

# Unlocking Biofuel Potential: Addressing Challenges and Seizing Opportunities





# The Importance of Bioenergy in Decarbonisation

The shift toward renewable energy is a fundamental strategy for achieving global decarbonisation objectives and mitigating climate change. Among renewable technologies, bioenergy plays a crucial role due to its ability to harness waste materials for generating clean energy and producing sustainable biofuels.

Bioenergy refers to energy generated from organic materials, such as plant and animal-derived biomass or so-called bio-wastes. It is a critical component in the transition to cleaner energy systems due to its ability to significantly reduce greenhouse gas emissions compared to fossil fuels. The carbon-neutral potential of bioenergy arises from the balance between carbon dioxide (CO<sub>2</sub>) emissions during biomass combustion and CO<sub>2</sub> absorption through photosynthesis during biomass growth. This carbon neutrality makes bioenergy an attractive alternative to conventional fossil fuels like coal and natural gas, particularly for power generation.

As global urbanisation intensifies and population growth accelerates, the World Bank projects waste production will rise by 70% by 2050<sup>1</sup>. This trend underscores the pressing need for efficient waste management solutions that integrate bioenergy technologies to support a circular economy and to close the loop on biomass material streams. Leveraging waste-to-energy pathways not only addresses the growing waste burden but also contributes to sustainable energy generation by converting organic waste into renewable fuels and electricity.

The bioenergy market is expected to reach 175.81 gigawatts in 2025 and is projected to grow at a compound annual growth rate (CAGR) of 5.82% to reach 233.28 gigawatts by 2030<sup>2</sup>.

It is however complex with multiple different feed stocks, processes and products as summarised in Figure 1.

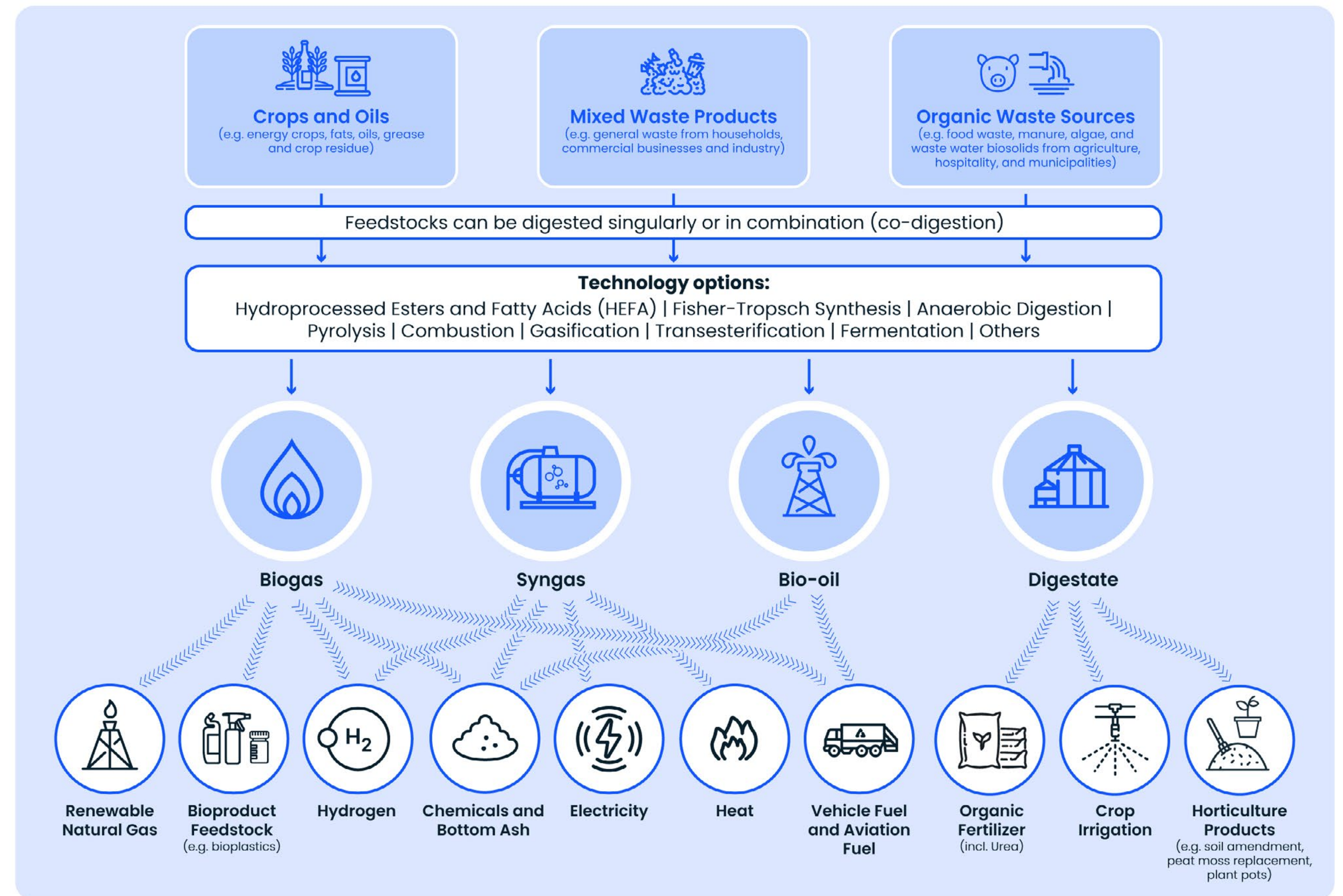


Figure 1: General bio-energy generation pathways

<sup>1</sup> <https://openknowledge.worldbank.org/entities/publication/d3f9d45e-115f-559b-b14f-28552410e90a>

<sup>2</sup> <https://www.mordorintelligence.com/industry-reports/bioenergy-market>

# Feedstock Types and Their Implications

The classification of feedstocks for biofuel production has evolved over time, reflecting advancements in technology and growing concerns about sustainability and food security. Understanding these categories is crucial for assessing the implications of their use in biofuel production.

## First Generation Feedstocks

First-generation feedstocks primarily consist of food-grade oils and crops that are intended for human consumption. Common examples include:

- **Crops:** Corn, sugarcane, soybeans, and rapeseed are widely used for biofuel production. These crops can be processed into bioethanol or biodiesel.
- **Oils:** Vegetable oils, such as palm oil and soybean oil, are converted into biodiesel through transesterification.

## Implications:

- **Food Security Concerns:** The use of food crops for biofuel production raises significant ethical concerns regarding food availability and pricing. When food-grade crops are diverted to fuel production, it can lead to increased prices and scarcity of essential food items, particularly affecting vulnerable populations.
- **Deforestation Risks:** The expansion of agricultural land for biofuel crops can contribute to deforestation and habitat loss. For instance, the palm oil industry has been linked to extensive deforestation in Southeast Asia, leading to biodiversity loss and increased greenhouse gas emissions.
- **Sustainability Issues:** The environmental impact of first-generation feedstocks needs careful consideration of their sustainability. Practices such as monoculture farming can deplete soil health and increase reliance on chemical fertilisers and pesticides.



## Second Generation Feedstocks

Second-generation feedstocks encompass non-food biomass sources that do not compete directly with food supplies. This category includes:

- **Waste Vegetable Oils:** Used cooking oils from restaurants and food processing facilities can be repurposed for biodiesel production.
- **Inedible Animal Fats:** The animal fats from butcheries and residues from livestock processing plant.
- **Yellow Traps and Fatty Acids Distillates:** These are the collections from waste streams originated from household and industrial food processing facilities.
- **Solid Waste:** Waste collected from households and commercial industry can be converted into biofuels using advanced technologies like anaerobic digestion or gasification.

### Implications:

- **Sustainability Benefits:** The use of 2G feedstock is typically more sustainable than 1G, as they achieve a higher reduction in greenhouse gas emission abatement, without requiring additional land usage.
- **Lower Competition with Food Supply:** Since these feedstocks do not compete directly with food crops, they mitigate concerns related to food security.
- **Economic Opportunities:** The utilisation of agricultural residues can provide additional income streams for farmers while promoting circular economy practices within agricultural systems.
- **Environmental Benefits:** Utilising solid waste for biofuel production helps address waste management challenges while reducing landfill contributions and associated greenhouse gas emissions.

## Third Generation Feedstocks

Third-generation feedstocks represent an emerging category that includes innovative sources such as:

- **Algae:** Microalgae and macroalgae can be cultivated to produce biofuels through processes like lipid extraction or fermentation.
- **Other Organic Materials:** This category also encompasses industrial by-products and other abundant organic materials that can be converted into biofuels.

### Implications:

- **High Potential for Resource Efficiency:** Algae have a high growth rate and can produce significant amounts of oil per hectare compared to traditional crops. Additionally, they can use wastewater or carbon dioxide emissions from industrial processes, enhancing resource efficiency.
- **Advanced Conversion Technologies Required:** While the potential for third-generation feedstocks is vast, they often need sophisticated conversion processes that are still under development. Research is needed to optimise these technologies for commercial viability.

Figure 2 shows the categories of the feedstock from a typical Crude Palm oil production facility – more than one category can be produced by a single facility.

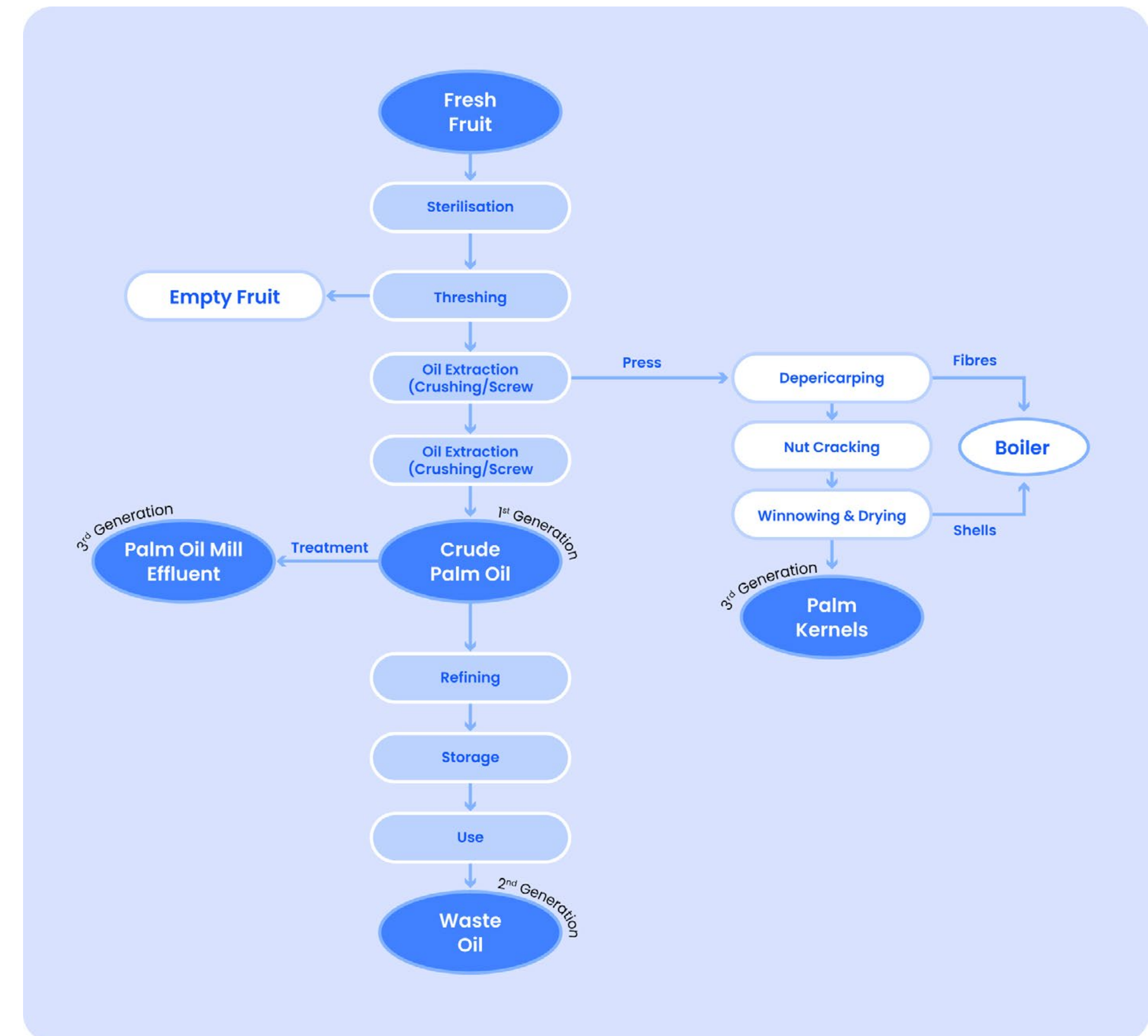


Figure 2: Feedstocks for biofuels production

# Technology Pathways for Biofuel Production

Various technological pathways exist for converting biomass into renewable fuels, each with its unique processes, advantages, and challenges with implications for biofuel production.

## Hydroprocessed Esters and Fatty Acids (HEFA)

HEFA technology involves the hydrogenation of fats and oils to produce biodiesel and sustainable aviation fuel (SAF). This method is currently the most commercially viable due to its relatively low capital costs and established infrastructure.

- **Process Overview:** The HEFA process begins with the collection of feedstocks, which can include waste cooking oils, animal fats, or virgin vegetable oils. These feedstocks undergo a hydrogenation process where hydrogen gas is added under high pressure and temperature, converting triglycerides into fatty acid methyl esters (FAME) suitable for use as biodiesel or SAF.
- **Advantages:** HEFA technology can use a wide range of feedstocks, including those that are waste-derived, thus promoting sustainability. Additionally, it produces high-quality fuels that meet stringent aviation fuel specifications.
- **Challenges:** While HEFA is commercially viable, scaling up production to meet global demand requires significant investments in processing facilities and infrastructure. Furthermore, competition for feedstock with food production can pose ethical concerns.

## Gasification and Fischer-Tropsch Synthesis

PtL technology uses renewable electricity to produce hydrogen through electrolysis, which is then used in a Fischer-Tropsch reactor. This pathway converts biomass into syngas—a mixture of hydrogen and carbon monoxide—which can then be transformed into liquid hydrocarbons through Fischer-Tropsch synthesis.

- **Process Overview:** Biomass is subjected to high temperatures in a low-oxygen environment during gasification, producing syngas. The syngas is then processed in a Fischer-Tropsch reactor where catalysts convert it into liquid hydrocarbons suitable for use as fuels or chemical feedstocks.
- **Advantages:** This method allows for the production of high-quality fuels from diverse feedstocks, including agricultural residues and municipal solid waste. It also enables the integration of carbon capture technologies to reduce greenhouse gas emissions.
- **Challenges:** The complexity of the gasification process requires advanced technology and significant capital investment. Additionally, optimising the Fischer-Tropsch synthesis process for different feedstocks is still an area of ongoing research.

## Alcohol-to-Jet Fuel (AtJ)

AtJ technology involves fermenting biomass to produce alcohols that can be further processed into jet fuel through dehydration, oligomerisation, and hydrogenation.

- **Process Overview:** Lignocellulosic biomass is pretreated to break down complex sugars into fermentable sugars. Microorganisms then ferment these sugars into alcohols (typically ethanol or butanol). The alcohols undergo further chemical transformations to produce jet fuel.
- **Advantages:** AtJ offers a practical way to produce jet fuel from lignocellulosic biomass without competing with food crops. It also offers the potential for utilising existing fermentation infrastructure in the bioethanol industry.
- **Challenges:** The need for effective catalysts in the conversion steps can complicate the process. Additionally, optimising fermentation conditions and improving yields from lignocellulosic sources are still key research areas.

## Power-to-Liquid (PtL)

PtL technology uses renewable electricity to produce hydrogen through electrolysis, which is then combined with captured CO<sub>2</sub> to create liquid fuels via Fischer-Tropsch synthesis.

- **Process Overview:** Renewable energy sources (like wind or solar) generate electricity used for electrolysis to split water into hydrogen and oxygen. The hydrogen is then reacted with captured CO<sub>2</sub> in a Fischer-Tropsch reactor to produce synthetic hydrocarbons.
- **Advantages:** PtL is a promising solution for integrating renewable energy into fuel production while providing a method for carbon capture and utilisation. It can help decarbonise sectors that are difficult to electrify directly.
- **Challenges:** The high costs associated with electrolysis and carbon capture technologies present economic hurdles. Additionally, scaling this technology requires substantial investment in infrastructure and energy supply chains.



## Pyrolysis and Hydrothermal Liquefaction

These thermochemical processes convert biomass into bio-oil or biocrude at high temperatures in the absence of oxygen.

- **Process Overview:** In pyrolysis, biomass is rapidly heated in an oxygen-free environment, resulting in bio-oil, char, and syngas as by-products. Hydrothermal liquefaction uses high pressure and temperature conditions using water as a solvent to convert wet biomass directly into biocrude oil.
- **Advantages:** Both processes allow for the conversion of a wide range of feedstocks, including wet materials like algae or food waste. The resulting bio-oil can be further refined using conventional refinery techniques to produce drop-in fuels compatible with existing infrastructure.
- **Challenges:** The consistency and quality of bio-oil can vary significantly based on feedstock composition and processing conditions. Additionally, further refining processes may be needed to meet fuel specifications.

## Anaerobic Digestion

Anaerobic digestion is a biological process that breaks down organic matter in the absence of oxygen to produce biogas—primarily methane—and digestate.

- **Process Overview:** Organic materials such as food waste, agricultural residues, or manure are placed in anaerobic digesters where microorganisms decompose the material over time. The produced biogas can be used directly for heating or electricity generation or upgraded to biomethane for use as vehicle fuel or injection into natural gas grids.
- **Advantages:** Anaerobic digestion effectively manages organic waste while producing renewable energy. It also results in nutrient-rich digestate that can be used as fertiliser, promoting circular economy practices in agriculture, especially as it can replace artificial fertilisers and promote soil health.
- **Challenges:** The efficiency of anaerobic digestion depends on factors such as feedstock composition and digester design. Ensuring consistent feedstock supply and managing operational costs are essential for successful implementation.

# Current Projects and Case Studies

Having explored the various feedstocks and pathways to produce bioenergy below are two examples of significant projects currently under execution which serves to illustrate the practical application of these technologies:

Firstly, a biofuel project utilising HEFA technology aims to produce SAF from waste streams derived from palm oil processing facilities and used cooking oils collected in various sources such as food processing plants, eateries, canteen, etc.

The side products from the process such as bio-naphtha, LPG, etc (shown in Figure 3) could be used as clean feedstocks to ethylene crackers to make basic chemicals without further treatment to remove noxious substances and improve the performance of the crackers in major petrochemical complex, or to offset its own energy consumption in the processing plant.

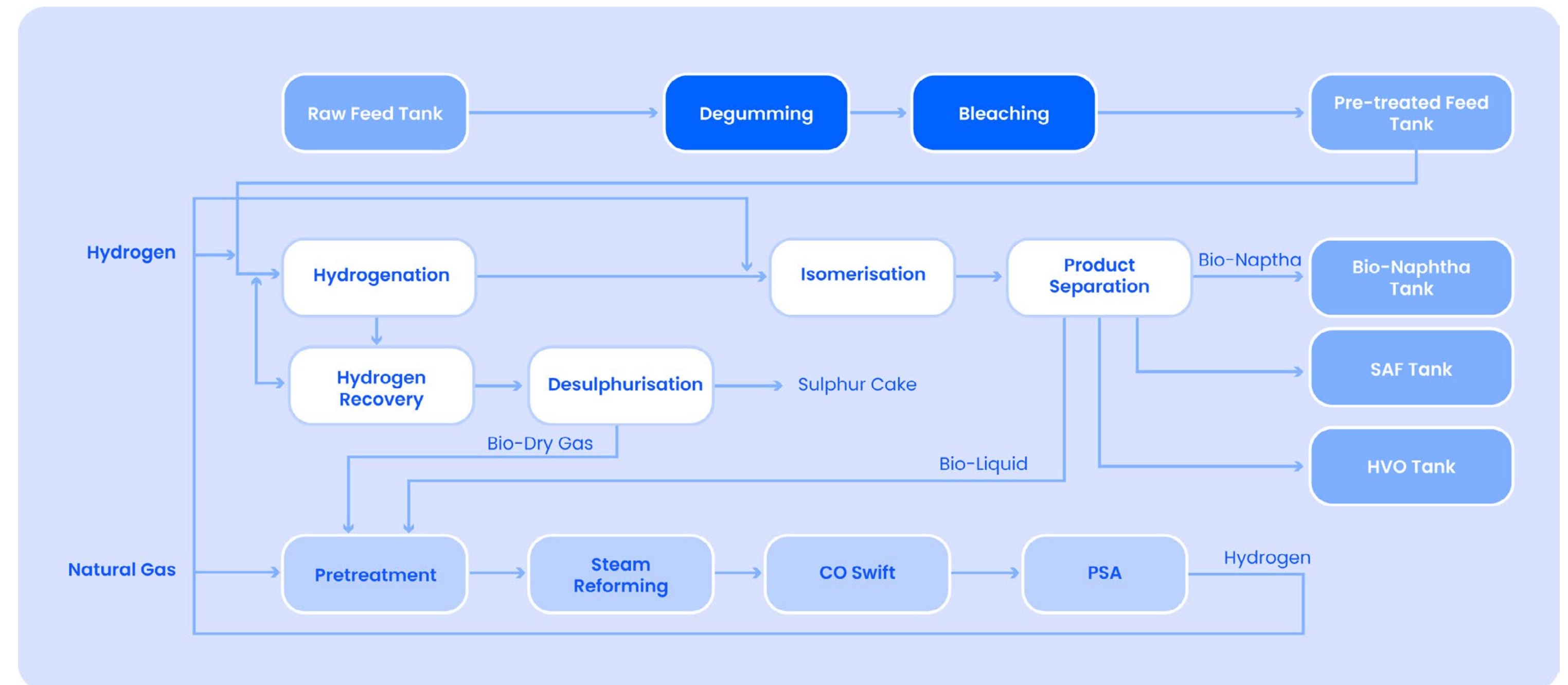


Figure 3: SAF production block flow diagram based on HEFA technology



Secondly, a large-scale biomass thermal power plant is being developed to generate 120 megawatts of electricity using palm kernel shell (PKS) and or wood pellets as feedstock, showcasing a direct replacement for coal-fired power generation. This facility will use approximately eighty tons per hour of PKS, demonstrating an effective method for converting agricultural waste into energy.

With advanced technology adopted in Circulating Fluidised Bed (CFB) Boiler (shown in Figure 4) for the biomass combustion, the thermal efficiency is enhanced to harvest the maximum bioenergy from the biomass. A second phase is also planned with similar capacity to have a seamless integration to the power plant.

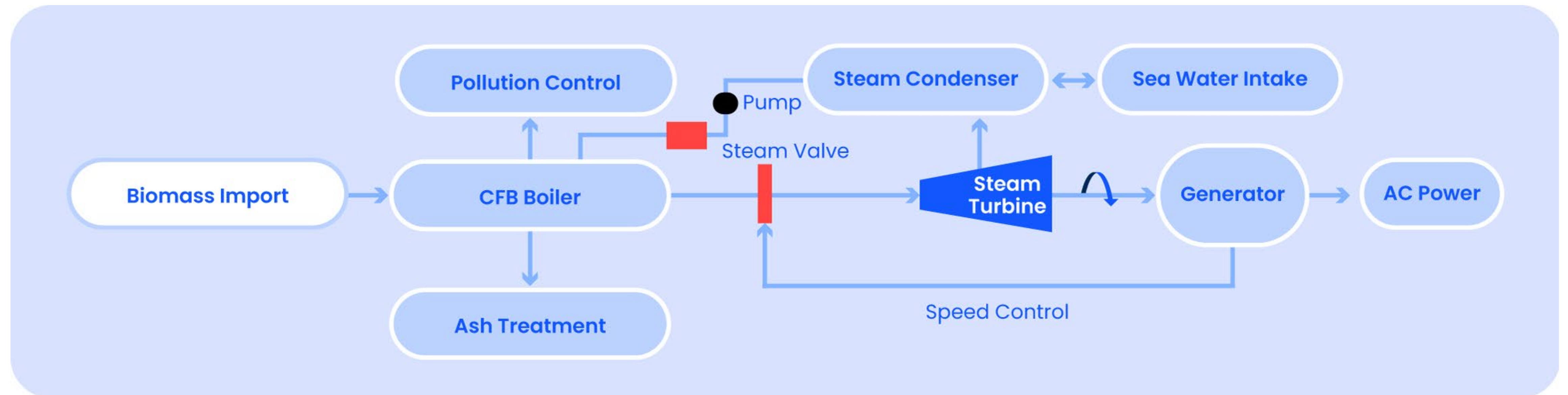


Figure 4: Biomass thermal power plant flow scheme

# Challenges in Scaling Biofuel Production

Despite the promising potential of biofuels, several significant challenges hinder their widespread adoption:

## Feedstock Availability

Ensuring a consistent supply of sustainable feedstocks is one of the most pressing challenges in scaling biofuel production. The competition between food crops and biofuel feedstocks must be carefully managed to avoid compromising food security.

- **Impact on Food Prices:** The diversion of food-grade crops such as corn and sugarcane for biofuel production can lead to increased food prices, affecting low-income populations who are most vulnerable to fluctuations in food costs. For instance, the rise in ethanol production in the United States has been linked to higher corn prices, which can have a cascading effect on global food markets.
- **Sustainable Sourcing:** There is a growing need for sustainable biomass sources that do not compete with food production. Second-generation feedstocks, such as agricultural residues, solid waste, waste vegetable oils, and non-food crops (e.g., switchgrass or miscanthus), present viable alternatives and have a positive environmental impact as well as often being legislated through strategic waste reduction targets. However, even though these sources are potentially 'never-ending' they often require additional infrastructure for collection and processing, which can be costly and logistically challenging.
- **Regional Disparities:** Different regions may have varying access to suitable feedstocks based on local agricultural practices and climate conditions. For example, Southeast Asia has abundant palm oil waste that can be used for biofuels, but other regions may lack similar resources. This disparity necessitates tailored approaches to feedstock sourcing based on regional capabilities.

## Economic Viability

The economic viability of biofuels is another critical barrier to their widespread adoption. The "green premium" associated with biofuels—higher costs compared to fossil fuels—needs to be addressed through technological advancements and supportive policies.

- **Production Costs:** Biofuel production often involves higher upfront capital costs for technology and infrastructure compared to traditional fossil fuels. For example, advanced biofuel technologies like gasification or enzymatic hydrolysis require significant investment in research and development before they can be commercialised effectively.
- **Market Volatility:** The fluctuating prices of fossil fuels can impact the competitiveness of biofuels. When oil prices are low, biofuels may struggle to compete economically, leading to reduced investment in the sector. Conversely, when oil prices rise, there may be renewed interest in biofuels as an alternative energy source.
- **Policy Support:** The lack of consistent government policies and incentives for biofuel production can create uncertainty for investors. Countries that have implemented supportive policies—such as blending mandates or tax credits—have seen more robust growth in their biofuel sectors compared to those without such frameworks.



## Technological Complexity

Many emerging technologies for biofuel production are still in early development stages, requiring substantial investment in research and development before they can be commercialised effectively.

- **Research Gaps:** There are significant gaps in knowledge regarding the optimal conversion processes for various feedstocks. For instance, while technologies like pyrolysis and anaerobic digestion show promise, further research is needed to improve their efficiency and scalability.
- **Infrastructure Requirements:** The infrastructure needed for biofuel production—including processing facilities, transportation networks, and distribution systems—can be complex and costly to develop. This is particularly challenging in regions where existing infrastructure is limited or outdated.
- **Integration with Existing Systems:** Integrating new biofuel technologies into existing energy systems poses added challenges. For example, transitioning from fossil fuels to biofuels in transportation may require modifications to engines or fuel distribution systems that are currently optimised for petroleum-based fuels.

Figure 5 shows a glimpse of the more advanced technology producing biofuels from biogenic materials, which consists of feedstock treatment, intermediate processes, and final refining/polishing process to produce the on-spec products—drop-in fuels.

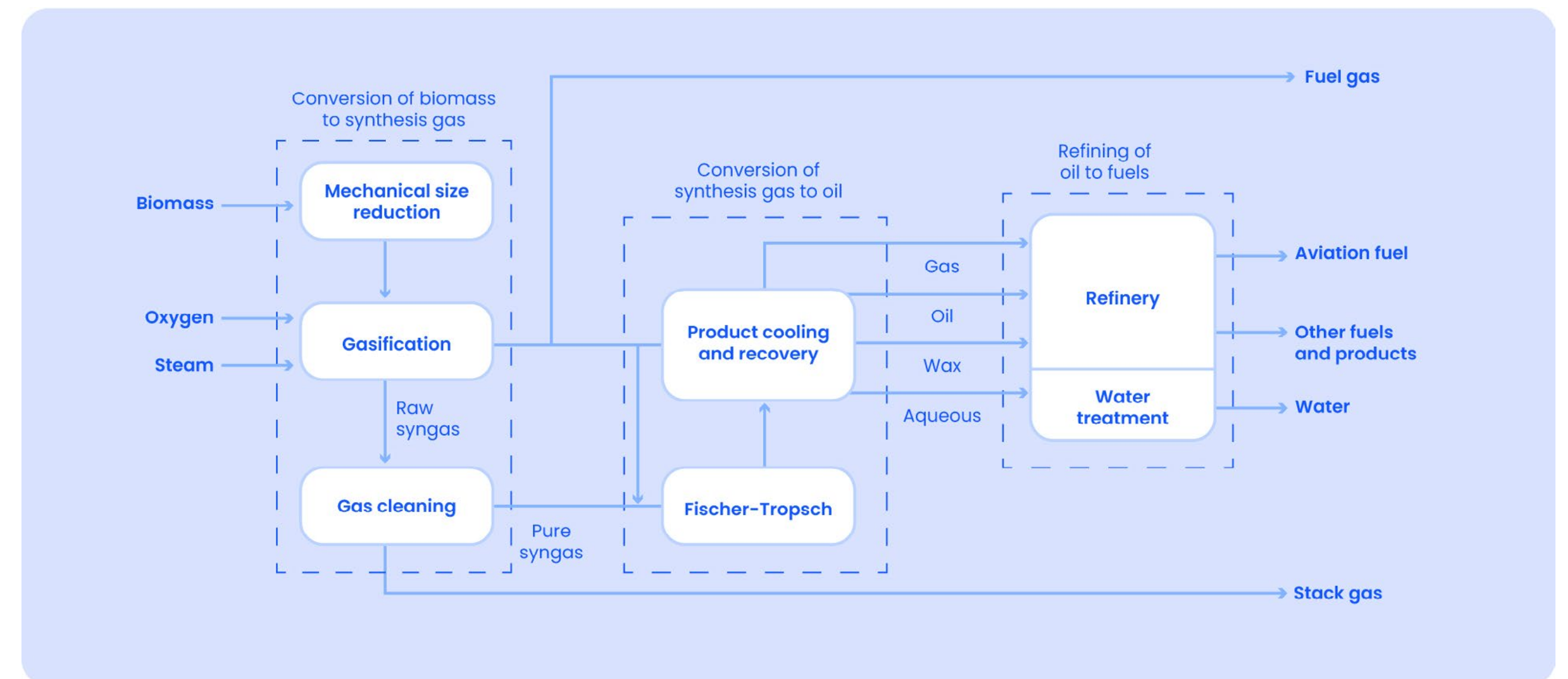


Figure 5: Biofuels production technology

# Solutions and Future Directions

To effectively address the challenges hindering the widespread adoption of biofuels, a multifaceted approach is essential. Specific strategies can be implemented to enhance the viability and scalability of bioenergy solutions.

## Policy Support

### Incentives for Sustainable Practices

Governments should establish clear and supportive policies that incentivise sustainable biomass sourcing and enable reliable end markets. This can include tax breaks, grants, and subsidies for companies that use waste materials or non-food crops as feedstocks. For example, countries like Indonesia and Malaysia have started programs to promote the use of palm oil waste in biofuel production, which not only supports local economies but also reduces environmental impact.

### Regulatory Frameworks

Creating robust regulatory frameworks that ensure environmental sustainability is crucial. Policies should mandate sustainability certifications for biofuel production processes, ensuring that they do not contribute to deforestation or land-use changes. The European Union's Renewable Energy Directive (RED II) provides a model by setting strict sustainability criteria for biofuels used within its member states.

## Market Development

### Expanding Biofuel Markets

To stimulate demand for biofuels, governments can implement mandates requiring a certain percentage of biofuels in transportation fuels. This has been successfully adopted in countries like Brazil, where the government mandates the blending of ethanol with gasoline. Additionally, developing markets for advanced biofuels in aviation and maritime sectors can create new opportunities for growth.

### Carbon Pricing Mechanisms

Implementing carbon pricing can make fossil fuels less economically attractive compared to biofuels. By placing a price on carbon emissions, governments can encourage industries to transition to cleaner alternatives. For instance, Singapore has introduced a carbon tax aimed at reducing greenhouse gas emissions, which could incentivise the adoption of biofuels in various sectors.



## Research Collaboration

### Public-Private Partnerships

Encouraging collaboration between public institutions and private companies can accelerate innovation in biofuel technologies. Joint research initiatives can focus on optimising production processes and developing new conversion technologies. For example, partnerships between universities and industry leaders in Southeast Asia could lead to breakthroughs in algae-based biofuels or advanced fermentation processes.

### International Research Networks

Establishing international research networks can facilitate knowledge sharing and technology transfer among countries. Collaborative projects focused on regional feedstock availability and processing techniques can help tailor solutions to local contexts. Initiatives like the Global Bioenergy Partnership (GBEP) promote international cooperation in bioenergy research and development.

## Technological Advancements

### Investment in R&D

Increased investment in research and development is crucial for advancing biofuel technologies. Governments and private investors should prioritise funding for innovative projects that explore new feedstocks, such as agricultural residues or municipal solid waste, and improve conversion efficiencies through advanced processes like gasification or enzymatic hydrolysis.

### Pilot Projects and Demonstration Facilities

Developing pilot projects can offer valuable insights into the feasibility of innovative technologies at scale. Demonstration facilities allow stakeholders to assess economic viability, operational challenges, and environmental impacts before full-scale implementation. These facilities are often a good addition in circular economy precincts, where feedstocks are consolidated from commercial and municipal sources and industrial symbioses can be leveraged, such as the Bio Hub in Bundaberg, Australia and others. Countries like Thailand have started pilot projects focusing on converting agricultural waste into biofuels, providing a blueprint for future developments.

## Capacity Building

### Training Programs

Investing in training programs for local communities and industry professionals is vital for building capacity in bioenergy sectors. Educational initiatives can equip individuals with the necessary skills to operate advanced biofuel production facilities and manage sustainable biomass sourcing practices.

### Community Engagement

Engaging local communities in bioenergy projects fosters ownership and ensures that initiatives align with community needs. Participatory approaches can help identify suitable feedstocks available locally while promoting sustainable practices among farmers and local businesses.

## Economic Incentives

### Financial Instruments

Exploring innovative financial instruments such as green bonds or impact investments can attract capital toward bioenergy projects. These instruments align investor interests with sustainability goals while providing necessary funding for research, development, and commercialisation of biofuels.

### Reducing Production Costs

Efforts should be made to reduce production costs associated with biofuels through technological advancements and economies of scale. Encouraging larger-scale operations or cooperative models among small producers can enhance efficiency while lowering costs.



# Conclusion

The conversion of waste into renewable fuels presents a transformative opportunity in the global shift toward sustainable energy systems. By integrating advanced technologies and adopting sustainable practices, bioenergy offers a viable solution to reduce dependence on fossil fuels while addressing critical environmental challenges such as waste management and greenhouse gas emissions.

To fully realise the potential of biofuels as a key component of a renewable energy future, ongoing investment in innovative research, supportive policy frameworks, financial support, and robust market infrastructure will be indispensable. These efforts will drive technological advancements, improve economic feasibility, and foster widespread adoption of biofuels as a cornerstone of sustainable energy transitions.



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