae have moderate C/N ratios. Imbalances can lead to ammonia accumulation (low C/N) or limited microbial growth (high C/N) (Gebreegziabher et al., 2025).

## 6.2 Inhibitory Compounds

### 6.2.1 Residual Oils and Lipids

High lipid content in oilseed cakes can lead to long-chain fatty acid accumulation, which inhibits methanogenic activity.

### 6.2.2. Phorbol Esters

Jatropha seed cake contains phorbol esters, which are toxic to microorganisms and require removal before digestion (Hag et. al., 2023).

### 6.2.3. Ammonia

High nitrogen content in some feedstocks can lead to ammonia inhibition, particularly at elevated pH levels.

**6.2.4 Sulfide**

Hydrogen sulfide production during digestion of sulfur-containing substrates can inhibit methanogens and corrode equipment.

**6.3 Process Instability****6.3.1 Rapid Acidification**

High organic loading rates, particularly with readily biodegradable substrates like crude glycerol, can lead to rapid VFA accumulation and pH drop (Tomczak et al., 2025).

**6.3.2. Foaming**

Protein-rich substrates can cause foaming, leading to operational challenges.

**6.3.3. Scum Formation**

Lipids and floating solids can form scum layers, reducing gas-liquid transfer and causing blockages.

**6.4 Mitigation Strategies****6.4.1 Co-digestion**

Mixing biodiesel byproducts with other substrates balances C/N ratios and dilutes inhibitors (Gebreegziabher et al., 2025).

**6.4.2 Pretreatment**

Removing inhibitors and breaking down recalcitrant structures improves digestibility.

**6.4.3 Optimization of Operating Conditions**

Careful control of OLR, HRT, pH, and temperature maintains process stability (Tomczak et al., 2025).

**6.4.4 Additives**

Supplementation with trace elements (iron, cobalt, nickel) and buffering agents can enhance methanogenic activity.

**7. Nigeria's Potential for Biodiesel Byproduct Valorization****7.1 Palm Kernel Cake Availability**

Nigeria is a major palm oil producer, with substantial quantities of palm kernel cake generated as a byproduct of palm oil and biodiesel production. The proliferation of cottage oil palm processing industries has increased PKC availability (Jimoh & Babatola, 2018). Studies have confirmed the biogas/methane generation potential of de-oiled PKC, with quality that can be improved by the addition of other biogas-producing wastes (Jimoh & Babatola, 2018; Ugheoke et al., 2026).

**7.2 Jatropha Potential**

*Jatropha curcas* has high potential for producing biodiesel in Nigeria, particularly on marginal lands that are unsuitable for food crops (Sharma et al., 2022). The de-oiled cake from *jatropha* biodiesel production can be co-digested with cattle dung for biogas production.

**7.3 Microalgae Opportunities**

Nigeria's abundant water resources and tropical climate present opportunities for microalgae cultivation for biodiesel production. Microalgae can be cultivated using wastewater and CO<sub>2</sub> from biogas plants, creating integrated systems (Dalal et al., 2026; Uggetti et al., 2014).

**7.4 Integration with Existing Agriculture**

Nigeria's agricultural sector generates substantial organic wastes that can be co-digested with biodiesel byproducts. Co-digestion of palm kernel cake with cow dung (Ugheoke et al., 2026) and food waste (Ofon et al., 2024) has demonstrated significant biogas potential.

**8. CIRCULAR ECONOMY FRAMEWORK FOR BIODIESEL-BIOGAS INTEGRATION****8.1 Closed-Loop Systems**

The integration of biodiesel production with biogas generation creates a closed-loop system that maximizes resource efficiency. Key components include:

**8.1.1 Biodiesel production**

Oil extraction and transesterification produce biodiesel, oilseed cakes, and crude glycerol.

**8.1.2 Anaerobic digestion**

Oilseed cakes, crude glycerol, and microalgal residues are converted to biogas and digestate.

**8.1.3 Biogas utilization**

Biogas can be used for heat, electricity, or upgraded to biomethane for vehicle fuel.

**8.1.4 Digestate application**

Nutrient-rich digestate serves as biofertilizer for oilseed and microalgae cultivation.

**8.1.5 CO<sub>2</sub> utilization**

CO<sub>2</sub> from biogas can be used for microalgae cultivation.

**8.2 Economic Benefits**

Studies have demonstrated that biogas generation from biodiesel residues can reduce manufacturing costs by 40–80% (Khuntia et al., 2017). Additional economic benefits include:

- i Reduced waste disposal costs
- ii Revenue from biogas and biofertilizer sales
- iii Carbon credits and environmental credits

iv Energy cost savings

### 8.3 Environmental Benefits.

- i Reduced greenhouse gas emissions (up to 81% reduction compared to fossil diesel)
- ii Waste diversion from landfills and open dumps
- iii Reduced reliance on synthetic fertilizers
- I. Improved soil health through digestate application

### 8.4 Social Benefits

- i. Creation of green jobs in waste management and energy sectors
- ii. Improved access to clean energy in rural communities
- iii. Enhanced food security through improved soil fertility
- iv. Reduced indoor air pollution from cooking with firewood

## 9.0 CHALLENGES AND BARRIERS

### 9.1 Technical Challenges

**9.1.1 Limited Technical Capacity:** There is a shortage of trained personnel for digester design, operation, and maintenance (Adeleke, 2023).

### 9.1.2 Inadequate Infrastructure

Poor road networks and lack of storage facilities complicate feedstock collection and digestate distribution (Dickson et al., 2023).

### 9.1.3 Feedstock Inconsistency

Seasonal availability and varying quality of biodiesel byproducts create challenges for consistent digester operation.

### 9.1.4 Limited Analytical Capabilities

GC analysis for methane, VFA monitoring, and other analytical capabilities are concentrated in few research institutions.

## 9.2 Institutional and Policy Challenges

### 9.2.1 Policy Gaps

Nigeria lacks a comprehensive policy framework for biodiesel byproduct valorization and biogas integration (Imoisi & Okongwu 2020).

### 9.2.2 Limited Incentives

Unlike countries with feed-in tariffs or renewable energy certificates, Nigeria offers limited financial incentives for biogas development (Ogunwale & Ogunleye, 2021).

### 9.2.3 Low Awareness

Awareness of the potential of biodiesel byproducts for biogas production remains low among stakeholders (Nwachukwu & Okafor, 2020).

**Weak Enforcement:** Environmental regulations are poorly enforced, reducing incentives for waste valorization.

## 9.3 Economic Challenges

**9.3.1 High Capital Costs:** Initial investment in biogas infrastructure can be prohibitive for small-scale operators.

**9.3.2 Limited Access to Finance:** Lack of access to affordable credit constrains investment in biogas systems.

**9.3.3 Low Energy Prices:** Subsidized fossil fuel prices reduce the economic competitiveness of biogas.

## 10.0 STRATEGIC FRAMEWORK FOR IMPLIMENTATION

### 10. Strategic Framework for Implementation

#### 10.1 Policy Recommendations

##### 10.1.1 Develop a National Biodiesel-Byproduct Valorization Policy

Establish clear targets, incentives, and regulatory frameworks for converting biodiesel byproducts to biogas (Imoisi & Okongwu, 2020).

##### 10.1.2 Integrate with National Renewable Energy Policy

Include biodiesel byproduct valorization in Nigeria's renewable energy and waste management policies.

##### 10.1.3 Provide Financial Incentives

Implement feed-in tariffs, tax credits, and low-interest loans for biogas projects using biodiesel byproducts (Ogunwale & Ogunleye, 2021).

##### 10.1.4 Promote Public-Private Partnerships

Facilitate collaboration between government, private sector, and development partners.

##### 10.1.5 Establish Quality Standards

Develop standards for biogas composition, digestate quality, and system safety.

#### 10.2 Technical Recommendations

##### 10.2.1 Feedstock Characterization

Develop a comprehensive database of biodiesel byproduct properties in Nigeria.

##### 10.2.2 Pilot-Scale Demonstration

Install pilot-scale digesters at palm oil mills and biodiesel plants to demonstrate technical feasibility.

##### 10.2.3 Co-Digestion Optimization

Optimize mixing ratios for co-digestion of PKC with cow dung, food waste, and other substrates.

##### 10.2.4 Pretreatment Development

Develop and validate low-cost pretreatment methods suitable for Nigerian conditions.

**10.2.5 Capacity Building**

Establish training programs for digester design, construction, and operation.

**10.3 Phased Implementation Roadmap****Phase 1: Assessment and Planning (0–6 months)**

- i. Conduct feedstock mapping and characterization
- ii. Identify priority locations (palm oil clusters, biodiesel plants)
- iii. Develop policy framework and business models

**Phase 2: Pilot Demonstration (6–18 months)**

- i. Install pilot digesters at 3–5 sites
- ii. Monitor and optimize performance
- iii. Train local operators

**Phase 3: Scale-Up (18–36 months)**

- i. Scale up successful pilot systems
- ii. Develop commercial business models
- iii. Establish quality standards and certification

**Phase 4: National Rollout (36–48 months)**

- i. Implement national policy and regulatory framework
- ii. Facilitate access to finance
- iii. Establish monitoring and evaluation systems

**11. RESEARCH GAPS AND FUTURE DIRECTION****12.0 CONCLUSION**

Biodiesel byproducts—oilseed cakes, crude glycerol, and microalgal biomass residues—represent valuable feedstocks for biogas production through anaerobic digestion. The global growth in biodiesel production has generated substantial quantities of these byproducts, which, if properly managed, can contribute to renewable energy generation, waste reduction, and sustainable agricultural practices.

Oilseed cakes, particularly palm kernel cake, rapeseed oil cake, and jatropha seed cake, exhibit significant biogas potential. Crude glycerol, the major byproduct of biodiesel production, demonstrates remarkable synergy as a co-substrate, with methane yield boosts ranging from 14 to 226% when co-digested with other feedstocks (Gebreegziabher et al., 2025). Microalgal biomass residues, representing 60–70% of total biomass after oil extraction, offer additional energy recovery through anaerobic digestion, with co-digestion of rapeseed oil cake and microalgae achieving methane contents of 62.42% and energy yields of 3.76 kWh·kg<sup>-1</sup> DM (Hawrot-Paw & Drzewicka, 2025).

Nigeria's position as a major palm oil producer and emerging biodiesel market presents significant

**11.1 Critical Research Gaps****11.1.1 Limited Nigerian-Specific Data**

There is a lack of comprehensive data on the biogas potential of Nigerian biodiesel byproducts, including PKC, jatropha cake, and crude glycerol from Nigerian biodiesel plants.

**11.1.2 Inadequate Co-Digestion Optimization**

Optimal mixing ratios for co-digesting Nigerian biodiesel byproducts with locally available co-substrates have not been systematically determined.

**11.1.3 Limited Pretreatment Studies**

Pretreatment methods suitable for Nigerian conditions and feedstocks remain underexplored.

**11.1.4 No Economic Analysis in Local Currency**

Cost-benefit analysis and life cycle assessment in Nigerian Naira are lacking.

**11.1.5 Microbial Community Characterization**

The microbial communities in Nigerian AD systems using biodiesel byproducts have not been characterized.

**11.1.6 Integration Studies**

The integration of biodiesel production, biogas generation, and microalgae cultivation has not been systematically studied in the Nigerian context.

opportunities for integrating biodiesel byproduct valorization into the national energy mix. Studies have confirmed the biogas potential of palm kernel cake, with cumulative biogas production of 14,005 mL and methane content of 53.33% when co-digested with cow dung (Ugheoke et al., 2026). The integration of biodiesel production with biogas generation aligns with circular economy principles, reducing waste, generating renewable energy, and producing biofertilizer.

However, challenges including substrate C/N ratio imbalances, inhibitory compounds, limited technical capacity, and weak policy frameworks must be addressed. Strategic implementation requires policy support, technical capacity building, pilot-scale demonstration, and stakeholder engagement. With appropriate investment and policy frameworks, biodiesel byproduct-to-biogas systems can contribute significantly to Nigeria's energy transition, waste management, and sustainable development goals.

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