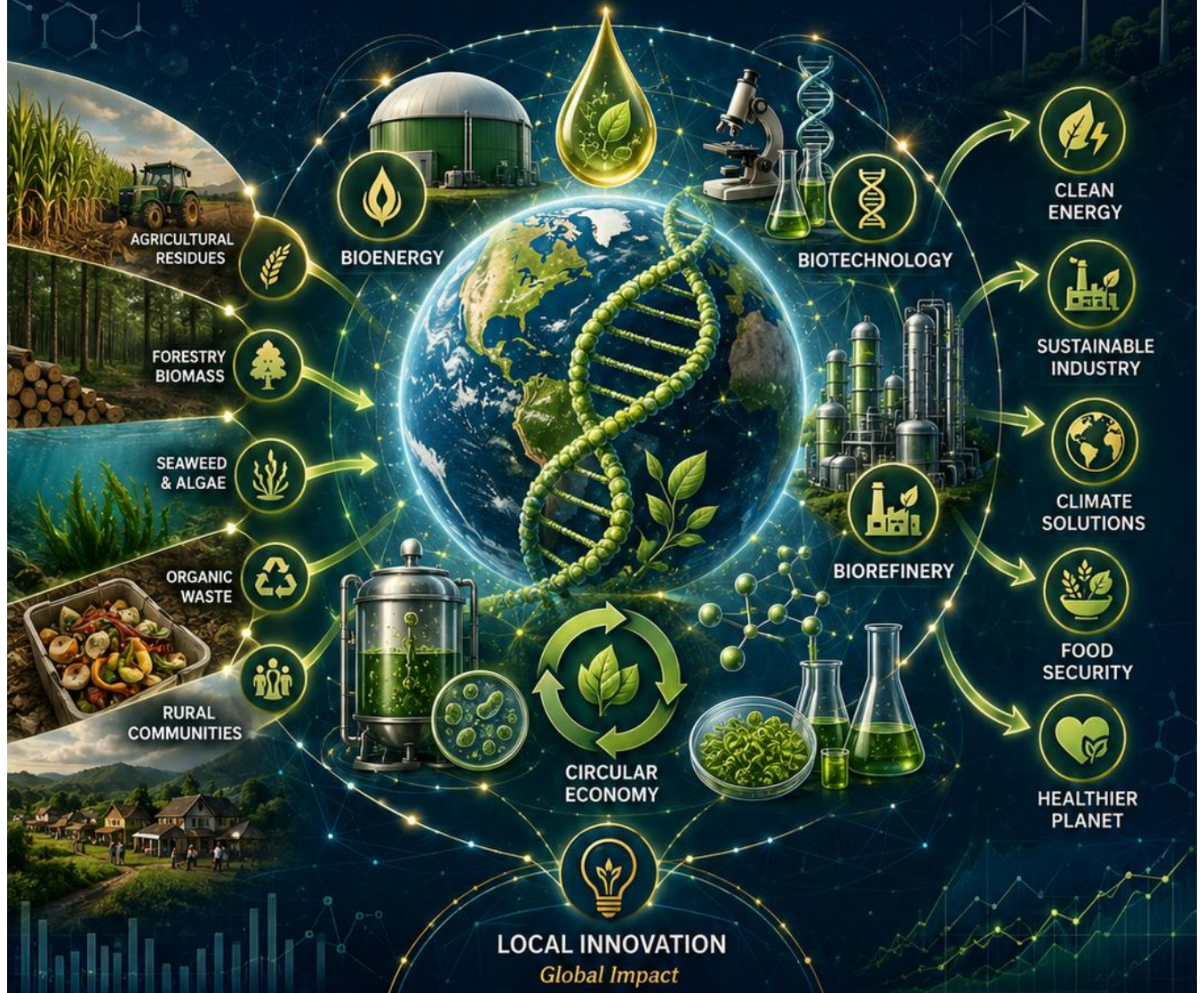


Bioenergy and Biotechnology

Local Solutions for Global Needs

(Solusi Lokal untuk Kebutuhan Global)

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BIOMASS



BIOGAS



BIOFUELS



ALGAE



BIOREFINERY



SUSTAINABILITY

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BIOENERGY AND BIOTECHNOLOGY: LOCAL SOLUTIONS FOR GLOBAL NEEDS

Abstract

The world faces interconnected crises involving climate change, energy insecurity, food-system vulnerability, biodiversity loss, waste accumulation, public-health risks, and unequal access to technology. These problems are global in scale, but many of their most effective solutions must be developed from locally available resources, ecological knowledge, institutional capabilities, and community needs. Bioenergy and biotechnology occupy a strategic position within this local–global relationship because they transform renewable biological resources, organic residues, microorganisms, enzymes, cells, and biological information into energy, food, materials, chemicals, environmental services, and health-related products.

Bioenergy includes heat, electricity, gaseous fuels, liquid fuels, and solid fuels obtained from biomass. Biotechnology employs biological organisms, cellular components, molecular processes, genetic information, and engineering principles to produce goods and services. Their integration creates the foundation of a modern bioeconomy in which agricultural residues, forestry by-products, animal manure, municipal organic waste, wastewater, industrial effluents, algae, and other biological resources can be converted into higher-value outputs. Biotechnology improves this conversion through enzyme engineering, microbial fermentation, metabolic

engineering, genomics, gene editing, synthetic biology, bioprocess optimization, artificial intelligence, and advanced monitoring.

The global importance of these technologies is increasing. The International Energy Agency expects renewable energy consumption in transportation to rise substantially through 2030, with road biofuels providing an important share of the increase and advanced fuels becoming increasingly relevant for aviation, shipping, and other difficult-to-electrify activities. Combined production of biogas and biomethane is also expected to expand as governments recognize its potential to convert agricultural, municipal, and industrial wastes into useful energy. Modern bioenergy continues to play an important role in industrial heat, renewable fuels, waste management, and power-system flexibility. ([IEA](#))

The potential of bioenergy, however, is conditional rather than automatic. Biomass is renewable only when biological stocks are regenerated, soil fertility is maintained, ecosystems are protected, and harvesting does not exceed ecological limits. Biofuels can reduce fossil-energy dependence, but poorly governed production can also intensify deforestation, land conflict, food-price pressure, water consumption, and biodiversity loss. Similarly, biotechnology can increase productivity and resource efficiency, but it can also create concerns involving biosafety, biosecurity, genetic ownership, unequal technological access, and excessive corporate concentration.

This article develops an integrated framework for understanding bioenergy and biotechnology as local solutions for global needs. It discusses major conversion pathways, including anaerobic digestion, fermentation, transesterification, gasification, pyrolysis, hydrothermal processing, enzymatic hydrolysis, microbial synthesis, algal biotechnology, biohydrogen production, and integrated biorefineries. It analyzes the application of biotechnology to lignocellulosic biomass, biogas, biomethane, ethanol, biodiesel, sustainable aviation fuel, marine biomass, wastewater, bio-based materials, agriculture, and carbon management.

Particular attention is given to Indonesia. As a tropical archipelagic country with substantial agricultural, plantation, forestry, marine, livestock, and municipal biological resources, Indonesia can develop decentralized bioenergy and biotechnology systems adapted to local ecological and socioeconomic conditions. Palm-oil mill effluent, rice straw, cassava residues, sugarcane by-products, livestock manure, municipal food waste, seaweed, microalgae, and forest-industry residues all provide potential feedstocks. Indonesia officially launched its mandatory B50 biodiesel program on July 9, 2026, strengthening the role of palm-based biofuel in national energy policy. The program illustrates both the strategic value and the sustainability challenges of large-scale bioenergy development. Government projections concerning foreign-exchange savings and emission reductions should therefore be evaluated through transparent life-cycle accounting, land-use safeguards, smallholder inclusion, and independent monitoring. ([Kementerian ESDM](#))

The article concludes that bioenergy and biotechnology should not be treated as universal technological substitutes for fossil resources. They should instead be designed as components of diversified, circular, territorially grounded, and socially inclusive systems. Priority should be given to wastes, residues, degraded-land resources, cascading biomass use, ecosystem restoration, local processing, and applications that are difficult to electrify. Success requires scientific capacity, sustainability standards, lifecycle assessment, responsible innovation, community participation, transparent governance, long-term financing, and fair distribution of value. When these conditions are fulfilled, locally rooted bioenergy and biotechnology can contribute meaningfully to global energy security, climate mitigation, food resilience, rural development, industrial transformation, and ecological sustainability.

Keywords: *bioenergy, biotechnology, bioeconomy, biomass, biorefinery, biogas, biomethane, biofuels, synthetic biology, circular economy, local innovation, energy transition, Indonesia, sustainable development.*

1. Introduction

Human civilization is entering a period in which several systems must be transformed simultaneously. The energy system must reduce its dependence on fossil fuels. The food system must feed a growing and increasingly urban population under conditions of climate instability. Industrial production must reduce carbon emissions, toxic pollution, and material waste. Health systems must respond to emerging diseases, antimicrobial resistance, demographic change, and unequal access to medicine. Cities must manage increasing quantities of wastewater, food waste, packaging, and organic refuse. Rural regions must create productive employment without degrading forests, soils, water, and biodiversity.

These challenges are global, but they are experienced locally. Climate change is expressed through droughts, floods, heat, crop failures, coastal erosion, forest fires, and changing disease patterns in specific territories. Energy insecurity appears as unstable fuel prices, unreliable electricity, insufficient clean cooking, and high transportation costs. Food insecurity is experienced by households, farmers, fishers, and communities whose livelihoods depend on local ecosystems.

This geographical reality has important implications. Global problems cannot be solved exclusively through uniform technologies designed for centralized implementation. Solutions must be adapted to ecological conditions, resource availability, cultural practices, institutional capacity, infrastructure, and local knowledge.

Bioenergy and biotechnology provide a particularly important bridge between global objectives and local action. Every territory possesses some

form of biological resource: crops, forests, livestock, fisheries, microorganisms, wastewater, food residues, or municipal organic waste. The composition and scale vary, but biological material is embedded in all economies.

Bioenergy transforms part of this biological material into usable energy. Biotechnology improves the productivity, selectivity, safety, and efficiency of biological transformations. The interaction between the two allows societies to produce fuel, electricity, heat, chemicals, fertilizers, feed, materials, pharmaceuticals, and environmental services from renewable biological systems.

The potential is considerable because biological systems perform chemical transformations under conditions that are often milder than conventional industrial processes. Microorganisms synthesize complex molecules, enzymes catalyze specific reactions, plants capture solar energy, algae convert carbon dioxide into biomass, and anaerobic microbial communities transform organic matter into methane.

Biological resources nevertheless differ fundamentally from fossil resources. A tonne of coal is comparatively standardized. A tonne of biomass may differ in water content, density, ash composition, lignin content, seasonality, contamination, and geographical distribution. Biological production also depends on soil, water, climate, biodiversity, and labor.

Consequently, the bioeconomy cannot be governed only as an industrial supply system. It must be understood as an ecological, technological, economic, and social system. Decisions about biomass affect food, land, ecosystems, employment, rural communities, and future generations.

The International Energy Agency emphasizes that sustainable fuels complement electrification and efficiency, particularly in aviation, shipping, industrial heat, and other activities that remain dependent on energy-dense fuels. Bioenergy is therefore not a competitor that must replace

solar, wind, batteries, or efficiency. Its strategic role lies in applications in which biological carbon, stored energy, dispatchability, or compatibility with existing fuel infrastructure provides distinctive value. ([IEA](#))

This article advances five propositions.

First, biological origin does not automatically imply sustainability. A bio-based product can produce serious environmental and social damage if its feedstock causes deforestation, excessive water use, displacement of food production, or labor exploitation.

Second, local resource availability should determine technological choices. Regions should not import expensive technological models without examining whether local feedstocks, skills, markets, infrastructure, and institutions can sustain them.

Third, residues and wastes generally offer better starting points than purpose-grown energy crops because their conversion can provide energy while reducing unmanaged waste and methane emissions. Even residues, however, must be harvested within ecological limits because some material is needed to protect soil fertility, provide animal feed, or support other economic uses.

Fourth, biotechnology can improve bioenergy economics by increasing yield, expanding feedstock flexibility, reducing inhibitors, lowering processing requirements, and producing valuable co-products.

Fifth, governance determines whether bioenergy and biotechnology become instruments of sustainability or new mechanisms of ecological extraction and economic concentration.

2. Conceptual Foundations

2.1 Bioenergy

Bioenergy is energy derived from recently living biological material. Feedstocks include woody biomass, agricultural crops, crop residues, livestock manure, sewage sludge, food waste, industrial organic effluents, algae, and fractions of municipal solid waste.

Bioenergy may be used in solid, liquid, or gaseous form. Solid bioenergy includes wood pellets, briquettes, charcoal, and processed agricultural residues. Liquid biofuels include ethanol, biodiesel, renewable diesel, bio-oil, methanol, and sustainable aviation fuels. Gaseous bioenergy includes biogas, biomethane, syngas, and biologically produced hydrogen.

Bioenergy must be distinguished from the traditional use of biomass. Traditional biomass is frequently burned in inefficient stoves or open fires. Such practices may cause indoor air pollution, health damage, deforestation, and heavy labor burdens, particularly for women and children.

Modern bioenergy uses engineered conversion systems, emission controls, improved efficiency, and regulated supply chains. Its purpose is not to preserve inefficient combustion practices but to obtain more useful energy and economic value from less material.

2.2 Biotechnology

Biotechnology is the application of biological organisms, cells, enzymes, genetic information, and biological processes to create products or services.

Traditional biotechnology includes fermentation, selective breeding, composting, and food preservation. Modern biotechnology incorporates molecular biology, genomics, recombinant DNA, gene editing, systems biology, synthetic biology, metabolic engineering, bioinformatics, and automated bioprocessing.

In bioenergy production, biotechnology may be used to:

1. improve feedstock characteristics;

2. develop enzymes that break down complex biomass;
3. engineer microorganisms to ferment multiple sugars;
4. increase tolerance to heat, acids, solvents, and process inhibitors;
5. redirect cellular metabolism toward fuels and chemicals;
6. improve methane production in anaerobic digesters;
7. increase algal growth or lipid accumulation;
8. monitor microbial communities;
9. reduce waste and energy requirements; and
10. generate valuable co-products that improve financial viability.

The development of CRISPR–Cas gene-editing systems has expanded the ability to modify plants, algae, yeasts, bacteria, and other organisms with greater precision than many earlier methods. CRISPR does not eliminate biological complexity, but it greatly accelerates experimental design and strain improvement (Doudna & Charpentier, 2014; Jinek et al., 2012).

2.3 Bioeconomy

The bioeconomy includes the production, transformation, and use of biological resources, biological knowledge, and biotechnology to generate economic and social value.

A sustainable bioeconomy differs from an economy that merely extracts more biomass. It seeks to maintain ecological regeneration, use resources efficiently, reduce waste, support rural livelihoods, and replace high-impact fossil-based processes where appropriate.

FAO describes bioeconomy development as a pathway for transforming agrifood systems, increasing resource efficiency, reducing pollution, and converting waste into useful products. The organization has also emphasized that biotechnology should be developed inclusively and

responsibly so that benefits reach smallholders, vulnerable communities, and developing countries. ([FAOHome](#))

2.4 Circular Bioeconomy

The circular bioeconomy integrates biological production with circular-economy principles.

In a linear system, resources are extracted, processed, consumed, and discarded. In a circular system, products are designed for longer use, repair, recovery, recycling, and biological reintegration.

The circular bioeconomy applies a cascading-use principle. High-quality biomass should first be used for purposes that preserve the greatest value. Timber, for example, may be used in durable buildings before residues are converted into panels, chemicals, or energy. Food-grade material should generally serve nutritional needs before it is directed to lower-value energy applications.

Energy recovery is important, but it should often occur after prevention, reuse, and material valorization opportunities have been considered.

3. Why Bioenergy and Biotechnology Matter Globally

3.1 Climate Change

The combustion of fossil fuels transfers carbon that has been stored underground for geological periods into the atmosphere. Bioenergy operates within a shorter carbon cycle because biological growth removes carbon dioxide from the atmosphere.

This difference can create climate benefits, but only when biomass stocks are regenerated and supply-chain emissions remain sufficiently low. Carbon neutrality cannot simply be assumed at the smokestack.

Climate performance depends on:

- previous land use;
- changes in soil carbon;
- cultivation inputs;
- fertilizer-related nitrous oxide;
- harvesting;
- transportation;
- conversion efficiency;
- methane leakage;
- co-product allocation;
- ecosystem recovery; and
- the fossil system displaced.

The IPCC recognizes a role for sustainable bioenergy in mitigation pathways while repeatedly emphasizing constraints involving land, biodiversity, water, food security, and carbon accounting. Technical land availability should not be interpreted as proof that large-scale energy-crop production is the most beneficial use of that land. ([IPCC](#))

3.2 Energy Security

Energy security includes availability, affordability, accessibility, reliability, and resilience.

Bioenergy can strengthen security by using domestic resources and diversifying energy supply. Unlike wind and solar generation, stored biomass and biomethane can be used when required, although their costs and ecological limits remain important.

Local biogas can reduce dependence on liquefied petroleum gas, firewood, or diesel. Agricultural industries can use residues to provide process heat and electricity. Biomethane can replace fossil gas in selected applications.

The energy-security benefit is especially significant where imported fuel creates pressure on foreign-exchange reserves or exposes consumers to international price volatility.

3.3 Waste and Pollution

Organic waste creates multiple environmental problems. When disposed of in uncontrolled landfills, it decomposes and produces methane. Untreated animal manure contaminates water. Industrial effluents may contain high organic loads. Crop residues may be openly burned, contributing to particulate pollution.

Anaerobic digestion, composting, fermentation, insect bioconversion, and thermochemical processing can transform these liabilities into energy, fertilizer, feed ingredients, chemicals, or materials.

Waste-to-bioenergy systems create an important double benefit: energy production and environmental management. Their value should therefore be assessed across the entire system rather than only through fuel prices.

3.4 Food Security

Biotechnology can increase crop resistance, improve nutrient-use efficiency, reduce post-harvest losses, develop biological fertilizers, support disease diagnostics, and produce alternative proteins.

Bioenergy can also support food systems through reliable electricity, cold storage, irrigation, drying, and processing. Nevertheless, bioenergy may undermine food security if energy crops displace food production or raise land prices.

The relevant policy question is therefore not whether food and fuel always compete, but under what conditions they compete, complement one another, or create synergies.

3.5 Industrial Decarbonization

Many industrial activities require high-temperature heat or carbon-containing molecules. Direct electrification may not be technically or economically sufficient in every application.

Biomass, biogas, renewable fuels, and bio-based chemicals can complement electrification. Industrial biotechnology can also replace fossil-intensive chemical synthesis with fermentation and enzymatic processing.

3.6 Rural and Regional Development

Biomass is geographically dispersed. Its collection, processing, and conversion can create rural employment and local enterprises.

Decentralized bioenergy may generate value in agricultural regions that otherwise export raw products and import energy. Local processing can reduce transport costs, stabilize waste management, and create income from residues.

These benefits are not automatic. Large centralized facilities may capture most value while communities bear environmental costs. Inclusive ownership and benefit-sharing therefore matter.

4. Biological Resources as Local Capital

Local biological resources can be treated as a form of territorial capital. They include not only physical biomass but also genetic diversity, ecosystems, traditional practices, agricultural knowledge, microbial diversity, and institutional experience.

A resource becomes economically meaningful only when several conditions are present:

1. its quantity and quality are known;
2. its ecological functions are understood;
3. collection costs are manageable;

4. processing technology is available;
5. demand exists for outputs;
6. legal rights are clear;
7. social acceptance is established; and
8. sustainability can be monitored.

A region may appear to possess large quantities of crop residue, but only part of that residue may be available for energy. Farmers may use it as animal feed, bedding, mulch, cooking fuel, construction material, or soil amendment.

Similarly, forestry residues are not “waste” in an ecological sense. Deadwood, branches, leaves, and organic matter contribute to nutrient cycling, habitat, moisture retention, and soil formation.

Local resource assessment must therefore distinguish:

- gross theoretical potential;
- technical potential;
- ecological potential;
- economically recoverable potential; and
- socially acceptable potential.

The IEA’s global work on biogas and biomethane applies this type of sustainability filtering by emphasizing feedstocks that can be mobilized without direct competition with food or animal feed and without unacceptable environmental consequences. ([IEA](#))

5. Feedstock Hierarchy

A sustainable bioenergy strategy should use an explicit feedstock hierarchy.

5.1 Organic Wastes

Food waste, sewage, animal manure, and industrial organic effluents often represent high-priority feedstocks because their unmanaged decomposition causes pollution and greenhouse-gas emissions.

Their conversion can reduce waste-management expenses while producing energy.

5.2 Agricultural and Forestry Residues

Residues such as rice straw, corn stover, bagasse, coconut shells, sawdust, and pruning material can support energy and biorefinery systems.

Only surplus residues should be removed. Minimum retention levels must protect soil organic carbon, nutrient cycling, erosion control, and other existing uses.

5.3 By-products

Industries generate concentrated by-products that can be easier to collect than field residues. Examples include molasses, crude glycerol, black liquor, spent grain, whey, and palm-oil mill effluent.

These materials may support fermentation, anaerobic digestion, chemical recovery, or combined heat and power.

5.4 Degraded-Land Biomass

Perennial crops established on genuinely degraded land may reduce direct competition with food and forests.

However, “degraded land” must be defined carefully. Land classified as economically underused may still support biodiversity, pastoral livelihoods, customary rights, or ecosystem services.

5.5 Dedicated Energy Crops

Purpose-grown crops can provide consistent supply, but they also create the greatest risk of land competition.

Their use should be limited to situations in which lifecycle benefits, land rights, water demand, food-system effects, and biodiversity impacts have been independently assessed.

6. Bioenergy Conversion Pathways

Bioenergy systems use biochemical, thermochemical, chemical, and physical conversion pathways.

6.1 Combustion

Combustion converts biomass into heat through oxidation. Heat may be used directly or to generate steam and electricity.

Combustion is technologically mature but sensitive to moisture, ash, alkali metals, chlorine, sulfur, and particle emissions. Proper boiler design and emission controls are essential.

6.2 Gasification

Gasification converts solid biomass into a combustible gas mixture under limited oxygen or steam. The resulting syngas contains hydrogen, carbon monoxide, methane, carbon dioxide, and impurities.

Syngas can be used for heat, electricity, hydrogen, methanol, or synthetic fuels. Gas cleaning remains a critical challenge because tars, particulates, and contaminants can damage downstream equipment.

6.3 Pyrolysis

Pyrolysis heats biomass without oxygen and produces bio-oil, biochar, and gas.

Fast pyrolysis maximizes liquid production, while slow pyrolysis generally produces more biochar. Bio-oil may be upgraded into fuel or chemicals, although instability, acidity, and oxygen content complicate direct substitution for petroleum.

Biochar can store relatively stable carbon and improve certain soils, but benefits vary with feedstock, production temperature, soil type, application rate, and agricultural conditions.

6.4 Hydrothermal Processing

Hydrothermal liquefaction processes wet biomass under elevated temperature and pressure, producing biocrude.

It is particularly relevant for algae, sewage sludge, and wet organic feedstocks because energy-intensive drying can be avoided.

6.5 Anaerobic Digestion

Anaerobic digestion uses microbial communities to break down organic material without oxygen.

The process includes hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Products include biogas and digestate.

Raw biogas generally contains methane, carbon dioxide, water vapor, hydrogen sulfide, and trace contaminants. It can be burned for heat and power or upgraded to biomethane.

The IEA expects combined biogas and biomethane production to grow between 2025 and 2030, with biomethane attracting interest because it can replace fossil gas in existing infrastructure. Direct biogas remains particularly relevant where pipeline systems are limited. ([IEA](#))

6.6 Fermentation

Fermentation uses microorganisms to convert sugars and other substrates into ethanol, butanol, organic acids, solvents, proteins, and many other products.

Conventional ethanol production uses sugarcane, molasses, corn, wheat, or other sugar- and starch-rich crops. Advanced processes seek to use cellulose and hemicellulose from residues.

6.7 Transesterification

Transesterification converts oils or fats into fatty-acid esters used as biodiesel.

Feedstocks include vegetable oils, used cooking oil, animal fats, and algal oils. Conventional biodiesel is commonly produced as fatty-acid methyl ester.

6.8 Hydrotreatment

Hydrotreatment converts oils and fats into hydrocarbon fuels that are chemically more similar to petroleum diesel and aviation fuels than conventional biodiesel.

These fuels may have better storage and cold-flow characteristics, but their production requires hydrogen and substantial processing infrastructure.

7. Biotechnology as an Enabling Platform

7.1 Enzyme Engineering

Plant cell walls are composed primarily of cellulose, hemicellulose, lignin, and other compounds. Their structure protects plants but creates resistance to industrial conversion.

Enzymes such as cellulases, hemicellulases, lignin-modifying enzymes, lipases, and amylases enable more selective processing.

Enzyme engineering seeks to improve:

- catalytic activity;
- thermal stability;
- tolerance to pH;
- resistance to inhibitors;
- substrate specificity;

- recyclability; and
- production cost.

Biological pretreatment may reduce severe chemical conditions, but it can require longer processing times.

7.2 Metabolic Engineering

Metabolic engineering redesigns cellular pathways so that organisms direct more carbon toward desired products.

A microorganism may naturally produce small amounts of ethanol or an organic acid. Through genetic modification, competing pathways can be reduced and target pathways enhanced.

The approach combines genetics, biochemistry, modeling, fermentation engineering, and analytical measurement.

7.3 Synthetic Biology

Synthetic biology applies engineering concepts to biological systems. Researchers may design genetic circuits, standardized components, artificial pathways, or modified organisms.

Its potential extends beyond biofuels to bio-based polymers, fragrances, pharmaceuticals, enzymes, food ingredients, and specialty chemicals.

Keasling (2010) and Nielsen and Keasling (2016) describe how engineered metabolism can convert renewable substrates into molecules traditionally derived from petroleum.

7.4 CRISPR Gene Editing

CRISPR–Cas systems enable targeted modification of genetic sequences.

Applications in bioenergy include:

- reducing lignin recalcitrance in plants;
- improving fermentation of pentose sugars;

- increasing microbial tolerance to ethanol;
- increasing algal lipid productivity;
- optimizing methane-producing communities;
- improving thermophilic microorganisms; and
- creating strains capable of using multiple waste-derived substrates.

Recent reviews identify CRISPR and synthetic biology as important tools for improving biofuel-producing microorganisms, although laboratory success does not guarantee industrial performance or biosafety. ([ScienceDirect](#))

7.5 Omics Technologies

Genomics examines DNA, transcriptomics examines RNA expression, proteomics examines proteins, metabolomics examines small molecules, and metagenomics examines genetic material in communities.

These technologies are especially valuable in anaerobic digestion, composting, soil systems, and marine biotechnology because the relevant processes involve complex microbial communities.

7.6 Artificial Intelligence and Machine Learning

Machine learning can identify patterns in biological and process data.

Potential applications include:

- enzyme prediction;
- strain selection;
- fermentation control;
- contamination detection;
- feedstock classification;
- reactor optimization;
- algal growth monitoring;

- predictive maintenance; and
- lifecycle modeling.

Machine learning has been explored across microalgal cultivation, harvesting, drying, and conversion, although its value depends on data quality and real-world validation. ([ScienceDirect](#))

8. Lignocellulosic Biomass

Lignocellulosic biomass includes crop residues, grasses, woody material, and processing waste. It is abundant and does not necessarily require food-grade feedstocks.

Its main challenge is recalcitrance. Cellulose fibers are embedded in hemicellulose and lignin, creating a structure that resists enzymatic degradation (Himmel et al., 2007).

Conversion usually requires four stages:

1. pretreatment;
2. enzymatic hydrolysis;
3. fermentation; and
4. product separation.

Pretreatment may be physical, chemical, physicochemical, or biological. Common methods include steam explosion, dilute acid, alkaline treatment, organosolv processing, ammonia fiber expansion, and ionic liquids.

Each method involves trade-offs. Severe treatment improves accessibility but may generate inhibitors. Washing removes inhibitors but consumes water and loses sugars.

Advanced microorganisms are being developed to ferment glucose and pentose sugars. Consolidated bioprocessing seeks to combine enzyme

production, hydrolysis, and fermentation into fewer stages (Lynd et al., 2005).

Commercial viability depends on obtaining value from lignin and other fractions. Burning lignin for process heat is useful, but higher-value applications include resins, carbon materials, aromatic chemicals, adhesives, and composites.

9. Biogas and Biomethane

Biogas is one of the most locally adaptable bioenergy pathways.

A small digester can serve a household or farm. A medium facility can serve a livestock cooperative, food processor, or wastewater plant. A large facility can inject biomethane into a gas grid or provide industrial fuel.

9.1 Suitable Feedstocks

Suitable materials include:

- animal manure;
- food waste;
- sewage sludge;
- palm-oil mill effluent;
- cassava wastewater;
- slaughterhouse waste;
- dairy effluent;
- crop-processing residues; and
- municipal organic waste.

Co-digestion can improve nutrient balance and methane yield. Food waste, for example, may acidify rapidly, while manure supplies buffering capacity and microbial diversity.

9.2 Digestate

Digestate contains nutrients and organic matter. When adequately treated and tested, it can replace part of synthetic fertilizer use.

Poorly managed digestate can release methane, nitrous oxide, ammonia, pathogens, and nutrients into water. It should therefore be considered a regulated product, not an automatically safe by-product.

9.3 Methane Leakage

Methane has a powerful short-term warming effect. Leakage from digesters, storage tanks, upgrading facilities, pipelines, or digestate handling can undermine climate benefits.

Facilities need gas-tight construction, continuous monitoring, flare systems, preventive maintenance, and transparent reporting.

9.4 Local Development

Biogas can provide farmers with energy and fertilizer while reducing odors and water contamination.

Cooperative ownership may allow small farms to aggregate feedstock. Municipal plants can combine waste fees, energy sales, fertilizer sales, and avoided landfill costs.

The economic model should recognize environmental services, not only the market value of methane.

10. Liquid Biofuels

10.1 Bioethanol

Ethanol is produced through fermentation of sugar- or starch-rich feedstocks and can be blended with gasoline.

Sugarcane ethanol can achieve favorable energy balances when bagasse supplies process heat. Corn ethanol benefits depend more strongly on agricultural inputs, energy sources, and co-product accounting.

Cellulosic ethanol seeks to use residues and non-food biomass but faces higher pretreatment, enzyme, and capital costs.

10.2 Biodiesel

Biodiesel is commonly produced from vegetable oils, used cooking oil, or animal fats.

Used oils and wastes often provide stronger environmental performance than virgin oils because they avoid additional cultivation. Their supply is limited and requires collection, quality control, and prevention of fraudulent labeling.

10.3 Renewable Diesel and Aviation Fuel

Hydroprocessed fuels can provide high-quality diesel and aviation components.

Aviation is difficult to electrify because aircraft require high energy density. Sustainable aviation fuels can therefore play a transitional and potentially long-term role.

The IEA expects renewable energy consumption in transportation to increase through 2030. Road biofuels provide an important share of projected growth, while aviation and maritime fuels become increasingly significant as mandates and commercial production expand. ([IEA](#))

10.4 Avoiding Technology Lock-In

Biofuels should be directed toward sectors in which alternatives are limited. Using scarce advanced biofuel in applications that can be electrified easily

may be less efficient than reserving it for aviation, shipping, heavy equipment, or specific industrial processes.

11. Microalgae and Marine Biotechnology

Microalgae can produce lipids, carbohydrates, proteins, pigments, antioxidants, and specialty compounds.

They may be cultivated in open ponds, closed photobioreactors, wastewater, saline water, or integrated industrial systems.

11.1 Advantages

Microalgae can have high areal productivity and do not require conventional cropland in every system. Some species grow in saline or wastewater and can capture nutrients.

11.2 Challenges

Major barriers include:

- cultivation cost;
- contamination;
- mixing energy;
- carbon-dioxide delivery;
- nutrient requirements;
- harvesting;
- dewatering;
- drying;
- extraction; and
- variable outdoor productivity.

Producing fuel alone is often economically difficult because fuel is a low-value bulk product. Integrated production of pigments, feed, nutraceuticals, chemicals, wastewater treatment, and fuel offers a more realistic pathway.

Recent research emphasizes strain selection, omics, gene editing, process integration, and stress management. It also recognizes that large-scale deployment remains constrained by cost and biological-control challenges. ([Springer Link](#))

11.3 Seaweed

Seaweed offers opportunities for food, hydrocolloids, fertilizer, animal-feed additives, bioplastics, chemicals, and energy.

Its low lignin content may simplify some conversion steps. However, water content, salt, seasonal composition, transport, ecological carrying capacity, and coastal rights must be managed.

For Indonesia, seaweed biotechnology offers a particularly important connection among the blue economy, rural coastal livelihoods, food systems, and bio-based industry. Indonesia's Blue Economy Roadmap identifies biotechnology and bioeconomy development as important components of marine economic transformation. ([Perpustakaan Bappenas](#))

12. Biohydrogen

Hydrogen may be produced biologically through dark fermentation, photofermentation, microbial electrolysis, and algal or cyanobacterial processes.

Biological hydrogen remains less mature than conventional hydrogen-production methods. Challenges include low yield, gas separation, microbial stability, reactor design, and scale-up.

Biomass gasification provides another pathway to hydrogen. It is not purely biological conversion, but it links biomass supply with gasification, gas cleaning, and hydrogen separation.

Biohydrogen may become valuable when integrated with waste treatment or biorefineries rather than developed as a single-product process.

13. Bioenergy for Heat, Power, and Flexibility

Electricity receives much attention in energy-transition debates, but heat represents a major share of energy consumption.

Biomass can provide industrial steam and high-temperature heat, especially where residues are generated on-site. Sugar mills, pulp mills, rice mills, and wood-processing industries can use their own by-products.

Combined heat and power improves overall efficiency by using thermal energy that would otherwise be wasted.

Flexible bioenergy can also complement variable renewable electricity. Biogas engines, biomethane turbines, or biomass plants may provide dispatchable power when solar and wind output is low.

This role should not justify inefficient biomass electricity where direct heat, material use, or other renewable options are superior. Technology selection should be based on system value rather than a single electricity-generation target.

14. Integrated Biorefineries

A petroleum refinery separates and transforms crude oil into fuels, chemicals, and materials. A biorefinery seeks to perform an analogous function using biological resources.

The biorefinery concept improves economic and environmental performance by producing multiple outputs.

A sugarcane biorefinery may produce:

- sugar;
- ethanol;
- electricity;
- heat;
- biogas;
- fertilizer;
- carbon dioxide;
- yeast;
- chemicals; and
- advanced fuels.

A lignocellulosic biorefinery may separate cellulose, hemicellulose, lignin, extractives, and minerals.

A palm-oil biorefinery may integrate oil products, biodiesel, oleochemicals, biogas from effluent, compost, fiber, shells, and bio-based chemicals.

The economic logic is important. Fuels are high-volume, low-margin products. Specialty chemicals and materials are lower-volume, higher-margin products. Combining them may improve project viability.

The environmental logic is equally important. Integrated systems can reduce waste, recover nutrients, use process heat, and improve carbon efficiency.

Kamm and Kamm (2004) and Cherubini (2010) identify integrated fractionation and cascading use as core principles of biorefinery development.

15. Biotechnology beyond Energy

Bioenergy should not be isolated from wider biotechnology because the same feedstocks, organisms, laboratories, and industrial platforms can produce multiple outputs.

15.1 Bio-based Chemicals

Fermentation can produce lactic acid, succinic acid, citric acid, acetone, butanol, amino acids, and many other chemicals.

These compounds may become building blocks for polymers, solvents, coatings, and consumer products.

15.2 Bioplastics

Bioplastics include bio-based polymers and biodegradable polymers. These categories are not identical.

A bio-based plastic may not be biodegradable, while a biodegradable plastic may be derived partly from fossil feedstocks.

Bioplastics should not be presented as a substitute for waste prevention. Their value depends on product design, collection, composting infrastructure, toxicity, and actual end-of-life conditions.

15.3 Industrial Enzymes

Enzymes can reduce processing temperatures, replace harsh chemicals, and improve selectivity in textiles, food, detergents, paper, leather, and pharmaceuticals.

15.4 Alternative Proteins

Microbial, fungal, algal, plant, and cultured-cell proteins may reduce pressure on land and water under appropriate production systems.

Energy requirements, feedstock sources, nutritional quality, consumer acceptance, and affordability must be assessed.

15.5 Biological Fertilizers and Biocontrol

Nitrogen-fixing organisms, phosphate-solubilizing microorganisms, mycorrhizae, and biological pest-control agents can reduce dependence on synthetic inputs.

Their effectiveness is context-specific and influenced by soil, climate, crop, formulation, and farmer practices.

16. Agriculture, Food, and Biotechnology

Agricultural biotechnology includes molecular breeding, tissue culture, diagnostics, biological inputs, gene editing, fermentation, and data-driven crop management.

Potential contributions include:

- drought tolerance;
- salinity tolerance;
- pest resistance;
- disease diagnosis;
- improved nutrient content;
- reduced post-harvest loss;
- improved feed conversion;
- vaccine development; and
- adaptation to climate change.

The use of biotechnology in agriculture should be evaluated case by case. The relevant questions include:

1. What problem is being solved?
2. Who owns the technology?

3. Can farmers save or reproduce inputs?
4. Does the innovation increase or reduce pesticide dependence?
5. What are the ecological risks?
6. How will benefits and liabilities be distributed?
7. Are local alternatives available?
8. Is long-term monitoring feasible?

Responsible agricultural biotechnology requires public research, farmer participation, transparent risk assessment, and protection against excessive concentration of seed and data ownership.

17. Wastewater Biotechnology

Wastewater contains water, organic carbon, nitrogen, phosphorus, heat, and microorganisms. Modern wastewater management increasingly treats these as recoverable resources.

Anaerobic treatment can produce biogas. Nutrients can be recovered as fertilizers. Algae can remove nitrogen and phosphorus. Microbial electrochemical systems may generate electricity or hydrogen.

Wastewater plants can become resource-recovery facilities.

Industrial wastewater often has sector-specific characteristics. Palm-oil mill effluent, dairy wastewater, brewery effluent, cassava wastewater, and pulp-industry streams require different microbial and engineering strategies.

The strongest systems integrate pollution control, energy production, water reuse, and nutrient recovery.

18. Climate Mitigation and Carbon Management

18.1 Substitution

Bioenergy can reduce emissions by substituting for fossil fuels. The benefit equals avoided fossil emissions minus all additional lifecycle emissions and carbon-stock changes.

18.2 Carbon Storage in Products

Biological carbon may be stored temporarily in timber buildings, durable materials, biochar, or other products.

Long-lived wood products can substitute for emission-intensive materials, although forest regeneration and market displacement effects must be included.

18.3 BECCS

Bioenergy with carbon capture and storage captures carbon dioxide released during biomass processing and stores it underground.

In theory, photosynthesis removes carbon dioxide from the atmosphere and geological storage prevents its return.

BECCS can produce negative emissions only if:

- biomass regrows;
- land-use emissions are limited;
- supply-chain emissions are controlled;
- capture rates are high;
- geological storage is durable; and
- ecosystem and food-system impacts remain acceptable.

Integrated assessment models frequently include BECCS, but large-scale reliance creates concerns involving land, water, biodiversity, and social feasibility (Smith et al., 2016; Fuss et al., 2018).

18.4 Fermentation Carbon Dioxide

Ethanol fermentation produces a relatively pure carbon-dioxide stream. Capturing this stream may be less expensive than capturing dilute combustion emissions.

Such opportunities can provide early BECCS applications where geological storage or durable utilization is available.

18.5 Biochar

Biochar can retain carbon for extended periods depending on production conditions and environmental context.

It may improve water retention, nutrient retention, or soil properties in some locations. It should not be promoted without soil-specific testing.

19. The Sustainability Debate

Bioenergy is neither inherently sustainable nor inherently unsustainable. Its performance depends on the system.

19.1 Carbon Debt

When forests or carbon-rich ecosystems are cleared, large emissions occur immediately. Even if biomass regrows, repayment of this carbon debt may require decades or centuries.

This timing matters because climate stabilization requires rapid reductions.

19.2 Direct Land-Use Change

Direct land-use change occurs when land is converted for energy-feedstock production.

Converting forest, peatland, grassland, or other carbon-rich ecosystems can eliminate expected climate benefits.

19.3 Indirect Land-Use Change

Indirect land-use change occurs when bioenergy demand displaces existing agriculture, causing production to expand elsewhere.

Its exact magnitude is difficult to estimate because it operates through markets, policies, yields, trade, and behavioral responses. Difficulty of measurement does not justify ignoring it.

Seminal studies demonstrated that land conversion and indirect effects could substantially alter biofuel climate balances (Fargione et al., 2008; Searchinger et al., 2008).

19.4 Food versus Fuel

Food and fuel competition occurs through land, water, crops, fertilizer, labor, and capital.

Competition can be reduced by using wastes, residues, non-food fractions, degraded-land systems, integrated food–energy production, yield improvement, and cascading use.

Bioenergy policies should contain safeguards that respond to food-price shocks and local food-security conditions.

19.5 Biodiversity

Monoculture expansion can reduce habitat diversity and ecological resilience.

Certification may reduce some risks but cannot substitute for landscape-level planning and enforcement.

19.6 Water

Bioenergy consumes water through cultivation, processing, cooling, and pollution assimilation.

Water impacts are highly local. A crop that is acceptable in a humid region may be unsuitable in a water-stressed area.

19.7 Soil

Excessive residue removal reduces soil organic matter and nutrients.

Sustainable harvesting rates must be adapted to soil type, slope, rainfall, crop system, and erosion risk.

19.8 Air Quality

Modern bioenergy can reduce exposure to traditional biomass smoke, but poorly controlled combustion emits particulates, nitrogen oxides, carbon monoxide, and other pollutants.

Air-quality standards and emission controls are necessary.

20. Life-Cycle Assessment

Life-cycle assessment evaluates environmental impacts across production, conversion, use, and end-of-life stages.

A bioenergy LCA should specify:

- functional unit;
- system boundary;
- time horizon;
- reference fossil system;
- land-use assumptions;
- co-product allocation;
- carbon-stock change;
- fertilizer emissions;
- transport distances;
- conversion efficiency;
- methane leakage;

- infrastructure; and
- uncertainty.

Different assumptions can produce very different results. Transparency is therefore more important than presenting a single number without context.

20.1 Attributional and Consequential LCA

Attributional LCA describes average environmental burdens associated with a product system.

Consequential LCA estimates the changes caused by a decision, including market responses and indirect effects.

Policy evaluation often requires consequential analysis, while product reporting may use attributional methods.

20.2 Temporal Accounting

Biogenic carbon is emitted and absorbed at different times. Static accounting may hide the significance of delayed regrowth.

Dynamic approaches can represent timing more accurately.

20.3 Multi-Criteria Assessment

Climate performance alone is insufficient. Evaluation should include biodiversity, water, soil, air pollution, employment, land rights, food security, and distributional effects.

21. Socioeconomic Dimensions

21.1 Employment

Bioenergy supply chains can create jobs in farming, collection, transportation, engineering, construction, operations, laboratory services, and maintenance.

Job quality matters. Informal labor, unsafe conditions, and low wages should not be counted as unqualified development benefits.

21.2 Smallholder Inclusion

Small farmers can supply feedstock, own digesters, participate in cooperatives, or receive revenue from residues.

Contract terms, price transparency, access to finance, extension services, and land rights determine whether inclusion is meaningful.

21.3 Energy Access

Small-scale biogas, biomass gasification, and waste-to-energy systems may support remote areas.

Projects should prioritize reliability and maintenance. Many rural-energy projects fail when spare parts, technical support, ownership, and payment systems are neglected.

21.4 Gender

Women are often responsible for cooking fuel, agricultural processing, water collection, and household waste.

Clean bioenergy can reduce time burdens and indoor pollution, but women must participate in design, ownership, finance, training, and governance.

21.5 Local Value Addition

Exporting raw biomass may provide limited local benefit. Processing near the source can create jobs and reduce transport of low-density material.

However, plant scale must match feedstock availability. Oversized facilities can encourage unsustainable harvesting.

22. Indigenous and Local Knowledge

Local communities possess knowledge of crops, forests, fermentation, medicinal plants, marine organisms, soil, and ecological change.

This knowledge can inform biotechnology and bioeconomy innovation. It must not be treated as freely extractable information.

Ethical collaboration requires:

- prior informed consent;
- recognition of customary rights;
- equitable benefit-sharing;
- transparency;
- community participation;
- respect for cultural values; and
- protection against misappropriation.

Local knowledge and modern science should not be placed in opposition. They can complement one another when power relations are addressed.

23. Responsible Innovation, Biosafety, and Biosecurity

Biotechnology creates benefits but also uncertainties.

23.1 Biosafety

Biosafety concerns accidental harm to people, animals, plants, or ecosystems.

Risk assessment should consider:

- organism characteristics;
- inserted or edited traits;
- gene flow;

- persistence;
- toxicity;
- allergenicity;
- ecological interactions;
- containment; and
- monitoring.

23.2 Biosecurity

Biosecurity concerns deliberate misuse, theft, unauthorized access, or harmful application of biological materials and knowledge.

Laboratories need physical security, personnel reliability, information governance, and incident-response capacity.

23.3 Responsible Research and Innovation

Responsible innovation requires anticipation, inclusion, reflexivity, and responsiveness (Stilgoe et al., 2013).

Scientists and companies should ask not only whether a technology can be developed, but also:

- whether it should be developed;
- for whose benefit;
- under whose control;
- with what alternatives;
- under what safeguards; and
- with what exit strategy if harm emerges.

23.4 Intellectual Property

Patents can encourage investment but may restrict access to foundational tools, genetic resources, or locally developed knowledge.

Publicly funded research should balance commercialization with public benefit.

Licensing models can support humanitarian use, local manufacturing, and developing-country access.

24. Indonesia's Strategic Potential

Indonesia is exceptionally well positioned to develop a diversified bioeconomy. It possesses tropical agriculture, extensive plantation industries, forestry resources, marine biodiversity, aquaculture, livestock, food-processing industries, and a large domestic market.

Its archipelagic geography also creates a strong case for decentralized systems. Transporting fossil fuels to remote islands is costly, while local biological residues may be available.

The strategic opportunity is not simply to produce more commodity biofuel. Indonesia can develop integrated regional bioeconomies based on local resource profiles.

24.1 Palm-Oil Regions

Potential resources include:

- palm-oil mill effluent;
- empty fruit bunches;
- fibers;
- shells;
- pruned fronds;
- used cooking oil; and
- crude glycerol.

POME can produce biogas and reduce methane emissions. Fibers and shells can provide process energy. Empty fruit bunches can be composted, converted thermochemically, or processed into materials.

The system should prioritize methane capture, water protection, traceability, smallholder productivity, and zero conversion of forests and peatlands.

24.2 Rice-Producing Regions

Rice systems generate straw and husks.

Rice husks are concentrated at mills and can provide heat, electricity, silica, and biochar. Straw is geographically dispersed and has important soil and livestock uses.

Technologies should be adapted to local collection economics and agronomic needs.

24.3 Sugarcane Regions

Bagasse can supply heat and power. Molasses can produce ethanol, yeast, and chemicals. Filter cake and vinasse can support fertilizer and biogas systems.

Integrated sugarcane biorefineries can improve resource efficiency.

24.4 Cassava Regions

Cassava starch and wastewater can support ethanol, biogas, animal feed, and bio-based products.

Wastewater management is essential because untreated effluent has a high organic load.

24.5 Livestock Regions

Manure digesters can produce biogas and improve nutrient management.

Cooperative systems are appropriate where individual farms are too small.

24.6 Urban Areas

Cities generate food waste, sewage, market waste, restaurant oils, and landscaping residues.

Source separation is fundamental. Mixed waste reduces feedstock quality and increases contamination.

24.7 Coastal and Marine Regions

Seaweed, fish-processing residues, and marine microorganisms can support food, feed, enzymes, pharmaceuticals, fertilizers, materials, and energy.

Marine biotechnology should be linked to biodiversity protection and coastal livelihoods.

25. Indonesia's B50 Biodiesel Program

Indonesia officially launched mandatory B50 biodiesel in July 2026. The blend contains 50 percent palm-derived biodiesel in diesel fuel and represents the latest stage of a program that progressed through lower blending levels. ([Kementerian ESDM](#))

The program has several strategic objectives:

1. reducing diesel imports;
2. improving energy security;
3. supporting domestic palm-oil demand;
4. increasing value addition;
5. creating rural income;
6. reducing exposure to oil-price volatility; and
7. lowering greenhouse-gas emissions relative to fossil diesel.

Government statements associated with the launch projected significant foreign-exchange savings and substantial emission reductions. Such estimates should be interpreted as policy projections that require continuing verification through independent lifecycle analysis.

([Kementerian ESDM](#))

The B50 program also raises critical questions.

First, can demand be met through higher yields, existing plantations, wastes, and improved efficiency rather than land expansion?

Second, how will the program affect food-oil markets, exports, and prices?

Third, can smallholders meet traceability and sustainability standards?

Fourth, what are the fiscal implications of price support and export-levy arrangements?

Fifth, what are the effects of higher blends on engines, storage, oxidation, filters, maintenance, and fuel quality?

Sixth, how will indirect land-use pressures be monitored?

Seventh, what share of lifecycle emissions arises from fertilizers, mill energy, methane, transport, and land-use change?

The program should therefore evolve from a volume-based mandate into a performance-based system.

A high-quality biofuel policy would reward:

- lower lifecycle emissions;
- methane capture;
- verified zero-deforestation supply;
- peatland protection;
- smallholder inclusion;
- yield improvement;

- use of waste oils;
- traceability;
- efficient mills; and
- independent disclosure.

Indonesia's experience is globally important because it demonstrates both the possibilities and the tensions of using a major agricultural commodity for national energy policy.

26. A Local Bioeconomy Model for Indonesia

Indonesia should avoid a single-feedstock strategy. A diversified model is more resilient.

26.1 Village Scale

At village scale, suitable systems include:

- livestock-manure digesters;
- small food-processing units;
- biomass drying;
- biofertilizer production;
- community composting;
- seed and tissue-culture services; and
- solar–bioenergy hybrid systems.

26.2 District Scale

At district scale, projects can aggregate:

- market waste;
- slaughterhouse waste;

- rice-mill residues;
- cassava effluent;
- used cooking oil;
- municipal organic waste; and
- wastewater sludge.

26.3 Industrial-Cluster Scale

Industrial clusters can support:

- biomethane;
- bio-based chemicals;
- advanced fuels;
- carbon capture;
- enzyme manufacturing;
- integrated wastewater recovery;
- algae cultivation;
- shared laboratories; and
- industrial symbiosis.

26.4 National Scale

National policy should provide:

- sustainability standards;
- research infrastructure;
- carbon accounting;
- biosafety regulation;
- financing;

- national data;
 - market incentives;
 - export strategy;
 - skills development; and
 - international partnerships.
-

27. Business Models

27.1 Feedstock Ownership

Feedstock contracts must define quantity, quality, price, sustainability, and delivery obligations.

Long-term contracts support financing but may disadvantage farmers if prices are inflexible.

27.2 Cooperative Ownership

Cooperatives can aggregate feedstock and distribute value.

They require professional management, transparent accounting, technical support, and member participation.

27.3 Energy-Service Companies

An energy-service company may finance and operate a digester or biomass boiler while customers pay for heat, gas, or waste treatment.

27.4 Public-Private Partnerships

Municipal waste and wastewater projects may use public-private partnerships.

Contracts must allocate feedstock risk, technology risk, demand risk, environmental liability, and performance obligations.

27.5 Biorefinery Revenue Stacking

Projects may combine revenue from:

- energy;
- waste-management fees;
- carbon credits;
- fertilizers;
- chemicals;
- feed;
- water recovery; and
- environmental services.

Carbon finance should reward additional and verifiable mitigation, not compensate for legally required performance.

28. Financing

Bioenergy projects often face high initial costs, feedstock risk, and uncertain output markets.

Financing instruments include:

- commercial loans;
- development-bank finance;
- guarantees;
- concessional capital;
- green bonds;
- blended finance;
- carbon finance;
- viability-gap funding; and

- results-based payments.

Small projects face particularly high transaction costs. Standardized contracts, technical templates, aggregated portfolios, and credit guarantees can improve access.

Investors need reliable data on feedstock, technology performance, offtake, regulation, and environmental compliance.

29. Research and Innovation Strategy

A national bioeconomy requires more than individual research projects. It requires an innovation system.

29.1 Mission-Oriented Research

Research missions could include:

- low-cost enzymes for tropical biomass;
- high-solids anaerobic digestion;
- methane-leak detection;
- POME biorefineries;
- seaweed bioproducts;
- sustainable aviation fuel;
- lignin valorization;
- microbial protein;
- bio-based fertilizers;
- tropical biochar;
- plastic-degrading enzymes; and
- decentralized bioprocessing.

29.2 Pilot and Demonstration Facilities

Many technologies fail between laboratory research and commercial deployment.

Shared pilot facilities allow researchers and firms to test scale-up, contamination control, separation, energy use, and economics.

29.3 University–Industry Collaboration

Universities can provide scientific depth, while industry provides process data and commercialization pathways.

Agreements must protect academic independence and ensure fair management of intellectual property.

29.4 Open Data

National biomass maps, residue data, waste flows, lifecycle factors, microbial resources, and pilot results should be made accessible where security and confidentiality permit.

Open data reduces duplication and supports innovation by smaller firms.

30. Human-Capital Development

The bioeconomy requires interdisciplinary skills.

Relevant fields include:

- microbiology;
- molecular biology;
- chemical engineering;
- agricultural science;
- forestry;
- marine science;

- environmental engineering;
- data science;
- economics;
- law;
- ethics;
- public policy; and
- community development.

Education should connect laboratory science with systems thinking. A technically efficient reactor can fail because of poor contracts, unreliable feedstock, community opposition, or weak maintenance.

Vocational programs are needed for operators, laboratory technicians, mechanics, fermentation specialists, boiler technicians, and environmental monitors.

31. Governance Architecture

A coherent governance architecture should integrate energy, agriculture, forestry, industry, waste, environment, marine resources, research, health, trade, and regional development.

Fragmented regulation can produce contradictory incentives. One ministry may subsidize a feedstock while another seeks to reduce land conversion.

31.1 Core Governance Principles

The core principles should include:

Scientific integrity. Claims must be supported by transparent evidence.

Lifecycle accountability. Emissions and impacts must be measured across the supply chain.

Additionality. Incentives should support benefits that would not occur otherwise.

Traceability. Feedstock origin should be verifiable.

Ecological limits. Harvesting must remain within regenerative capacity.

Social inclusion. Communities and small producers should receive fair benefits.

Technology neutrality with sustainability differentiation. Policy should reward performance rather than labels.

Adaptive regulation. Standards should evolve with evidence.

Public participation. Affected groups should influence decisions.

31.2 Monitoring

Remote sensing, digital ledgers, sensors, fuel testing, methane detection, and public dashboards can strengthen monitoring.

Technology does not replace enforcement. Data must be independently audited, and violations must produce credible consequences.

32. A Strategic Roadmap

Phase I: Resource and Institutional Mapping

The first phase should map biological resources, existing uses, ecological constraints, technology capacity, infrastructure, and community rights.

Projects should not begin with a preferred technology and then search for feedstock. They should begin with local needs and resource conditions.

Phase II: No-Regret Applications

Priority should be given to applications with clear multiple benefits:

- methane capture from waste;

- POME treatment;
- livestock digesters;
- used-cooking-oil collection;
- industrial residue utilization;
- efficient biomass heat;
- wastewater resource recovery; and
- reduction of open burning.

Phase III: Integrated Demonstration

Regions should develop integrated demonstration facilities combining energy, materials, fertilizer, water recovery, and high-value products.

Phase IV: Sustainable Scaling

Scaling should occur only after technical, economic, environmental, and social performance is demonstrated.

Phase V: Advanced Biomanufacturing

Long-term development should include synthetic biology, precision fermentation, advanced materials, marine biotechnology, enzymes, and carbon-negative processes.

33. Policy Recommendations

33.1 Prioritize Residues and Wastes

Public incentives should favor feedstocks that reduce waste and avoid new land demand.

33.2 Adopt Lifecycle-Based Standards

Fuel mandates should include minimum greenhouse-gas savings and progressively stronger sustainability requirements.

33.3 Protect High-Carbon and High-Biodiversity Land

Forests, peatlands, wetlands, and other critical ecosystems should not be converted for bioenergy.

33.4 Strengthen Smallholder Productivity

Yield improvement, replanting, extension, finance, and certification can reduce pressure for expansion.

33.5 Develop Methane Regulation

Biogas facilities should monitor and report methane leakage.

33.6 Build Local Manufacturing

Domestic production of digesters, boilers, sensors, enzymes, pumps, and processing equipment can increase value creation.

33.7 Integrate Food, Energy, and Land Planning

Bioenergy targets should be assessed against food security, water, biodiversity, and land rights.

33.8 Support Public Biotechnology

Public research institutions should develop technologies for locally important crops, wastes, diseases, and environmental conditions that may not attract private investment.

33.9 Strengthen Biosafety and Biosecurity

Regulatory agencies need scientific expertise, laboratories, information systems, and enforcement authority.

33.10 Create Transparent Benefit-Sharing

Communities providing biological resources or knowledge should receive fair economic and institutional benefits.

34. Future Scenarios

34.1 Extractive Bioeconomy

In this scenario, biomass demand expands rapidly without adequate safeguards.

Large companies control land and processing. Commodity exports increase, but deforestation, land conflict, and inequality worsen.

Biotechnology primarily serves corporate efficiency.

34.2 Technocratic Bioeconomy

In this scenario, advanced technologies expand through centralized planning.

Efficiency improves, but community participation and local ownership remain limited. Public acceptance becomes fragile.

34.3 Circular Local Bioeconomy

In this scenario, regions prioritize wastes, residues, local enterprises, cooperatives, and integrated processing.

Benefits are widely distributed, although scale and capital may remain limited.

34.4 Networked Sustainable Bioeconomy

This scenario combines local systems with national standards, research networks, digital monitoring, industrial clusters, and international markets.

It offers the strongest potential if governance remains inclusive and ecological limits are respected.

35. Conclusion

Bioenergy and biotechnology occupy a distinctive position in the transition toward sustainable development. They connect energy, food, agriculture, forestry, oceans, industry, health, waste, climate, and rural development.

Their greatest promise lies not in replacing every fossil resource with biomass. Such a strategy would exceed ecological limits. Their promise lies in using biological resources intelligently, selectively, and circularly.

Local solutions are essential because biological resources are territorially specific. Rice residues, palm-oil effluent, livestock manure, municipal food waste, cassava wastewater, seaweed, algae, forestry by-products, and microbial diversity each require different technological and institutional arrangements.

Biotechnology increases the capacity to transform these resources. Enzyme engineering can reduce biomass recalcitrance. Metabolic engineering can increase fermentation yield. CRISPR can accelerate strain development. Omics can explain microbial communities. Artificial intelligence can improve process control. Synthetic biology can produce fuels, chemicals, materials, proteins, and medicines.

Technology alone, however, cannot determine sustainability.

A biofuel may be renewable but environmentally destructive. A biorefinery may be efficient but socially exclusive. A gene-edited organism may be scientifically impressive but inappropriate for local farmers. A waste-to-energy plant may generate electricity but weaken recycling and waste prevention.

The decisive questions are systemic:

- What resource is used?
- What would otherwise happen to it?
- What land and water impacts occur?
- What fossil product is displaced?

- How much energy is consumed?
- Who owns the technology?
- Who receives the benefits?
- Who bears the risks?
- What alternatives exist?
- Can the system be monitored?
- Can it adapt to new evidence?

Indonesia demonstrates the significance of these questions. Its biomass, biodiversity, agricultural economy, marine resources, and domestic market provide enormous potential. The launch of mandatory B50 biodiesel in July 2026 highlights Indonesia's ambition to use biological resources for energy sovereignty. Yet the long-term legitimacy of this strategy will depend on lifecycle performance, zero-deforestation implementation, smallholder inclusion, fiscal transparency, food-market stability, and ecosystem protection. ([Kementerian ESDM](#))

A sustainable national strategy should therefore be diversified. Palm-based fuels can form one component, but they should be accompanied by biogas, biomethane, ethanol, municipal organic-waste recovery, wastewater biotechnology, seaweed, microalgae, forest-industry residues, bio-based chemicals, biological fertilizers, and advanced biomanufacturing.

The most defensible hierarchy is clear. Prevent unnecessary consumption. Protect ecosystems. Use biomass efficiently. Preserve higher-value material uses. Prioritize unavoidable wastes and residues. Direct scarce sustainable fuels toward sectors that are difficult to electrify. Recover nutrients. Monitor methane. Evaluate complete lifecycles. Share benefits fairly.

When embedded in this hierarchy, bioenergy and biotechnology can become more than technical alternatives. They can form a development paradigm in which local biological resources, knowledge, institutions, and

enterprises contribute to global climate stability, energy resilience, food security, industrial innovation, and ecological restoration.

The phrase *local solutions for global needs* should therefore not be interpreted as technological isolation. Local systems must participate in international scientific collaboration, common standards, trade, finance, and knowledge exchange.

The principle is instead one of rooted innovation: technology should emerge from or adapt to territorial realities, strengthen local capabilities, respect ecological limits, and contribute to wider human needs.

Under these conditions, bioenergy and biotechnology can help build an economy that is not merely less dependent on fossil carbon, but also more circular, resilient, inclusive, knowledge-intensive, and regenerative.

Glossary

Anaerobic Digestion

A microbial process that decomposes organic material without oxygen and produces biogas and digestate.

Bio-based Product

A product manufactured partly or entirely from renewable biological resources.

Biobutanol

Butanol produced through biological fermentation and used as a fuel, solvent, or chemical intermediate.

Biochemical Conversion

Conversion of biomass through enzymes, microorganisms, or biological reactions.

Biodegradable

Capable of being decomposed by microorganisms under specified environmental conditions.

Biodiesel

A fuel composed mainly of fatty-acid esters produced from oils or fats.

Biodiversity

The diversity of genes, species, and ecosystems.

Bioeconomy

Economic activity based on biological resources, biological knowledge, and biotechnology.

Bioenergy

Energy obtained from biomass or biologically derived materials.

Bioethanol

Ethanol produced by fermenting biological feedstocks.

Biofertilizer

A biological product containing organisms or biologically derived substances that improve plant nutrition or soil function.

Biofuel

A liquid, solid, or gaseous fuel derived from biological material.

Biogas

A gas mixture, primarily methane and carbon dioxide, produced through anaerobic digestion.

Biohydrogen

Hydrogen produced through biological or biomass-based processes.

Bioinformatics

The use of computation to store, analyze, and interpret biological information.

Biomass

Biological material derived from plants, animals, microorganisms, or organic wastes.

Biomethane

Purified biogas containing a high concentration of methane and suitable for use similarly to natural gas.

Bioreactor

A controlled vessel or system in which biological reactions occur.

Biorefinery

An integrated facility that converts biomass into fuels, energy, chemicals, materials, food, feed, or other products.

Biosafety

Measures for preventing accidental harm from biological organisms, materials, or processes.

Biosecurity

Measures for preventing deliberate misuse, theft, or unauthorized release of biological agents and information.

Biotechnology

The application of organisms, cells, enzymes, and biological knowledge to produce goods and services.

Biochar

Carbon-rich material produced by heating biomass under limited oxygen.

Carbon Debt

The initial increase in greenhouse-gas emissions caused by biomass harvesting or land conversion before future savings compensate for it.

Carbon Negative

A condition in which a system removes more greenhouse gases from the atmosphere than it emits.

Cascading Use

Sequential use of biomass for higher-value products before energy recovery.

Cellulose

A structural carbohydrate forming a major component of plant cell walls.

Circular Bioeconomy

A bioeconomy that combines renewable biological resources with resource-efficiency, reuse, recycling, and ecological regeneration.

Co-digestion

Anaerobic digestion of two or more feedstocks together.

Consolidated Bioprocessing

Integration of enzyme production, biomass hydrolysis, and fermentation in a single or simplified biological process.

CRISPR–Cas

A gene-editing system adapted from microbial immune mechanisms.

Digestate

The nutrient-containing material remaining after anaerobic digestion.

Direct Land-Use Change

Conversion of land directly for feedstock or project development.

Enzyme

A biological catalyst that accelerates a specific chemical reaction.

Feedstock

Raw material supplied to a biological, chemical, or energy-conversion process.

Fermentation

Metabolic conversion of substrates by microorganisms into fuels, foods, chemicals, or other products.

First-Generation Biofuel

Biofuel produced mainly from food-related sugar, starch, or oil crops.

Gasification

Thermochemical conversion of biomass into syngas using limited oxygen, steam, or other gasifying agents.

Gene Editing

Targeted alteration of genetic sequences.

Greenhouse-Gas Intensity

Quantity of greenhouse-gas emissions per unit of energy, product, service, or economic output.

Hemicellulose

A heterogeneous group of plant-cell-wall carbohydrates surrounding cellulose fibers.

Hydrothermal Liquefaction

Conversion of wet biomass into biocrude under elevated temperature and pressure.

Indirect Land-Use Change

Land conversion occurring elsewhere because existing agricultural production is displaced by bioenergy demand.

Industrial Biotechnology

Use of biological systems for industrial production of chemicals, fuels, materials, enzymes, and other products.

Lignin

A complex aromatic polymer that strengthens plant cell walls and contributes to biomass recalcitrance.

Lignocellulosic Biomass

Plant material composed mainly of cellulose, hemicellulose, and lignin.

Life-Cycle Assessment

A method for evaluating environmental impacts across all stages of a product or system.

Metabolic Engineering

Modification of cellular pathways to increase production of desired compounds.

Metagenomics

Analysis of genetic material recovered directly from microbial communities.

Methane Leakage

Unintended release of methane from production, storage, processing, or distribution systems.

Microalgae

Microscopic photosynthetic organisms used for food, feed, chemicals, wastewater treatment, and bioenergy.

Microbial Electrolysis Cell

A bioelectrochemical system that uses microorganisms and applied voltage to produce hydrogen or other products.

Omics

Collective term for large-scale biological disciplines such as genomics, proteomics, transcriptomics, and metabolomics.

Palm-Oil Mill Effluent

High-organic-content wastewater produced during palm-oil processing.

Photobioreactor

A closed or semi-closed cultivation system designed for photosynthetic organisms.

Precision Fermentation

Use of engineered microorganisms to produce specific molecules, proteins, fats, or other compounds.

Pretreatment

Physical, chemical, thermal, or biological processing used to make biomass easier to convert.

Pyrolysis

Thermal decomposition of biomass in the absence or near-absence of oxygen.

Renewable Diesel

A hydrocarbon diesel fuel produced from renewable oils, fats, or other biological feedstocks.

Residue

Material remaining after agricultural, forestry, food, or industrial production.

Responsible Innovation

Innovation that anticipates impacts, involves stakeholders, reflects on values, and responds to social needs and risks.

Second-Generation Biofuel

Biofuel produced mainly from lignocellulosic biomass, residues, or non-food feedstocks.

Sustainable Aviation Fuel

A non-fossil or lower-carbon aviation fuel meeting applicable technical and sustainability standards.

Syngas

A mixture mainly containing hydrogen and carbon monoxide produced through gasification.

Synthetic Biology

Design and construction of biological systems using engineering principles.

Third-Generation Biofuel

A term commonly associated with fuels derived from algae or other advanced biological platforms.

Transesterification

A chemical reaction converting oils or fats into esters such as biodiesel.

Waste Valorization

Conversion of waste into energy, materials, chemicals, nutrients, or other valuable products.

Whole-Genome Sequencing

Determination of the complete DNA sequence of an organism.

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