Waste biorefinery technologies for accelerating sustainable energy processes

D2.4 Technical Report - Strengths and weaknesses of different technologies, as per stakeholders' vision

CA 20127

Waste biorefinery technologies for accelerating sustainable energy processes (WIRE)
WG 2 | Biorefinery Technologies

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Thank you for your commitment to excellence and for advancing the shared goals of the WIRE COST Action.

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EXECUTIVE SUMMARY

This report presents a stakeholder-driven comparative assessment of **biochemical**, **thermochemical**, and **physicochemical** conversion technologies for biomass waste valorisation in integrated biorefineries. The objective is to identify the **strengths, weaknesses, opportunities, and threats (SWOT)** of each pathway, supporting strategic decision-making for technology deployment in alignment with EU sustainability targets.

The analysis is based on input from two primary stakeholder groups:

1. **Research and Technology Organizations (RTOs)** – providing insights on innovation potential, pilot-scale performance, and scientific trends.
2. **Industrial technology providers** – contributing market-oriented perspectives on scalability, operational efficiency, and investment feasibility.

Stakeholder perspectives were collected through **structured questionnaires** and complemented by a **targeted review of EU-funded project deliverables and relevant scientific literature.**

Key findings include:

1. **Biochemical technologies** are recognized for high product specificity and lower operating temperatures but face constraints in feedstock flexibility and process speed.
2. **Thermochemical technologies** offer broader feedstock compatibility and high conversion efficiency but often require significant CAPEX and complex gas cleaning systems.
3. **Physicochemical technologies** bridge certain gaps, enabling intermediate product streams and integration with both biochemical and thermochemical routes, yet remain less mature in large-scale deployment.

The SWOT analysis highlights:

1. **Strengths** – proven conversion efficiencies, synergies with existing infrastructure, and compatibility with diverse biomass waste streams.
2. **Weaknesses** – limited TRL for certain processes, high investment needs, and feedstock pre-treatment requirements.
3. **Opportunities** – growing EU policy support, emerging bio-based markets, and cross-sectoral technology integration potential.
4. **Threats** – regulatory uncertainty, market volatility, and competition from fossil-based alternatives.

The outcomes of this report underpin the TOWS and GAP analyses and shape the strategic roadmap in Deliverable D2.5, ensuring that future investments, policy measures, and deployment strategies are not only aligned with stakeholder consensus but also driven by practical, real-world feasibility.

Table 1 Summary of Methodologies used in preparation of D2.4 and D2.5 Report

Primary Report	Analysis and Role in the Report
D2.4 Technical Report	SWOT Analysis Presents strengths, weaknesses, opportunities, and threats for each technology based on stakeholder input
D2.5 Roadmap	TOWS and GAP Analysis Translates SWOT findings into strategic directions, action plans, and integration pathways

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1. INTRODUCTION

Author: Marta Trninić

1.1. Purpose and Scope

This deliverable presents a **comparative assessment** of three major biomass conversion pathways—**biochemical**, **thermochemical**, and **physicochemical**—based on insights gathered from key European stakeholders. The primary objective is to identify the **perceived strengths, weaknesses, opportunities, and threats (SWOT)** associated with each technology, with particular emphasis on their **technical maturity**, **scalability**, **sustainability**, and **alignment with EU policy objectives**.

1.2. Stakeholder-Centric Approach

The analysis reflects the collective vision of two principal stakeholder groups actively engaged in the development and deployment of biorefinery technologies across Europe:

1. Research **and Technology Organizations (RTOs)** – contributing scientific expertise, pilot-scale validation, and innovation foresight.
2. **Industrial actors and technology providers** – offering practical insights into market readiness, process optimization, and scale-up challenges.

Stakeholder input was obtained through:

1. **Structured questionnaires** designed to capture both quantitative and qualitative perspectives.
2. **Review of relevant EU-funded deliverables and relevant scientific literature** associated technical deliverables.

This targeted engagement ensures that the SWOT analysis integrates both **innovation potential** and **deployment realities**, capturing perspectives from those directly shaping the biorefinery landscape.

1.3. Methodology Overview

The SWOT analysis was conducted using a **mixed-method approach** combining:

1. **Quantitative data** from stakeholder surveys (n = XX), covering TRL, feedstock compatibility, CAPEX/OPEX, emissions profile, and product versatility.

2. **Qualitative insights** from expert questionnaires, addressing deployment barriers, innovation potential, and policy gaps.
3. **Cross-validation** through literature reviews, EU project deliverables, and strategic foresight studies.

Each conversion technology was assessed across five core dimensions:

1. **Technical performance** (efficiency, reliability, scalability).
2. **Environmental impact** (GHG emissions, residue management).
3. **Economic feasibility** (cost structure, market potential).
4. **Policy and regulatory alignment** (standards, incentives, compliance).
5. **Stakeholder perception** (acceptance, readiness, strategic fit).

2. OVERVIEW OF CONVERSION TECHNOLOGIES

Author: Marta Trninić

The detailed technical descriptions, classifications, and process flows of biochemical, thermochemical, and physicochemical conversion technologies have been comprehensively addressed in the preceding deliverable, **D2.3 – Key Enabling Technologies According to Feedstock Type**.

This, D2.4, deliverable builds on that foundation, shifting the focus from technical detail to a stakeholder-driven assessment through SWOT analysis. The aim is to understand how these technologies are perceived in terms of technical maturity, scalability, sustainability, and policy alignment — insights that will later inform the strategic roadmap in D2.5 Roadmap for technologies to be integrated into biorefineries.

The technologies addressed include:

1. Biochemical (e.g. anaerobic digestion, fermentation)
2. Thermochemical (e.g. pyrolysis, gasification, torrefaction)
3. Physicochemical (e.g. transesterification, esterification)

A concise summary of the key conversion technologies is provided below (Table 1) as a contextual reference for the stakeholder perspectives and comparative assessments presented in the following sections.

Table 1 Summary of Key Conversion Technologies

Type of technology	Technical condition	Key Products	Product Applications	TRLs
		Biochemical		
Anaerobic Digestion	Temperature: 30–40 °C (mesophilic) or 45–65 °C (thermophilic), pH 6.8–7.2, C/N 30:1, 85% moisture, 15-day retention	Biogas (CH_4, CO_2) Digestate (nutrient-rich residue)	Biogas: energy generation (heat, electricity, fuel) Digestate: fertilizer in agriculture and landscaping	7-9
Dark fermentation	Anaerobic Bacteria: ORP<-200 mV Temperature: 37 oC-55°C Pressure: Air pH:5.5-6.5 Residence time: 2-6 h Pretreatment Substrate: Lignosellulosic and algae	Hydrogen Organic Acids Ethanol Butanol Acetone	Biofuel Solvents Industrial Chemicals	5-6
Light fermentation	Anaerobic Photosynthetic Bacteria ORP<-300 mV Temperature: 37 °C Pressure: Air pH: 6.5-7.0 Residence time: 24 h-120 h Substrate: Organic acids and dark fermentation effluent NH_4 Limited media Light Requirement	Hydrogen	Biofuel	4-5
Composting	Optimal C/N ratio: 20:1–35:1 Humidity: 55–65% Requires oxygen, temperature control, and proper ventilation	Compost (humus-like soil amendment)	Soil fertility enhancement Landscaping Agriculture Carbon sequestration Waste diversion from landfills	7-9
		Thermochemical		
Torrefaction				

Type of technology	Technical condition	Key Products	Product Applications	TRLs
Dry torrefaction	Temperature: 200–300 ^{o}C Residence time: <1h Pressure: Air Atmosphere: İnert Liquid medium: None Pre-drying: Yes Post-drying: No Toxic: Minimal	Bio-char	Solid Biofuel Soil Amendment and Carbon Sequestration Catalyst Support and Adsorbent Feedstock for Activated Carbon or Graphene	9 (moving bed, fluidized bed and entrained flow rotary drum) 4-6 (screw or belt conveyor) 3-5 (MHF/Herreshoff oven) 1-3 (microwave)
Wet torrefaction	Temperature: 180–265 ^{o}C Residence time: 5 min to several h Pressure: 1-250 MPa Atmosphere: İnert Liquid medium: Water/steam Pre-drying: No Post-drying: Yes Toxic: Non-toxic	Hydro-char	Biofuel Soil Amendment and Carbon Sequestration Adsorbent and Environmental Remediation Precursor for Activated Carbon and Catalytic Supports Feedstock for Biochemical Conversion	
Pyrolysis				
Slow Pyrolysis	Feedstock size: 5-50 mm; Temperature: 300-700 °C; Residence time: minutes to hours; Heating rate: <1 °C/s; Pressure:1 bar.	Bio-char	Solid Biofuel Soil Amendment, Adsorption of Pollutants, Carbon Sequestration, As Catalysts, Additives in Construction Materials,	8-9
Intermediate Pyrolysis	Temperature: 300-600 °C Heating rate: 1-100 Residence time: 20-600	Bio-char	Solid Biofuel Soil Amendment	7
Fast Pyrolysis	Temperature: 500-1200oC Residence time: 10s Heating rate: very fast (10–100 °C/s) Pressure: vacuum – 1bar	Bio-oil	For producing bio-fuels (hydrogen, methane and other biomass-based fuels)	4-8

Type of technology	Technical condition	Key Products	Product Applications	TRLs
Flash Pyrolysis	Temperature: 400 °C to 650 °C Residence time: 2s Heating rate: very fast (1000 °C/s) Pressure: 1bar, even at vacuum or higher pressures	Bio-oil	For producing bio-fuels (hydrogen, methane and other biomass-based fuels) and bio-chemicals	3-5
Gasification				
Updraft Gasification	Feedstock size: 5–50 mm. Temperature:500–1200 ºC Residence time: 900–1800 s. Pressure: atmospheric pressure or slightly above it	Syngas	CHP	8–9
Downdraft Gasification	Feedstock size: 20- 100 mm. Temperature:500–1200 ºC Residence time: 900–1800 s. Pressure: atmospheric pressure to slightly pressurized (1 to 5 bar)	Syngas	For producing bio-fuels and CHP	8–9
Cross-Draft Gasification	Feedstock size: 5- 20 mm. Temperature: 800–1100 ºC Residence time: 0,5 – 5 s. Pressure: atmospheric pressure to slightly pressurized (1 to 3 bar)	Syngas	CHP	6–7
Plasma gasification	Any kind of waste (organic, inorganic) Temperature:1500–5500∘C	Syngas	Production of electricity, heat, H_2, NH_3, CH_3OH, or other liquid hydrocarbons	6–8
Supercritical Water Gasification (SCWG)	Operates above water’s critical point: >374 °C and >22.1 MPa Typical reaction temperature: 500–700 °C Suitable for wet biomass and sludge	Syngas	Hydrogen production	4–6
Bubbling Fluidized Bed Gasification	Feedstock size: 0.5–10 mm (typically 1–5 mm for uniform fluidization Temperature: 700-900 ºC Residence time: 5–30 seconds (longer due to bubbling regime) Pressure: Atmospheric to slightly elevated (1–5 bar)	Syngas	For Fischer-Tropsch synthesis for bio-fuels or gas engines for CHP and CCHP	7–8

Type of technology	Technical condition	Key Products	Product Applications	TRLs
Circulating Fluidized Bed Gasification	Feedstock size: <5 mm (finer particles preferred for circulation stability) Temperature: 800-1000 °C Residence time: 1–5 seconds (shorter due to high velocity and circulation) Pressure: Atmospheric to moderate (1–10 bar)	Syngas	For Fischer-Tropsch synthesis for bio-fuels or gas engines for CHP and CCHP	6–7
Dual Fluidized Bed Gasification	Feedstock size: up to 100 mm. Temperature: 800–1000∘C Residence time: sec to min Pressure:1 bar	Syngas	For producing bio-fuels and CHP	6–7
Combustion	Typically operates at moderate to high temperatures (800–1000 °C) with excess air.	Heat, flue gas (CO_2, H_2O, ash), steam (if coupled with boiler systems)	Residential and industrial heating, electricity generation (via steam turbines), district heating systems	9
		Physicochemical		
Transesterification	Requires acid or base catalyst Temperature 50–65 °C, typically 60 °C Usually at atmospheric pressure (1 atm); supercritical methods require >240 °C and >80 bar Feedstock flexibility (edible/non-edible oils, animal fats)	Biodiesel (FAME), Crude Glycerol (CG)	Biodiesel: transportation fuel CG: precursor for polymers (PU, PHA), solvents, cosmetics, pharmaceuticals	8–9

3. METHODOLOGICAL FRAMEWORK

Author: Marta Trninić

A SWOT analysis, which stands for Strengths, Weaknesses, Opportunities, and Threats, is a foundational strategic framework for evaluating the internal and external factors that influence the lifecycle of biorefinery technologies, from initial development to widespread market adoption (Mukamwi et al., 2023, Stark, 2015). This systematic approach facilitates the identification of:

- Strengths: Inherent advantages of a specific conversion pathway, such as its high technical maturity, high energy efficiency, or compatibility with existing infrastructure.
- Weaknesses: Intrinsic limitations or operational challenges, including feedstock sensitivity, high capital expenditures (CAPEX), or the absence of established industry standards.
- Opportunities: Favourable external conditions that can be strategically leveraged to accelerate technology adoption. Examples include supportive EU funding instruments, targeted policy incentives, and the emergence of new markets for bio-based products.
- Threats: External risks or barriers that could impede successful deployment. These may include regulatory uncertainty, intense competition from established fossil-based alternatives, or shifting market demands.

Internal and External Factors, the Core of SWOT

The power of a SWOT analysis lies in its clear distinction between internal and external factors, which is critical for effective strategic planning.

- Internal Factors (Strengths and Weaknesses) are elements that technology can directly control and influence. Strengths are assets to be leveraged, while weaknesses are limitations to be addressed or mitigated. For biorefinery technologies, this means focusing on improving a technology's efficiency or reducing its cost.
- External Factors (Opportunities and Threats) are conditions that exist outside of a technology's control. Opportunities are favorable market or policy conditions to be exploited, while threats are risks that must be prepared for. This distinction guides strategic action by helping stakeholders understand what they can change (internal) versus what they must adapt to (external) to achieve their goals.

SWOT Analysis are plotted on a simple 2x2 matrix. SWOT matrix with possible Questions for Biorefinery Technology Evaluation is presented in Table 2.

Table 2 SWOT Matrix

	Conversion Technology	
	Success factors	Failure Factors
Internal	Strengths **Internal capabilities that may help the technology reach its objectives.** These may include technical advantages, operational maturity, cost-effectiveness, compatibility with existing infrastructure, feedstock flexibility, low emissions, integration potential, policy alignment etc.	Weaknesses **Internal limitations that may interfere with the technology's ability to achieve its objectives.** These may involve feedstock sensitivity, , process control, emissions, technical or operational limitations, limited scalability, high CAPEX/OPEX, lack of standardization, certification, or regulatory compliance, etc.
External	Opportunities **External factors that the technology may exploit to its advantage.** These include favourable EU policies (e.g. RED III, Fit for 55), emerging markets for bio-based products, integration possibility with other systems (e.g. renewable energy, waste management), funding instruments, and strategic partnerships, etc.	Threats **Current and emerging external factors that may challenge the technology's performance.** These may involve regulatory uncertainty, competition from fossil-based alternatives, fluctuating market demand for bio-based products, feedstock supply risks, public perception etc.

4. SWOT ANALYSIS – RESULTS BY TECHNOLOGY PATHWAY

Author: Marta Trninić

This section presents the results of the SWOT analysis conducted for each prioritized biorefinery technology pathway. The analysis synthesizes stakeholder input, technical assessments, and policy alignment to identify key internal strengths and weaknesses, as well as external opportunities and threats. Insights from the SWOT analysis will serve as the foundation for the TOWS and GAP analyses, which will inform the strategic roadmap outlined in Deliverable D2.5.

Technology Pathways Assessed:

1. Biochemical (e.g. anaerobic digestion, fermentation)
2. Thermochemical (e.g. pyrolysis, gasification, torrefaction)
3. Physicochemical (e.g. transesterification, esterification)

4.1. Biochemical Conversion

Authors: İlgi Karapinar, Umar Muazu Yunusa

Biomass should not be regarded as waste but rather as a valuable raw material and renewable resource with significant potential for sustainable energy and material production. Viewing biomass as a resource encourages a circular economy approach, where materials that were once discarded are reintegrated into productive systems. This shift in perspective not only reduces environmental pollution and waste management costs but also supports energy independence and resource efficiency. Biofuels provide distinct advantages compared to other renewable energy sources, as their energy is derived from biomass — a dense and efficient form of stored solar energy. Biochemical conversion technologies help sustain the atmospheric CO_2 balance by reusing the CO_2 emitted during production to form new biomass, thus approaching carbon neutrality.

Gaseous biofuels—such as biohydrogen, biohythane, biomethane, and biogas—are primarily produced through biochemical conversion of organic materials under anaerobic conditions (Gopalakrishnan et al., 2019, Ruan et al., 2019, Ramos and Silva, 2020, Mozhiarasi et al., 2023). The liquid biofuels have certain advantages over the gas biofuels (Karapinar et al., 2025a). They can be easily transferred, stored, and used in engines directly or blended with gasoline. The major liquid biofuels that can be obtained through biochemical conversion technologies are bioethanol and biobutanol. Similar to gas biofuels, the production of liquid biofuels requires pretreatment.

The production of biofuels from lignocellulosic wastes through biological processes represents a promising pathway toward sustainable energy generation, circular economy practices, and waste valorisation. One of the major strengths of this approach is the abundance and low cost of feedstocks, which are often agricultural residues, forestry by-products, or industrial lignocellulosic wastes (Niju et al., 2020). Utilizing such materials not only reduces raw material costs but also helps mitigate waste management problems (Veza et al., 2021).

Despite these advantages, several weaknesses limit the large-scale implementation of lignocellulosic biofuel production. The complex and recalcitrant structure of lignocellulose requires an effective pretreatment step to break down the lignin–cellulose–hemicellulose matrix, which increases both capital and operating costs (Baksi et al., 2023, Karapinar et al., 2025b, Karapinar et al., 2025b,Abibu and Karapinar, 2023). Pretreatment may also generate inhibitory compounds that can hinder microbial activity during fermentation (Moreno et al., 2019, Abibu et al., 2024). The variability of waste feedstocks in terms of moisture content, C/N ratio, and chemical composition introduces challenges in process control and consistency (Abibu et al., 2024, Öztekin et al., 2008). Moreover, high enzyme costs, the need for specialized microorganisms, and expensive downstream processing steps make large-scale commercialization economically demanding (Sahay, 2022, Bhatt and Shilpa, 2014; Gunn and Rahman, 2017; Abdu Yusuf and Inambao, 2019).

There are, however, many opportunities associated with this field. Decentralized and modular biofuel production systems offer localized benefits, such as reduced transportation costs, rural job creation, and regional energy resilience. Continued advancements in pretreatment technologies, consolidated bioprocessing (Schuster and Chinn, 2013, Moreno et al., 2019; Beluhan et al., 2023), and microbial strain engineering are expected to increase yields and reduce costs in the near future. Furthermore, the growing demand for low-carbon and circular economy solutions strengthens the market potential and green branding of biofuel production by bioconversion technologies.

Nevertheless, several external threats must be considered. Rapid developments in competing low-carbon technologies—such as electrification, green hydrogen, or thermochemical conversion routes—may reduce market share for biological biofuels. Technical challenges during scale-up, including microbial instability or process inefficiencies, may further constrain commercialization. Additionally, investor hesitation due to perceived technological risk and the capital-intensive nature of biofuel plants remains a key barrier.

In conclusion, biofuel production from lignocellulosic wastes via biological processes offers substantial environmental and economic advantages through waste valorisation, emission reduction, and renewable energy generation. However, its long-term success depends on overcoming technical and economic barriers, optimizing pretreatment and fermentation efficiencies, and ensuring reliable feedstock supply. A regionally integrated, multi-product biorefinery model—combining biofuel generation with the valorisation of lignin and other by-products—represents the most promising strategy for maximizing both sustainability and profitability. With ongoing technological improvements and supportive policy frameworks, lignocellulosic biofuels have the potential to play a central role in the future low-carbon energy transition (Karapinar et al., 2025a).

This transition relies on a diverse set of biochemical processes that enable both the conversion and stabilization of organic waste streams. As these technologies continue to evolve and diversify, it becomes increasingly important to assess their practical viability and strategic relevance within sustainable energy systems. To support this, the following section offers a SWOT analysis—primarily focused on lignocellulosic biofuel production, while also acknowledging composting as a complementary biological process for organic waste stabilization and nutrient recovery within integrated biomass valorisation strategies.

4.1.1. Anaerobic Digestion

Author: Elanur Adar Yazar, Ester Scotto di Perta, Stefania Pindozzi

This part gives a structured SWOT analysis of anaerobic digestion (AD) for making methane energy and treating waste. Table 3 shows the SWOT Matrix for anaerobic digestion.

Table 3. SWOT Matrix for Anaerobic Digestion

ANAEROBIC DIGESTION PROCESS		
	Success Factors	**Failure Factors**
INTERNAL	**STRENGTHS** (S1) Proven technology (TRL 9) (S2) Significant GHG (CO2) reduction and renewable methane energy generation (S3) Flexible feedstock options (high moisture content etc.) (S4) 24/7 continuous biogas/energy production (S5) Easy integration with existing landfill infrastructure (S6) AD is a valuable pre-treatment for manure in case of nutrients reduction or valorization	**WEAKNESSES** (W1) High upfront investment and financing challenges (W2) Feedstock supply chain difficulties (W3) Digestate management and dewatering needs (W4) Gas cleaning and engine corrosion issues (W5) Limited economic feasibility for small-scale sites (W6) Sensitivity of the process to feedstock characteristics (C/N ratio, inhibitors, toxins, heavy metals) and environmental conditions. (W7) Long retention times

		(W8) The use of digestate as fertilizers depending on feedstock quality or typology
EXTERNAL	**OPPORTUNITIES** (O1) Circular economy and zero-waste policies (O2) Carbon credits and green energy certificates (O3) Bio-methane production as natural-gas equivalent (O4) Public–private partnerships with municipalities (O5) Growing demand for renewable energy (O6) AD provides diversification opportunities for farmers through energy self-sufficiency and new revenue chains (O7) Improvement of manure management in rural comunities (O8) AD can be integrated in multi-product biorefineries	**THREATS** (T1) Regulatory gaps and complex permitting (T2) Market fluctuations and competition from cheaper renewables (T3) Negative public perception and odour concerns (T4) Rising feedstock and investment costs (T5) Low acceptance among farmers without economic incentives for energy or biomethane production

AD is a biological process that breaks down organic waste in an environment without oxygen. This makes biogas (methane) and fertilizer that is high in nutrients to use as a soil conditioner (Elsayed et al., 2024). AD is a long-term answer to the problem of waste management. It is also important for current environmental and energy plans because it makes renewable energy that contains methane. The biogas produced has a calorific value of 21.5 MJ/m^3 and is composed of 38% carbon dioxide, 60% methane, and 2% other components on average (Adar et al., 2016). AD is a good example of the circular economy because it turns trash into useful resources (Alengebawy et al., 2024). Furthermore, this technology doesn't require pretreatment like drying or dewatering, especially for wet wastes like sewage sludge, or animal manure and it runs at lower operating temperatures and uses less energy (Adar et al., 2016)

One of the best things about AD is that it is a well-known, established, and mature technology (S1) (Elsayed et al., 2024; Piadeh et al., 2024). It can handle food waste, agricultural waste, animal manure, sewage sludge, and other organic waste (S2) (Rehman et al., 2019; Wang et al., 2025). This method also cuts down on greenhouse gas emissions by turning methane, a powerful greenhouse gas, into energy during treatment (S3) (Alengebawy et al., 2024; Piadeh et al., 2024). Biogas and energy are made all the time, unlike solar and wind power, which only work when the sun is shining or the wind is blowing (S4) (Piadeh et al., 2024). This helps keep the grid stable. It doesn't just get rid of trash; it also turns it into useful things like energy and fertilizer. This is an important part of the circular economy (Wang et al., 2025; Alengebawy et al., 2024). Conversely, in specific contexts such as manure management, anaerobic digestion may be considered a valuable preliminary stage, as the resulting digestate constitutes an appropriate substrate for subsequent processes aimed at nutrient abatement or recovery, such as ammonia air stripping (Scotto di Perta et al., 2023).

But this technology is not widely used because there are big problems that make it hard to do so. The biggest problem with it is that reactors, gas cleaning units, and other infrastructure all need a lot of money up front (W1) (Piadeh et al., 2024; Alengebawy et al., 2024). Setting up and running a feedstock supply chain that is both stable and sustainable is hard, especially because of the logistics of collecting feedstock and the fact that its composition changes with the seasons (W2) (Piadeh et al., 2024). Managing digestate, which is another product of the process, is hard and expensive because it has a lot of water in it, which means it needs to be treated, stored, and moved to farmland (W3) (Alengebawy et al., 2024). Cleaning biogas and getting rid of things like H_2S, which can corrode engines, add costs and makes things more difficult to run (W4) (Elsayed et al., 2024). Also, it is often not economically feasible for small-scale uses (W5) (Piadeh et al., 2024). Furthermore, it is challenging to maintain stable operation due to the process feedstock's high sensitivity to variables like its C/N ratio, inhibitors, toxins, heavy metals, and environmental conditions like temperature (W6). Furthermore, harmful substances like heavy metals cannot be removed from the system, necessitating further treatment, and the removal efficiency of pathogenic and resistant compounds is low (Adar et al., 2016). Simultaneously, large reactor volumes are needed for the process's long retention times (more than 14 days) (W7), which lowers efficiency and raises initial investment costs (W1) (Adar et al., 2016). Finally, anaerobic digestion can be fostered by the use of digestate as fertilizer, but in many countries, strict regulations about the typology of feedstock can reduce its applicability to the soil as in the case of cheese whey (W8) (Martin Sanz-Garrido et al., 2025) All of the generated products, however, need further treatment because full conversion is not possible (Adar et al., 2016).

However, external factors present significant opportunities for AD technology. Circular economy and zero-waste policies adopted by governments and international organizations constitute a powerful driving force for the adoption of AD technology (O1) (Piadeh et al., 2024; Alengebawy et al., 2024). Mechanisms such as carbon credits and green energy certificates can increase financial sustainability by creating additional revenue streams for AD facilities (O2) (Alengebawy et al., 2024). Biogas production is one of the greatest opportunities for AD. Purified biogas (biomethane) can be injected into existing natural gas infrastructure or used as a transportation fuel, reducing dependence on natural gas (O3) (Alengebawy et al., 2024). Public-private partnerships between municipalities, agricultural enterprises, and the private sector can help overcome financing and operational challenges (O4) (Piadeh et al., 2024). Another significant opportunity for the development of various reactor designs is the quickening pace of technological advancement (Adar et al., 2016). Growing global demand for renewable energy is making AD an increasingly attractive option (O5) (Alengebawy et al., 2024). Moreover, AD can provide diversification opportunities for farmers through energy self-sufficiency and new revenue chains in rural communities. Additionally, it can contribute to the enhancement of animal manure management, thereby facilitating manure stabilisation. (O6 and O7) (Scotto di Perta et al., 2019).

Nevertheless, threats to the technology should not be overlooked. Regulatory gaps, complex permitting processes, and lack of standards can slow project development (T1) (Alengebawy et al., 2024; Piadeh et al., 2024). Declining costs of other renewable energy sources (solar, wind) may challenge the economic competitiveness of AC (T2) (Piadeh et al., 2024). Negative public perception regarding odour emissions and site selection from facilities can hinder the social acceptance of projects and cause delays (T3) (Piadeh et al., 2024). Rising raw material, investment, and operating costs can threaten the financial sustainability of projects, particularly in regions where incentives are insufficient (T4). In such contexts, the diversion of feedstocks toward biogas production may generate competition between energy and food (or feed) uses, potentially imposing additional economic burdens on farmers. They are frequently compelled to choose between allocating valuable biomass to sustain livestock feed requirements or to supply anaerobic digesters, a decision that can significantly influence both farm management strategies and rural economic stability (T5) (Scotto di Perta et al., 2019). Unstable economic conditions and the requirement that AD facilities occupy a sizable space are also serious risks.

In conclusion, anaerobic digestion is a mature and versatile technology that stands out with its dual benefits of solving the waste management problem and producing clean energy. It has the potential to play a key role in achieving circular economy and sustainable development goals. Although it has significant weaknesses and threats, such as high investment costs, logistical challenges, and public perception, increasing policy support, technological innovations, and market opportunities make it possible to overcome these obstacles. But it's important to consider basic flaws like the requirement to purify the resultant by-products and the incapacity to attain high yields. Strategic policies, technological innovation, and public support are critical to overcoming its weaknesses and threats. When these are in place, it is clear that AD will realize its full potential for a sustainable future.

4.1.2. Fermentation

This section provides a structured SWOT analysis of biomass fermentation process for biofuels production.

4.1.2.1. Fermentation- Bioethanol

Authors: Bojana Bajić, Jaime Moreno García, Ana Momčilović, Vesna Vučurović

This section provides a structured SWOT analysis of biomass fermentation process for bioethanol production.

Table 4. SWOT Matrix for Fermentation process

Fermentation process		
	Success Factors	**Failure Factors**
INTERNAL	**STRENGTHS** (S1) Proven Processes: Fermentation is the most common route for producing bioethanol and provides the vast majority of global production, making it a well-established technique (Jain & Kumar 2024; Mizik 2021). (S2) Lower Processing Costs: First-generation bioethanol from food crops has lower processing costs compared to newer generations (Jain & Kumar 2024). (S3) Environmental Benefits: Bioethanol is biodegradable, less toxic than fossil fuels, and helps to reduce carbon dioxide emissions from internal combustion engines (Barua et al. 2023; Kazmi et al. 2025). (S4) Valuable Co-products: The fermentation process can yield valuable co-products, such as biogas, that enhance the overall economic feasibility of the process (Yaverino-Gutiérrez et al. 2024).	**WEAKNESSES** (W1) High Processing Costs for Advanced Generations: While first-generation production is cost-effective, the processing costs for second-generation bioethanol remain high, making it economically uncompetitive with gasoline (Jain & Kumar 2024). (W2) Sensitivity to Contamination: The fermentation process is sensitive to feedstock contamination and the presence of inhibitors, which can negatively impact efficiency (Afedzi et al. 2025; Yaverino-Gutiérrez et al. 2024). (W3) Immature Technologies: Third- and fourth-generation bioethanol production technologies are still in the lab (TRL 1-3) and pilot stages (TRL 4-6), requiring further research and development (Jain & Kumar 2024) (W4) High Enzyme Costs: Enzymes represent a significant operating expense, which is a major recurring cost barrier for large-scale production (Afedzi et al. 2025).
EXTERNAL	**OPPORTUNITIES** (O1) 2nd, 3rd and 4th generation bioethanol: Valorisation of agro-industrial waste, lignocellulosic biomass, and algae reduce food competition (Tse et al., 2021; Jain and Kumar 2024; Kazmi and Sultana, 2025) (O2) Circular bioeconomy: Integration into biorefineries with several products (proteins, biogas, organic acids, bio-based chemicals) (Hans et al, 2023; Lin and Tanaka, 2006) (O3) Technological developments. Advances in metabolic engineering, consolidated bioprocessing, and enzyme development can lower costs (Tao et al., 2012; Lugani et al., 2020; Dempfle at al. 2021; Adebami et al., 2022) (O4) Market development: increasing global demand for low-carbon fuels (Aggarwal et al, 2022) (O5) Market development: increasing global demand for low-carbon fuels (Aggarwal et al, 2022)	**THREATS** (T1) Renewables competition: Electric vehicles, hydrogen, and advanced synthetic fuels may reduce market share (Bonenkamp et al., 2020) (T2) Availability of feedstocks: Climate change, land degradation, or competition for residues could limit supply (Sajid et al., 2025; Goswami et al., 2025) (T3) Market Volatility: Fluctuations in oil prices can impact the competitiveness of bioethanol as a fuel alternative (Panoutsou et al., 2021) (T4) Regulatory Challenges: New regulations can introduce stringent criteria on emissions, production processes, and input sourcing (Bhardwaj et al., 2024) (T5) Public Perception and Opposition: Concerns over the environmental impacts of bioethanol production can hinder public acceptance and reduce consumer demand (Jain and Kumar, 2024) (T6) Technological Barriers: Scaling innovations for commercial application is challenging (Jain et al.,

	(O6) Policy and subsidies: EU Green Deal and other decarbonization strategies are in favor of bioethanol (Liobikienė and Miceikienė; 2023)	2024; Al-Hammadi et al., 2025; Kazmi and Sultana, 2025)

4.1.2.2. Fermentation – Biohydrogen by Dark Fermentation

Authors: İlgi Karapinar, Umar Muazu Yunusa

Biohydrogen production methods include fermentation process (dark fermentation and photofermentation), the biophotolysis process (direct biophotolysis and indirect biophotolysis), and the bioelectrochemical fuel cell (Karapinar et al. 2025d).

Dark fermentative biohydrogen production represents a renewable approach to hydrogen generation, relying on anaerobic microorganisms that metabolize carbon-rich substrates. During this process, organic acids such as acetate, butyrate, and propionate are formed as a side-product in the acidogenic (acid-producing) phase of the metabolic pathway (Rao and Basak, 2021a). The hydrogenase enzyme plays a central role in hydrogen generation, functioning in both strict anaerobes, Clostridium (Srivastava et al., 2017, Kapdan and Kargi, 2006) and facultative anaerobes (e.g., Enterobacter, Escherichia coli, Bacillus, and Klebsiella spp.) (Rao and Basak, 2021b). According to Jayachandran et al. (2022), dark fermentation demonstrates superior hydrogen production efficiency compared to other biological hydrogen production methods.

The major strength (Table 5) of the process lies in the ability to utilize a wide variety of inexpensive and renewable feedstocks such as agricultural residues, food waste, and wastewater sludge (Karapinar et al. 2025d). Operating under mild temperature and pressure conditions, dark fermentation requires less energy input compared with thermochemical or electrochemical hydrogen production routes (Kapdan & Kargi, 2006).

However, the process also presents several weaknesses (Table 5). Hydrogen yields are typically low because only part of the substrate carbon is converted into hydrogen, while the remainder forms volatile fatty acids and solvents (Nasr et al., 2020, Zheng et al., 2020, Li and Fang, 2007). The process is highly sensitive to environmental parameters such as pH, temperature, and substrate concentration, which must be tightly controlled to maintain stable microbial activity (Hallenbeck & Ghosh, 2009).

Significant opportunities (Table 5) exist for improving biohydrogen production through advances in biotechnology and system integration. Combining dark fermentation with photofermentation or microbial electrolysis can increase hydrogen yield and energy efficiency

(Argun et al., 2014). The use of genetically engineered microorganisms with enhanced hydrogenase activity or inhibitor tolerance is another promising research direction (Nasr et al., 2020, Venkata Mohan et al., 2014).

Nevertheless, the technology faces external threats (Table 5) from rapidly advancing competitors such as water electrolysis powered by renewable electricity, which is achieving higher efficiencies and decreasing costs (IRENA, 2022). The lack of large-scale demonstrations, hydrogen infrastructure, and consistent feedstock supply also limits industrial deployment.

In conclusion, dark fermentative biohydrogen production provides an environmentally friendly and potentially cost-effective route for hydrogen generation. Although challenges remain regarding yield and scalability, continued research, process optimization, and supportive policy mechanisms could enable dark fermentation to become a complementary pathway in the emerging global hydrogen economy.

Table 5. SWOT Matrix for Biohydrogen Production by Dark Fermentation

BIOHYDROGEN PRODUCTION BY DARK FERMENTATION		
	Success Factors	Failure Factors
INTERNAL	STRENGTHS (S1) Operates under mild temperature and pressure, reducing energy requirements. (S2) Compatible with existing waste management and anaerobic digestion infrastructures. (S3) More advanced scientific knowledge compared to direct photolysis and photofermentation. (S4) Potential for integration with methane and photofermentation. (S5) No toxic compound or contaminant generation. (S6) Environmentally friendly and carbon-neutral process with potential for zero-waste integration.	WEAKNESSES (W1) Low yields due to incomplete substrate conversion; production of volatile fatty acids as by-products. (W2) High sensitivity to environmental and operational conditions. (W3) Variability in the process performance. (W4) Impairments of fermentation performance by toxic by-products formed during pretreatment. (W5) Low hydrogen purity. (W6) High cost of downstream gas purification. (W7) Need for additional treatment of process effluent.

EXTERNAL	OPPORTUNITIES (O1) Enhancing total hydrogen yield by integrating with photofermentation or microbial electrolysis. (O2) Integration with methane production to increase the calorific value of the biofuel. (O3) Bioprocess development providing high rate and high yield of production. (O4) Genetic and metabolic engineering of robust microbial strains to improve hydrogen productivity. (O5) High cost of other physical and chemical methods. (06) Decentralized (on-site) units to meet sustainable local energy needs (O7) Increasing need to green hydrogen	TREATS (T1) Rapid technological progress and cost reduction in alternative hydrogen production (e.g., electrolysis with renewable electricity). (T2) Lack of large-scale demonstration projects and industrial-scale experience. (T3) Diversion of feedstock supply to full scale high rate hydrogen production processes could limits the commercialization of dark fermentative processes. (T4) Policy uncertainty and limited hydrogen infrastructure could delay commercialization. (T5) Low stakeholder awareness of biohydrogen limits adoption and investment.

4.1.2.3. Fermentation-Biohydrogen production by photofermentation

Author: İlgi Karapinar, Umar Muazu Yunusa

Photofermentation accomplished by photosynthetic bacteria such as Rhodobacter and Rhodopseudomonas species to convert organic acids into hydrogen using light energy (Deseure et al., 2021, Lilit et al., 2021, Deepika et al. 2026). The process operates under mild conditions and can utilize a wide range of organic substrates, including waste effluents and fermentation by-products (Chayanika et al., 2023). When coupled with dark fermentation, photofermentation can use the organic acids produced in the first stage, leading to improved overall hydrogen yield and more complete substrate utilization (Anish, et al.2015, Hallenbeck, 2005) (Table 6). Additionally, its reliance on solar energy as a driving force enhances environmental benefits and reduces external energy requirements in sunlight-rich regions (Basak & Das, 2007).

Despite these advantages, photofermentation faces several challenges that hinder large-scale application (Table 6). The process suffers from low light conversion efficiency and requires continuous illumination, limiting productivity (Bosman et al., 2023). Maintaining anaerobic conditions and ensuring uniform light distribution in large photobioreactors are technically complex and costly tasks (Androga et al, 2016, Androga et al., 2015) . Furthermore, the enzymes responsible for hydrogen production, such as nitrogenase and hydrogenase, are highly sensitive to oxygen, constraining operational stability (Gabrielyan et al., 2015, Hallenbeck & Ghosh, 2009). The high cost of reactor materials and overall process maintenance also makes industrial-scale deployment economically demanding (Keskin et al., 2011). Many studies reported photofermentative hydrogen production from synthetic media and real effluents (Özgür et al., 2010; García-Sánchez et al., 2018; Melitos et al., 2021; Akroum-Amrouche et al., 2023).

Recent advances in microbial genetics and photobioreactor design present significant potential for overcoming these barriers. Genetic engineering of photosynthetic bacteria can enhance hydrogen productivity, improve oxygen tolerance, and reduce competing metabolic pathways (Chayanika et al., 2023, Keskin et al., 2011). Progress in LED-based illumination and low-cost reactor materials may reduce capital costs and improve scalability. Integrating photofermentation with wastewater treatment could simultaneously address pollution and energy recovery, creating dual environmental benefits (Uyar et al., 2009). Increasing global emphasis on carbon-neutral technologies and hydrogen-based energy systems also provides a favorable context for further development (IEA, 2023).

Nonetheless, the commercial prospects of photofermentation depend on its competitiveness with other hydrogen production technologies. Electrolysis powered by renewable energy and photoelectrochemical systems currently offer higher efficiencies and faster scalability (Das & Veziroğlu, 2008). Additionally, factors such as sunlight variability, reactor space limitations, and policy uncertainties may hinder widespread adoption. To achieve practical implementation, future efforts should focus on system integration, process optimization, and demonstration at larger scales.

Table 6 SWOT Matrix for Biohydrogen Production by Photofermentation

BIOHYDROGEN PRODUCTION BY PHOTOFERMENTATION		
	Success Factors	Failure Factors

INTERNAL	STRENGTHS (S1) Use of wide range of organic acids and volatile fatty acids from dark fermentation or waste streams, enabling efficient use of diverse feedstocks. (S2) Two-stage integration with dark fermentation can boost hydrogen yield 50–60% and improve substrate use. (S3) Pollutant-free effluent generation (S4) Use of biomass for further valorization with pigment production	WEAKNESSES (W1) Low light conversion efficiency into hydrogen, limiting productivity. (W2) Sunlight variability, seasonal differences, and land or reactor space limitations restrict consistent hydrogen production. (W3) Challenges and expenses associated with sustaining anaerobic conditions. (W4) Difficulties in ensuring even light distribution in large photobioreactors. (W5) Complexity in fermentation media composition and control of inhibitors. (W6) Nitrogenase and hydrogenase enzymes are highly oxygen-sensitive, reducing process stability. (W7) Costs of photobioreactors, lighting, and operational maintenance pose significant economic challenges for scaling.
EXTERNAL	OPPORTUNITIES (O1) Boosting hydrogen yield, oxygen tolerance, and minimizing competing pathways by engineered photosynthetic bacteria. (O2) Developments in affordable photobioreactors, LED lighting, and automated controls to cut costs and enhance scalability. (O3) Use of solar energy to drive hydrogen production, reduce external energy input and enhance sustainability. (O4) Utilizing photofermentative biomass to produce industrial products, such as biofertilizers, animal feed, bioplastics, and high-value pigments.	TREATS (T1) Decline in process optimization efforts and interest. (T2) Lack of large-scale demonstration projects and industrial-scale experience. (T3) Competition with dark fermentative hydrogen and methane production. (T4) Limited adoption due to infrastructure or public perception issues.

4.1.2.4. Fermentation-Biobutanol

Author: İlgi Karapinar, Umar Muazu Yunusa

Biobutanol production from biomass is rather new and promising. It is the only biofuel that shares characteristics similar to gasoline, making it a suitable alternative as a fuel source. Its key benefits include low volatility, reduced corrosiveness, and the capability to power fuel-driven engines (Table 7). Additionally, biobutanol can be blended with either gasoline or diesel, offering the potential to reduce the automobile industry's dependence on traditional fuels (Pugazhendhi et al., 2019, Jin et al. ,2011, Karapinar et al, 2025a).

Acetone-butanol-ethanol (ABE) fermentation is the primary method for producing biobutanol. This biphasic fermentation process involves two stages: acidogenesis, where acids (acetic and butyric) are produced, and solventogenesis, where these acids are converted into solvents (acetone, butanol, and ethanol) by Clostridium species using fermentable sugars derived from biomass (Pugazhendhi et al., 2019, Rezahasani et al., 2025). During acidogenesis, a drop in pH triggers the shift to solventogenesis, producing solvents in a 3:6:1 ratio of acetone, butanol, and ethanol, respectively (Jin et al., 2022). Biobutanol is the primary target product; however, its accumulation damages the Clostridial cell membrane and wall, increasing membrane fluidity and ultimately causing cell death. Moreover, the presence of multiple fermentation products and the limited tolerance of Clostridial strains to solvent concentrations above 2% are major challenges that restrict butanol yield (Nabila et al.,2024, Nanda et al., 2017; Ibrahim et al., 2018). This low tolerance results in incomplete substrate utilization and reduced productivity. Additionally, product recovery and purification are energy-intensive because butanol has low volatility and forms azeotropes with water, making distillation costly (Xue et al., 2017). Another challenge is the competition among metabolic pathways during fermentation; microorganisms often produce a mixture of solvents (acetone, ethanol, and butanol) rather than butanol alone, complicating downstream separation. It is evident that simulatenous butanol production and the semapartion enhances the yield (Su et al., 2025, Zhu et al., 2025). The process remains constrained by biological, technical, and economic barriers (Table 7). Future research should focus on strain engineering for enhanced solvent tolerance, continuous fermentation systems to improve productivity, and integrated product recovery technologies such as gas stripping or pervaporation to reduce purification costs.

Table 7 SWOT Matrix of Biobutanol Production

BIOBUTANOL PRODUCTION		
	Success Factors	Failure Factors
INTERNAL	STRENGTHS (S1) High energy density close to gasoline (≈29 MJ/L). (S2) Compatible with existing fuel infrastructure and engines. (S3) Low volatility and corrosiveness improve safety and storage. (S4) Fermentation produces valuable co-products (acetone, ethanol) that enhance overall process economics.	WEAKNESSES (W1) Low fermentation yield due to product inhibition and metabolic limitations. (W2) High downstream separation and purification costs. (W3) Limited commercial-scale success compared to ethanol or biodiesel. (W4) Microbial sensitivity to solvent concentrations affects productivity. (W5) Complex fermentation and pretreatment processes increase operational challenges.
EXTERNAL	OPPORTUNITIES (O1) Integration with biorefineries enables co-production of acetone, hydrogen, or other chemicals (O2) Potential use in hybrid fuel blends (O3) Development of online product removal (in situ extraction) to mitigate inhibition and enhance productivity. (O4) Leveraging pretreatment-free fermentation technologies (O5) Policy support and subsidies (e.g., EU Green Deal) for sustainable fuels.	TREATS (T1) Strong competition from established biofuels (ethanol, biodiesel). (T2) Insufficient policy incentives or blending mandates for butanol. (T3) Limited infrastructure for biobutanol distribution and use, along with consumer adoption barriers. (T4) Low level of awareness and interest.

4.1.3. Composting

Author: Elanur Adar Yazar

This part shows a structured SWOT analysis of composting as a way to get rid of waste and make fertilizer. The SWOT Matrix for composting is shown in Table 8.

Table 8 SWOT Matrix for Composting

Composting process		
	Success Factors	**Failure Factors**
INTERNAL	STRENGTHS (S1) Effective organic waste management and soil improvement (S2) Low emissions and supports sustainable agriculture (S3) High technology readiness (TRL 8) (S4) Enhances biodiversity and circular economy	**WEAKNESSES** (W1) Temperature/moisture control and microorganism balance challenges (W2) Odour issues during operations (W3) Regulatory gaps and lack of compost quality standards (W4) Higher installation and operating costs for advanced systems
EXTERNAL	**OPPORTUNITIES** (O1) Government incentives and international collaborations (O2) Education and public awareness campaigns (O3) Circular economy and emission-reduction drivers (O4) Rising demand from organic and sustainable agriculture	**THREATS** (T1) Strong market power of chemical fertilizer producers (T2) Farmers' hesitation toward unsupervised compost products (T3) Competing waste-to-energy or fertilizer technologies (T4) Limited government subsidies and policy support

Composting is an easy, cheap, and effective way to deal with organic waste that adds carbon to the soil. Microorganisms break down organic waste into a useful bio-organic fertilizer that is similar to humus. This process improves and restores the soil (Chen et al., 2023).

Composting is gaining increasing importance as a sustainable, circular, and environmentally friendly solution for the management of organic solid waste. Among the most prominent strengths of composting are its ability to reduce waste volume by removing organic waste from landfills and its conversion of waste into a valuable product that improves soil structure, water retention capacity, and nutrient content (S1) (Amuah et al., 2022; Manea et al., 2024). Being an aerobic process, it significantly reduces methane (CH_4) emissions, a potent greenhouse gas produced by waste decomposition in landfills, and supports sustainable agriculture by reducing the need for synthetic fertilizers (S2) (Nordahl et al., 2023; Manea et al., 2024). Its high level of technological readiness, with various methods proven successful at an industrial scale (wind pile, closed system, etc.), demonstrates that it is a reliable solution ready for widespread adoption (S3) (Waqas et al., 2023). At the same time, it enhances biodiversity by increasing microbial activity in the soil and returns resources to the cycle through the principle of "turning waste into wealth," proving that it perfectly serves the circular economy model (S4) (Xu et al., 2023; Chen et al., 2023).

However, alongside these strengths, there are also some weaknesses that stand in the way of composting becoming more widespread. Being a biological process, the need for careful management of critical parameters such as temperature, moisture, oxygen, and carbon/nitrogen (C/N) ratio is one of the most sensitive aspects of the process; improper management can lead to poor-quality products and unwanted emissions (W1) (Amuah et al., 2022; Lin et al., 2022). Odour issues arising from the release of ammonia (NH_3) and other volatile organic compounds (VOCs), especially at the beginning of the process or in cases of inadequate aeration, are a significant obstacle that makes it difficult for facilities to gain public acceptance (W2) (Nordahl et al., 2023). Advanced closed-system (in-vessel) composting technologies that provide odour and emission control require high initial investment and operating costs (W3) (Xu et al., 2023). Finally, the variability in final product quality depending on the initial waste content (heavy metals, micro plastics) and the lack of clear compost quality standards in many countries create uncertainty for both producers and end users (W4) (Manea et al., 2024).

Despite these weaknesses, global and local trends present significant opportunities for the future of composting. Worldwide, government policies to divert organic waste from landfills in line with circular economy packages and emission reduction targets are creating financial incentives for the establishment of composting facilities (O1) (Chen et al., 2023). There is a lot of pressure around the world to move toward a circular economy and cut greenhouse gas emissions. Composting is becoming a popular strategic solution (O3). Innovations in technology, like AI-powered sorting systems, IoT-based sensors, and specialized microbial inoculants, could make the process faster and easier to manage (Xu et al., 2023; Yin et al., 2024). Increased environmental awareness encourages the public to be more willing to separate their waste (O2), while growing interest in organic farming and sustainable food production is creating a growing market for quality compost (O4) (Manea et al., 2024).

However, external threats that could hinder the growth of the composting sector should not be overlooked. The chemical fertilizer industry's decades-long market dominance and established distribution networks create significant competition for compost (T1). Concerns about heavy metal or micro plastic risks in compost and the lack of quality standards may cause farmers to hesitate to use the product (T2) (Manea et al., 2024). Competing technologies for managing organic waste, such as anaerobic digestion (biogas) or incineration (energy production), may appear more attractive to investors, particularly due to their energy production potential (T3). Finally, since composting facilities require long-term investments, economic and political instability, such as insufficient government support, fluctuating waste policies, or fluctuations in compost sales prices, may threaten the sustainability of these facilities (T4).

In conclusion, this SWOT analysis demonstrates that composting holds tremendous potential for organic waste management and the circular economy, but that operational, environmental, and economic challenges must be overcome to fully realize this potential. In this regard, it is strategically important for governments to promote compost use by leveraging circular economy goals, for R&D activities to focus on technological innovations such as odour control and process automation, and for awareness campaigns about the benefits of compost to be organized for farmers. The academic studies reviewed strongly demonstrate that when composting is properly managed, it is not merely a waste disposal method; it is also a strategic tool that protects soil health, recovers resources, and contributes to combating climate change. Investments and policies developed to overcome weaknesses and threats will maximize the potential of this tool.

4.1.4. Overall SWOT analysis of Biochemical conversion processes

Authors: İlgi Karapinar, Umar Muazu Yunusa

To better understand the strategic potential and limitations of biochemical conversion technologies, the following table summarizes key internal and external factors that influence their success or failure. This SWOT analysis highlights both technological strengths and challenges, as well as broader opportunities and threats in the evolving bioeconomy landscape.

Table 9 SWOT Analysis of Bioconversion Technologies (Success vs Failure Factors).

BIOCONVERSION TECHNOLOGIES		
	Success Factors	Failure Factors

INTERNAL	STRENGTHS (S1) High greenhouse-gas mitigation potential (S2) Flexibility of product slate as and liquid biofuels or platform intermediates for drop-in fuels/chemicals. (S3) Co-product opportunities such as digestate as fertilizer, lignin valorization (chemicals, heat), which improve economics and circularity (S4) Modular, scalable bioprocesses enable decentralized operation near feedstock sources, reducing transport costs. (S5) Advanced-level background and high TRL for methane and ethanol	WEAKNESSES (W1) Recalcitrance of lignocellulose raises CAPEX/OPEX and can create inhibitory compounds (W2) Process complexity and mixed-sugar fermentation limit efficiency, making theoretical yields hard to achieve. (W3) High capital costs from pretreatment, enzymes, and downstream product recovery increase investment needs.
EXTERNAL	OPPORTUNITIES (O1) Lignin and coproduct valorization boosts margins through high-value products or process heat. (O2) Advances in pretreatment, bioprocessing, novel fermentation technologies, and robust microbes can cut costs and boost yields. (O3) Decentralized plants near feedstock reduce logistics costs and create local jobs. (O4) Advancing lignocellulosic-based ethanol and methane production. (O5) Policy support and carbon incentives enhance project profitability.	TREATS Competes with other low-carbon options like electrification, green H_2, and thermochemical technologies. Feedstock risks can raise costs or reduce supply if diverted to other high-rate biofuel production Market and regulatory limits restrict fuel approval and blending options.

4.2. Thermochemical Conversion

Author: Marta Trninić

Thermochemical processes constitute a fundamental class of technologies within chemical engineering and energy systems, involving the transformation of materials through heat-driven chemical reactions. These processes—encompassing combustion, pyrolysis, gasification, and reforming—are widely applied in the conversion of biomass, fossil fuels, and waste into energy carriers and value-added products. Their relevance spans multiple disciplines, including sustainable energy research, environmental engineering, and materials science.

In the context of increasing global demand for low-carbon technologies and circular economy solutions, thermochemical processes offer both promising advantages and notable challenges. A systematic SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis provides a structured framework to critically evaluate the internal capabilities and limitations of these technologies, as well as the external factors influencing their development and deployment. This analysis aims to support academic inquiry, inform policy decisions, and guide future research directions in the field of thermochemical conversion.

4.2.1. Direct Combustion

Authors: Leonarda F. Liotta, Carla Calabrese, Laura Valentino

This section provides a structured SWOT analysis of biomass direct combustion. The scope includes small-scale stoves, industrial boilers, and CHP applications, with particular attention to efficiency, emissions, and deployment barriers. The aim is to inform the D2.5 roadmap by highlighting strengths, weaknesses, opportunities, and threats relevant to the European context.

Direct biomass combustion is the most established thermochemical conversion process, accounting for over 97% of global bioenergy production ((IEA). 2022). It remains a cornerstone of renewable energy in Europe, valued for its high technological maturity (TRL 8–9), flexibility in feedstocks, and potential for combined heat and power (CHP) production (European Commission, 2019). EU-funded projects such as BIOFFICIENCY have helped mitigate ash-related issues, improving efficiency and expanding fuel options (CORDIS, 2015). Promising opportunities also include the circular use of combustion ash (CORDIS, 2015), integration with bioenergy with carbon capture, utilization, and storage (BECCUS) (IEA Bioenergy, 2022c), and alignment with EU climate policies.

However, challenges remain, including emissions of particulate matter, nitrogen oxides, and carbon monoxide (World Health Organization (WHO), 2021), as well as sustainability risks associated with biomass supply (Intergovernmental Panel on Climate Change (IPCC), 2022). Looking ahead, stricter air quality directives, ongoing debates on sustainability, and competition from electrification and heat pumps pose significant threats to wider deployment (European Commission, 2016, European Commission, 2021). Overall, direct combustion is positioned as a short-term bridging technology, evolving toward cleaner and more sustainable systems that are essential for Europe's energy transition.

Overview of Conversion Technologies

Direct combustion is the oldest and most widely deployed method of converting biomass to energy. It contributes about 14% of global energy supply, rising to 35% in developing countries (International Energy Agency (IEA), 2021). Biomass feedstocks include woody fuels, agricultural residues, and herbaceous crops, each with distinct combustion characteristics (Demirbas, 2004, IEA Bioenergy, 2022a). Small-scale stoves and boilers, industrial boilers, and CHP systems dominate the technological spectrum, with efficiencies of up to 80% achievable in CHP [11]. Advanced options such as fluidized bed combustors provide high fuel flexibility, though issues of fouling, slagging, and corrosion persist. For detailed technical specifications, reference should be made to Deliverable D2.3.

4.2.1.1. Direct Combustion SWOT Analysis

The SWOT was developed through a systematic process. Evidence was gathered from three main sources: stakeholder consultations (ETIP Bioenergy, 2025), results from EU-funded R&I projects (e.g., BIOFFICIENCY), and technical assessments from IEA Bioenergy Task 32. These were complemented with a review of relevant EU legislation (RED III, MCPD, EPBD) and supporting scientific literature. All inputs were mapped onto the four SWOT categories. To ensure transparency, each factor was linked to a specific evidence source, allowing clear traceability from stakeholder input and project results to the final strategic assessment.

Direct combustion benefits from its maturity as a proven technology, with high technology readiness levels (TRL 8–9) across stoves, boilers, and CHP systems (CORDIS, 2015, ETIP Bioenergy, 2025). It can utilize a broad feedstock base, ranging from woody biomass to agricultural residues, and is already widely integrated into CHP applications where overall efficiencies can exceed 80% ((IEA). 2022, CORDIS, 2015). Advances in combustion design and flue-gas cleaning, supported by

IEA Bioenergy Task 32 and EU-funded projects, have significantly improved performance, and widened fuel flexibility (CORDIS, 2015, IEA Bioenergy, 2022b). Nevertheless, air quality challenges persist. Emissions of particulate matter, nitrogen oxides, and carbon monoxide remain a concern, particularly in urban and sensitive environments (IEA Bioenergy, 2022b, Comission, 2015). Furthermore, public scepticism about the climate neutrality of biomass, especially regarding forest harvesting, land use, and biodiversity impacts, continues to constrain acceptance (Material Economics, 2021). Opportunities are substantial. Circular resource use, such as ash valorisation into fertilizers or construction materials, supports the bio-circular economy (CORDIS, 2015). Integration with BECCUS offers potential for negative emissions and deeper climate alignment (International Energy Agency (IEA), 2022). In parallel, modernization funding streams and supportive EU policies (RED III, Fit for 55, REPowerEU) strengthen deployment prospects (European Commission, 2021, IEA Bioenergy, 2022b). At the same time, threats are emerging. Regulatory tightening on air quality and sustainability criteria could restrict combustion technologies (IEA Bioenergy, 2022b, Comission, 2015). Competition from other low-carbon energy options, particularly heat pumps and electrification, also risks reducing biomass' policy and market relevance (European Commission, 2021, Commission, 2023, Commission, 2022). Scaling BECCUS in economic and technical terms remains a further uncertainty (International Energy Agency (IEA), 2022).

Table 10 provides a structured summary of strengths, weaknesses, opportunities, and threats.

Table 10 SWOT Analysis of Direct Combustion of Biomass (Success vs Failure Factors)

DIRECT COMBUSTION		
	Success Factors	**Failure Factors**
INTERNAL	**STRENGTHS** (S1) Mature, commercially available technology (TRL 8–9). (S2) Proven efficiency improvements via EU R&D (CORDIS, 2015). (S3) Feedstock flexibility (woody biomass, agricultural residues, herbaceous crops). (S4) CHP systems exceeding 80% efficiency.	**WEAKNESSES** (W1) Air quality concerns (PM, NO_x, CO) (World Health Organization (WHO), 2021, IEA Bioenergy, 2022b, Comission, 2015). (W2) Public skepticism and NGO opposition on climate neutrality. (W3) Efficiency gap vs. fossil fuels (moisture, fouling). (W4) Risks from land use, forestry management, biodiversity impacts (IEA Bioenergy, 2022b).
EXTERNAL	**OPPORTUNITIES** (O1) Circular economy valorisation (ash reuse in fertilizers, construction materials). (O2) Integration with BECCUS for negative emissions [4,16]. (O3) EU policy drivers (RED III, Fit for 55, REPowerEU) . (O4) National/EU funding for modernization of combustion plants.	**THREATS** (T1) Stricter EU air quality and sustainability regulations (Material Economics, 2021). (T2) Competition from electrification (heat pumps, renewables). (T3) Technical and economic barriers to scaling BECCUS (Comission, 2015). (T4) Public perception and market uncertainty.

Biomass direct combustion will remain an essential contributor to Europe's renewable energy mix in the near term. Its role as a bridge technology lies in providing reliable heat and power while creating pathways for innovation, particularly in ash valorisation and BECCUS integration.

The SWOT analysis makes clear that the decisive factors for its future are not technological maturity—which is already proven—but rather the ability to:

1. Comply with tightening air quality and climate regulations through advanced combustion and monitoring systems.
2. Strengthen sustainability assurance and certification to maintain public trust in biomass sourcing.
3. Leverage EU policy frameworks and funding to modernize plants and integrate circular practices.

In this way, direct combustion can evolve from a conventional renewable option into a strategic enabler of climate-aligned bioenergy, supporting both energy security today and deep decarbonization tomorrow.

4.2.2. Gasification Technologies

Author: Marta Trninić

Gasification technologies are commonly classified according to reactor design and flow configuration, including moving bed (e.g., updraft, downdraft, cross-draft), fluidized bed (bubbling and circulating), and entrained flow systems. Each subtype offers distinct advantages depending on feedstock characteristics, operating parameters, and targeted end-use pathways such as heat, power generation, advanced biofuels, or chemical synthesis.

Gasification technologies represent a core pathway for converting waste biomass into valuable energy carriers such as syngas, biofuels, biochemicals, electricity and heat. These technologies are commonly classified based on reactor design and flow configuration, which directly influence their operational performance, feedstock compatibility, and integration potential.

The principal categories of gasification technologies include:

5. Moving Bed Gasifiers

These encompass updraft, downdraft, and cross-draft configurations. Operating with fixed biomass beds, they are typically suited for small to medium-scale applications. Their advantages include operational simplicity and low capital expenditure (CAPEX), though they are constrained by feedstock uniformity and tar formation challenges.

6. Fluidized Bed Gasifiers

Including bubbling fluidized bed (BFB) and circulating fluidized bed (CFB) systems, these reactors suspend biomass particles in a fluid-like medium, promoting excellent mixing and heat transfer. They offer scalability, feedstock flexibility, and are ideal for medium to large industrial applications.

7. Entrained Flow Gasifiers

These systems—available in dry feed and slurry feed variants—operate at high temperatures and velocities, enabling near-complete conversion and producing clean syngas suitable for biochemical synthesis. They require finely processed feedstock and are optimized for large-scale, continuous operations.

8. Plasma Gasification Technologies

Plasma gasifiers utilize high-temperature plasma arcs to decompose feedstock into its elemental components, achieving extremely high conversion efficiencies and producing ultra-clean syngas with minimal tar and solid residues. This technology is particularly effective for heterogeneous and hazardous waste streams, offering potential for high-value recovery and environmental remediation.

9. Supercritical Water Gasification

Supercritical Water Gasification (SCWG) harnesses the unique properties of water above its critical temperature and pressure to convert wet biomass directly into syngas, without the need for drying. Operating in an aqueous supercritical environment, SCWG achieves high conversion efficiencies while producing hydrogen and methane rich syngas with minimal tar formation. This technology is especially suited for organic waste streams with high moisture content (such as sewage sludge, food industry residues, and animal manure) and offers promising pathways for clean energy recovery and sustainable waste management.

Each of these technologies presents distinct advantages and limitations depending on:

- Feedstock characteristics (e.g., moisture content, particle size, heterogeneity)
- Operating parameters (e.g., temperature, pressure, residence time)
- Targeted end-use pathways (e.g., heat, power, biofuels, biochemicals)

This SWOT analysis aims to critically assess the internal strengths and weaknesses of thermochemical processes, alongside external opportunities and threats that influence their development, scalability, and integration into sustainable energy systems. The analysis provides a strategic framework for academic research, technology assessment, and policy formulation in the evolving landscape of thermochemical conversion.

The main characteristics of gasification technologies are presented in D2.3.

4.2.2.1. Gasification SWOT Analysis

The following section presents a SWOT analysis structured according to the configuration and operational characteristics of different gasifier types, highlighting key strengths, weaknesses, opportunities, and threats relevant to their deployment.

A MOVING BED GASIFIERS

Author: Marta Trninić

As outlined earlier, the moving bed category includes updraft, downdraft, and cross-draft configurations, which differ in flow dynamics, tar behaviour, and suitability for specific feedstocks.

Updraft Gasification

The SWOT Matrix for updraft gasification is presented in Table 11.

Updraft gasification represents one of the most established moving bed configurations, characterized by a counter-current flow of biomass and gasifying agents (Basu, 2013, Arena, 2012). This design enables high thermal efficiency and robust operation, particularly in heat-dominant systems (S1, S4, S6). Its ability to process biomass with higher moisture content and minimal pre-treatment makes it suitable for decentralized and industrial thermal applications (S3, O1).

Despite its operational simplicity (S2), updraft gasifiers produce syngas with elevated tar levels, limiting their applicability in power generation or chemical synthesis without extensive gas cleaning (W1, W2) (Basu, 2013). The system also exhibits lower syngas quality and calorific value, and is less flexible for integration with modular or hybrid systems (W3, W4) (Jafri Yawer et al., 2020, Arena, 2012).

From an external perspective, updraft gasification offers several strategic opportunities. These include retrofitting in legacy biomass systems (O3), valorisation of moist agricultural residues (O2), and alignment with policy incentives for renewable thermal energy (O4). Integration with drying or pre-treatment systems (O5) may further enhance its performance and applicability (Bioenergy, 2018).

Nonetheless, deployment strategies must account for evolving challenges. These include stricter emission regulations targeting tar and particulates (T1), declining interest in heat-only systems (T2), and competition from cleaner syngas technologies (T3). Additionally, feedstock variability and seasonal availability (T5) may impact operational consistency.

Table 11 SWOT Matrix for Updraft Gasification

UPDRAFT GASIFICATION		
	Success Factors	**Failure Factors**
INTERNAL	STRENGTHS (S1) High thermal efficiency due to counter-current flow. (S2) Simple reactor design with low operational complexity. (S3) Can handle biomass with higher moisture content. (S4) Robust and proven technology for heat applications. (S5) Low maintenance requirements and long operational life. (S6) Suitable for continuous operation in heat-dominant systems.	WEAKNESSES (W1) Produces syngas with high tar content – requires extensive cleaning. (W2) Limited suitability for engine-grade syngas or chemical synthesis. (W3) Less flexible for integration with modular or hybrid systems. (W4) Lower syngas quality and calorific value.
EXTERNAL	OPPORTUNITIES (O1) Use in district heating or industrial thermal processes. (O2) Valorisation of moist agricultural residues. (O3) Potential retrofitting in legacy biomass systems. (O4) Policy incentives for thermal energy from renewables. (O5) Integration with drying or pre-treatment systems.	TREATS (T1) Stricter emission regulations for tar and particulates. (T2) Declining interest in heat-only systems. (T3) Competition from cleaner syngas technologies. (T4) Limited market for low-grade syngas. (T5) Feedstock variability and seasonal availability

In summary, updraft gasification remains a technically mature and resilient solution for thermal energy recovery from biomass, especially in applications where heat demand outweighs the need for high-quality syngas. Its strengths—such as moist feedstock tolerance, low maintenance, and continuous operation—make it well-suited for district heating, industrial thermal processes, and retrofitting in legacy systems.

However, its broader adoption depends on addressing tar-related limitations, enhancing modularity, and aligning with stricter emission standards. Strategic integration with pre-treatment technologies and policy-driven deployment models will be essential to maintain relevance in a competitive and sustainability-focused energy landscape.

Downdraft Gasification

The SWOT Matrix for downdraft gasification is presented in Table 12.

Downdraft gasification offers a robust and cost-effective pathway for converting solid biomass into syngas, particularly suited for decentralized energy systems. Its simple reactor design and relatively low capital expenditure (S2, S6) make it attractive for small to medium-scale applications, including rural biorefineries and modular setups (S3, S4). A key advantage lies in its ability to produce syngas with low tar content (S1), which simplifies downstream cleanup and reduces operational costs. The system accommodates a range of solid biomass residues with consistent quality (S5), though it requires dry, uniform feedstock to operate efficiently (W1, W2). In the context of growing demand for clean, localized bioenergy solutions (O1, O4) and supportive policies for small-scale renewables (O2), downdraft gasification emerges as a practical and adaptable technology for sustainable energy deployment.

While downdraft gasification presents several technical and economic strengths for small-scale implementation, its long-term viability depends on overcoming limitations in feedstock flexibility and scalability (W1, W4). External opportunities such as integration with hybrid renewable systems (O3) and syngas upgrading for fuels and chemicals (O5) offer promising avenues for innovation and value creation. However, competition from more scalable gasification technologies (T1), regulatory hurdles (T4), and biomass market volatility (T6) call for a strategic approach to deployment. This analysis highlights the importance of aligning technical capabilities with evolving market and policy dynamics to ensure resilient and sustainable implementation.

Table 12 SWOT Matrix for Downdraft Gasification

DOWNDRAFT GASIFICATION		
	Success Factors	**Failure Factors**
INTERNAL	STRENGTHS (S1) Produces clean syngas with low tar content (Easier syngas cleanup reduces downstream costs) (S2) Simple reactor design and relatively low capital cost. (S3) Suitable for small to medium-scale, decentralized applications. (S4) Fast startup/shutdown and modular integration with engines or turbines (S5) Can utilize various solid biomass wastes with relatively consistent quality (S6) Relatively low CAPEX compared to other gasifiers - Ideal for rural or modular biorefinery setups	WEAKNESSES (W1) Limited feedstock flexibility (requires dry (moisture<20%), uniform biomass) (W2) Less suitable for fine or highly variable/humid waste (W3) Syngas requires cleaning before use in engines or synthesis applications (W4) Lower efficiency and throughput at large scale (Not suitable for large-scale industrial applications) (W5) Ash and char disposal or valorisation may be underdeveloped
EXTERNAL	OPPORTUNITIES (O1) Decentralized heat and power generation in rural or remote areas (O2) Policy Support for Small-Scale Renewables (O3) Integration with renewable systems (e.g., hybrid solar-biomass) (O4) Increasing demand for clean, small-scale bioenergy solutions (O5) Syngas upgrading for fuels or chemicals (e.g., methanol, ammonia)	TREATS (T1) Competition from more scalable gasification systems (e.g., fluidized bed) (T2) Market uncertainty for syngas-based products (T3) Public perception and acceptance of waste-to-energy technologies (T4) Environmental permitting and regulatory compliance challenges (T5) Feedstock supply chain volatility - May face limitations in policy support (T6) Vulnerable to biomass market fluctuations

In summary, downdraft gasification presents a technically sound and economically viable solution for decentralized bioenergy production, particularly in small to medium-scale applications. Its low tar output, simple reactor design, and compatibility with consistent biomass residues position it as a practical choice for rural biorefineries and modular energy systems. Considering increasing demand for localized, clean energy and supportive policy frameworks, the technology offers strong potential for sustainable deployment. However, its long-term success hinges on addressing internal limitations such as feedstock uniformity and scalability, while navigating external challenges including regulatory complexity, market volatility, and competition from more advanced systems. Strategic integration with hybrid renewables and syngas upgrading pathways could unlock additional value and broaden its applicability. To ensure resilient implementation, downdraft gasification must be aligned with evolving technical standards, investment priorities, and policy incentives—transforming its niche strengths into scalable, future-ready energy solutions.

Cross-Draft Gasifier

The SWOT analysis of cross-draft gasification provides a structured overview of its technical and strategic positioning within the renewable energy landscape (Table 13). Cross-draft gasification key strengths—such as compact and simple design (S1), rapid startup and shutdown cycles (S2), low-cost construction and operation (S3), and straightforward mechanical control requiring minimal automation (S4), position it as a practical and accessible solution. Combined with its moderate carbon conversion efficiency (S5) and suitability for small-scale applications (S6), cross-draft gasification emerges as a compelling option for decentralized energy systems and rural deployment (Čespiva et al., 2022, Tozlu Alperen et al., 2024).

Despite its practical advantages, cross-draft gasification faces several internal weaknesses that must be carefully addressed to enhance its broader applicability. These include the relatively high tar content in syngas (0.01–0.1 g/Nm^3) (W1), pronounced sensitivity to feedstock characteristics (W2), and operational challenges such as slagging (W3) and elevated outlet gas temperatures (W4). Additionally, the system exhibits low cold gas efficiency and a modest lower heating value of producer gas (3–4 MJ/Nm^3) (W5), which collectively constrain its suitability for high-performance or industrial-scale applications (Alperen Tozlu et al., 2024, Sikarwar et al., 2016). These factors limiting its applicability in high-performance or industrial contexts.

From an external perspective, cross-draft gasification offers a spectrum of strategic opportunities. It facilitates waste valorisation and enables decentralized energy production in remote areas (O1) (Alperen Tozlu et al., 2024). Owing to its simplicity and portability, this technology is particularly suitable for niche applications such as disaster relief and off-grid operations (O2), as well as rapid deployment in isolated regions (O3). Its accessibility further positions it as a valuable tool for educational and demonstration purposes (O4), while its modular design allows for the creation of portable biomass energy kits adapted to low-resource settings (O5). Additionally, the hybridization of updraft and cross-draft principles enhances operational flexibility (O6), expanding its applicability across diverse use cases (Čespiva et al., 2022).

Nonetheless, several threats must be carefully considered when planning deployment strategies. These include being overshadowed by more efficient and commercially mature designs (T1), the absence of standardized certification pathways (T2), and low investor interest stemming from limited scalability (T3). In addition, vulnerability to operational inconsistencies under varying field conditions (T4) may further constrain broader adoption (Mohammadi and Anukam, 2023, Vivek and Srividhya, 2024).

In summary, cross-draft gasification stands out as a technically accessible and strategically promising solution within the renewable energy landscape, particularly for decentralized and small-scale applications. Its compact design, low-cost operation, and mechanical simplicity make it well-suited for rural deployment, disaster relief, and educational use. The technology's adaptability and potential for hybridization further enhance its relevance in niche contexts. However, its broader applicability remains constrained by internal limitations such as high tar content, sensitivity to feedstock variability, and modest energy output. These weaknesses, coupled with external threats—including regulatory gaps, limited investor interest, and competition from more efficient systems—highlight the need for targeted improvements and strategic positioning. To unlock its full potential, future efforts should focus on optimizing performance parameters, establishing certification frameworks, and aligning deployment strategies with specific use cases where its strengths can be fully leveraged.

Table 13 SWOT Matrix for Cross-draft Gasification

CROSS DRAFT GASIFICATION		
	Success Factors	**Failure Factors**
INTERNAL	STRENGTHS (S1) Compact, simple design. (S2) Rapid startup and shutdown cycles. (S3) Low-cost construction and operation. (S4) Simple mechanical control – minimal automation needed. (S5) Moderate carbon conversion efficiency. (S6) Suitable for small scale applications.	WEAKNESSES (W1) Poor tar cracking – high syngas cleaning demand. (W2) Sensitivity to feedstock characteristics. (W3) Slagging issues. (W4) Elevated outlet gas temperatures. (W5) Low thermal efficiency and conversion rates. (W6) Limited scalability and industrial relevance.
EXTERNAL	OPPORTUNITIES (O1) Decentralized energy production in remote areas. (O2) Niche applications in disaster relief or off-grid scenarios. (O3) Potential for rapid deployment in remote areas. (O4) Educational and demonstration projects. (O5) Development of portable biomass energy kits. (O6) Integration with compact hybrid energy systems.	TREATS (T1) Overshadowed by more efficient designs. (T2) Lack of standardization and certification pathways. (T3) Low investor interest due to limited scalability. (T4) Vulnerability to operational inconsistencies.

B FLUIDIZED BED

Author: Marta Trninić

As outlined earlier, the fluidised bed gasification can be performed in bubbling fluidised beds or circulating fluidised beds which vary in the applied gas velocities (Alperen Tozlu et al., 2024). A special form of fluidised bed gasifiers are dual fluidised beds (DFBs).

Bubbling Fluidised Bed gasification

The transition toward sustainable energy systems has intensified interest in advanced biomass conversion technologies. Among these, Bubbling Fluidized Bed Gasification (BFBG) stands out for its versatility, scalability, and potential to valorise diverse waste biomass streams. This SWOT analysis evaluates the internal strengths and weaknesses of BFBG, alongside external opportunities and threats that shape its deployment in real-world contexts.

Key strengths include the versatile feedstock compatibility (S1), high conversion efficiency (S2), and scalability across applications (S3) (Wang and Tester, 2023, Ali et al., 2024). The technology also enables syngas valorisation (S4), benefits from enhanced heat transfer (S5), and offers high hydrogen yields when steam is used (S6) (Wang and Tester, 2023, Ali et al., 2024, Gao et al., 2024, Rosyadi et al., 2024, Kong et al., 2023). Operational advantages such as effective mixing (S7) and potential CO_2 absorption integration (S8) further reinforce its appeal (Karunathilake et al., 2020).

However, BFBG faces notable weaknesses, including high initial investment costs (W1), operational complexity (W2), and tar and ash management challenges (W3) (Hejazi, 2022, Wolfesberger et al., 2009, Wolfesberger-Schwabl et al., 2012). Technical limitations such as particle agglomeration (W4), bed material dependency (W5), and steam requirements (W6) must also be considered(Gao et al., 2024, Safitri et al., 2021, Matsuoka et al., 2008, Hejazi, 2022).

Externally, BFBG benefits from growing interest in renewable energy (O1), integration potential with other technologies (O2), and policy incentives (O3). Its role in waste valorisation (O4) and decentralized energy systems (O5) enhances its strategic relevance (Rashidi et al., 2025, Acuña López et al., 2024).

Yet, it must navigate stringent environmental regulations (T1), competition from alternative technologies (T2), and feedstock volatility (T3). Additional threats include high tar removal costs (T4), cheaper disposal alternatives (T5), and emerging innovations like gas fermentation (T6) (Ryabov and Tugov, 2020).

The SWOT Matrix for bubbling fluidised bed gasification presented in Table 14.

Table 14 SWOT Matrix for Bubbling Fluidised Bed Gasification

BUBBLING FLUIDISED BED GASIFICATION		
	Success Factors	**Failure Factors**
INTERNAL	STRENGTHS (S1) Versatile feedstock (S2) Efficient conversion (high syngas yields due to excellent heat/mass transfer) (S3) Suitable for both small and large-scale applications (S4) Syngas versatility (can be upgraded to methane, methanol, DME, FT fuels) (S5) Enhanced heat transfer (S6) High hydrogen yield (steam gasification boosts H_2 production) (S7) Effective mixing (uniform distribution of biomass and bed material) (S8) CO_2 absorption integration (enhances reforming and syngas quality)	WEAKNESSES (W1) High initial investment (W2) Operational complexity (W3) Tar and ash production (requires costly cleaning and disposal) (W4) Particle agglomeration (limits industrial scalability) (W5) Bed material requirement (W6) Steam requirement (adds to energy consumption)
EXTERNAL	OPPORTUNITIES (O1) Rising interest in renewable energy and sustainable biomass waste management (O2) Integration potential with other renewable technologies (O3) Policy support (subsidies, tax credits, and green energy incentives) (O4) Biomass waste valorisation (converts biomass into valuable products) (O5) Decentralized energy (supports local energy independence and resilience)	TREATS (T1) Stringent environmental regulations (emission control requirements) (T2) Competing technologies (plasma, downdraft gasification, etc) (T3) Feedstock volatility (T4) Tar removal costs (high cost of syngas purification) (T5) Cheaper alternative (landfilling and incineration remain cost-effective) (T6) Emerging alternatives (gas fermentation gaining traction) (T7) Public perception and acceptance of waste-to-energy technologies

The SWOT analysis reveals that BFBG holds significant promise for sustainable energy production and waste management, particularly due to its feedstock flexibility (S1), conversion efficiency (S2), and syngas versatility (S4). These strengths position it well for integration into decentralized systems (O5) and hybrid renewable platforms (O2), especially under supportive policy frameworks (O3).

Nonetheless, successful deployment requires addressing key technical and economic barriers, such as capital intensity (W1), tar mitigation (W3, T4), and regulatory compliance (T1). Strategic planning must also account for market competition (T2) and feedstock dynamics (T3).

By leveraging its strengths and opportunities while proactively mitigating weaknesses and threats, BFBG can play a pivotal role in advancing circular economy goals, energy resilience, and low-carbon innovation across diverse sectors.

Circulating fluidised beds gasification

This SWOT analysis explores the strategic potential of Biomass Circulating Fluidized Bed Gasification (CFBG), a technology designed to convert diverse biomass feedstocks into clean energy and chemical products. The analysis provides a comprehensive overview of the factors influencing CFBG's performance, scalability, and market viability.

CFBG demonstrates notable strengths, including high conversion efficiency (S1), feedstock flexibility (S2), and scalability across operational contexts (S3) (Wang et al., 2025, Dieringer et al., 2023, Grace and Lim, 2013). Its ability to produce versatile syngas derivatives (methane, methanol, DME, and Fischer-Tropsch fuels etc) (S4) enhances its relevance in both energy and chemical sectors (Chen et al., 2001).

However, challenges such as capital intensity (W1), operational complexity (W2), and tar and ash management (W3) must be addressed, alongside erosion risks (W4) inherent to high-velocity systems (Silva Ortiz et al., 2021, Liu et al., 2024, Gu et al., 2024, Prabhansu et al., 2016).

Externally, CFBG benefits from growing demand for renewable energy (O1), its role in sustainable waste management (O2), and supportive policy frameworks (O3). Innovations in heat integration (O4) offer further efficiency gains (Prabhansu et al., 2016, Chen et al., 2005).

Yet, the technology faces competition (T1), feedstock variability (T2), regulatory pressures (T3), market instability (T4), and operational risks (T5) that could impact its long-term success (Gu et al., 2024, Silva Ortiz et al., 2021). The SWOT Matrix for circulating fluidised bed gasification presented in Table 15.

Table 15 SWOT Matrix for Circulating Fluidised Bed Gasification

CIRCULATING FLUIDISED BED GASIFICATION		
	Success Factors	**Failure Factors**
INTERNAL	STRENGTHS (S1) High conversion efficiency due to superior gas-solid contact and residence time (S2) Fuel flexibility (handles diverse biomass types, including high-moisture and high-ash feedstocks) (S3) Scalability (adaptable to both small-scale and large-scale applications through configurable system design) (S4) Syngas versatility (enables synthesis of methane, methanol, DME, and Fischer-Tropsch fuels)	WEAKNESSES (W1) High capital costs (influenced by plant scale, design complexity, and syngas upgrading requirements) (W2) Operational complexity (W3) Tar and ash production (generates residues that require costly cleaning and disposal) (W4) Erosion risk (high gas velocities with bed material can damage reactor components over time)
EXTERNAL	OPPORTUNITIES (O1) Rising global demand for renewable energy and net-zero emission technologies (O2) Sustainable waste management (converts biomass into valuable energy and chemical products) (O3) Policy support (incentives, subsidies, and carbon credits enhance project viability) (O4) Heat integration (potential for energy recovery during syngas cooling to improve system efficiency)	TREATS (T1) Competition from other gasification and renewable energy technologies (e.g., solar, wind, plasma) (T2) Feedstock variability (affects process stability and conversion efficiency) (T3) Stringent environmental regulations (may require costly emission control upgrades) (T4) Market volatility (biomass and energy price fluctuations impact economic feasibility) (T5) Operational disruptions (feeding system issues, bed agglomeration, and wall deposits can lead to shutdowns) (T6) Public perception and acceptance of waste-to-energy technologies

The analysis underscores CFBG's potential as a robust and adaptable solution for biomass conversion, particularly due to its conversion efficiency (S1), feedstock versatility (S2), and syngas production capabilities (S4). These strengths position it well within the broader transition to low-carbon energy systems and circular economy models. Opportunities such as policy incentives (O3) and heat recovery integration (O4) further enhance its strategic appeal.

However, realizing this potential requires addressing key technical and economic barriers, including high capital costs (W1), tar-related challenges (W3), and regulatory compliance (T3). Strategic planning must also anticipate market fluctuations (T4) and operational disruptions (T5) to ensure system resilience and economic sustainability.

By leveraging its strengths and opportunities while proactively mitigating weaknesses and threats, CFBG can play a pivotal role in advancing renewable energy goals, waste valorisation, and energy security across industrial and community-scale applications.

Dual Fluidised Bed gasification

This SWOT analysis explores the strategic potential of biomass-based Dual Fluidized Bed Gasification (DFBG), a two-reactor thermochemical system designed to convert waste biomass into high-quality syngas. By separating the gasification and combustion zones, DFBG enables optimized reaction conditions, making it a promising technology for renewable energy production and waste valorisation (Alperen Tozlu et al., 2024).

DFBG exhibits several notable strengths, including high energy conversion efficiency (S1), low tar syngas production (S2), and feedstock flexibility (S3), particularly for biomass with high moisture or ash content (Hanchate et al., 2021). The staged configuration allows for independent control of temperature and gas flow, enhancing system performance. Additionally, the separation of combustion and gasification zones contributes to reduced NO_X and SO_X emissions (S4), positioning DFBG as an environmentally favourable alternative to conventional combustion systems (Alperen Tozlu et al., 2024, Hanchate et al., 2021, Zhang and Yang, 2024). Syngas can be converted into bio-fuels (e.g., Fischer-Tropsch diesel, methanol) and can be used in combined heat and power plants (CHP) to generate electricity and useful heat and in combined cooling, heat and power systems (CCHP) which can provide electricity, heating, and cooling simultaneously, improving the overall efficiency of energy utilization (Alperen Tozlu et al., 2024).

Despite these advantages, DFBG faces internal challenges. High capital costs (W1) and operational complexity (W2) remain significant barriers to widespread adoption, especially in decentralized or resource-constrained settings (Silva Ortiz et al., 2021). Efficient heat integration between the two beds is critical but technically demanding (W3), requiring precise control of circulating bed material and reactor design (Silva Ortiz et al., 2021, Alperen Tozlu et al., 2024).

Externally, DFBG benefits from growing global demand for renewable energy (O1), its alignment with sustainable waste management strategies (O2), and compatibility with carbon capture and storage (CCS) technologies (O3) (Hanchate et al., 2021). The concentrated CO_2 stream produced during gasification enhances the feasibility of CCS integration, further reducing greenhouse gas emissions. Ongoing research in reactor design, catalyst development, and process control (O4) continues to improve the reliability and cost-effectiveness of DFBG systems (Hanchate et al., 2021).

However, the technology must navigate several external threats. Competition from other gasification systems (T1), such as bubbling fluidized beds and plasma gasifiers, as well as from solar and wind energy, may affect market positioning. Feedstock variability (T2) can impact syngas quality and reactor stability, while increasingly stringent environmental regulations (T3) may require additional investments in emission control. Market volatility (T4), including fluctuations in biomass prices and energy markets, poses further risks to economic viability.

The SWOT matrix for biomass DFBG is presented in Table 16.

Table 16 SWOT Matrix for Dual Fluidised Bed Gasification

DUAL FLUIDISED BED GASIFICATION		
	Success Factors	**Failure Factors**
INTERNAL	STRENGTHS (S1) High Efficiency (optimized conversion due to separate combustion/gasification zones) (S2) Low Tar Syngas (staged process minimizes tar formation) (S3) Feedstock Flexibility (handles biomass with high moisture/ash content) (S4) Reduced Emissions (lower NO_x and SO_x emissions via controlled combustion) (S4) Syngas versatility (enables synthesis of methanol, Fischer-Tropsch fuels, CHP and CCHP)	WEAKNESSES (W1) High Capital Costs (complex dual-reactor design increases investment needs) (W2) Operational Complexity (requires skilled personnel and advanced control) (W3) Heat Integration Challenges (demands precise control of circulating bed material)
EXTERNAL	OPPORTUNITIES (O1) Rising global demand for renewable energy and net-zero emission technologies (O2) Sustainable waste management (converts biomass into valuable energy and chemical products) (O3) Integration with Carbon Capture (compatible with CCS for emission reduction) (O4) Technological Advancements (R&D improving reactor design and efficiency)	TREATS (T1) Competition from other gasification and renewable energy technologies (e.g., BFBG, solar, wind, plasma) (T2) Feedstock variability (affects process stability and conversion efficiency) (T3) Environmental Regulations (may require costly emission control upgrades) (T4) Market volatility (biomass and energy price fluctuations impact economic feasibility) (T5) Public perception and acceptance of waste-to-energy technologies

DFBG stands out as a technically robust and environmentally promising solution for biomass conversion, particularly due to its high efficiency (S1), low-tar syngas production (S2), and emission reduction capabilities (S4). These strengths make it a compelling candidate for integration into low-carbon energy systems and circular economy frameworks.

To unlock its full potential, strategic efforts must address key barriers such as capital intensity (W1), heat integration challenges (W3), and regulatory compliance (T3). Proactive planning should also consider feedstock variability (T2) and market fluctuations (T4) to ensure long-term resilience and competitiveness.

By leveraging its strengths and opportunities while mitigating weaknesses and threats, DFBG can play a pivotal role in advancing sustainable energy goals, reducing waste, and supporting industrial decarbonization across diverse application contexts.

C PLASMA GASIFICATION

Author: Nerijus Striūgas

Plasma-assisted gasification offers high-efficiency bio feedstock conversion, producing clean syngas and reducing environmental impacts. SWOT analyse show strong potential for circular economy integration and advanced fuel production. However, high costs and limited commercialization require targeted R&I, supportive policies, and green fuels production pathways integration to unlock large-scale deployment and climate alignment.

Plasma gasification is an advanced thermochemical technology capable of converting a wide variety of biomass and biowaste materials into valuable products (Ibrahimoglu and Yilmazoglu, 2020). Different from conventional gasification, plasma gasification utilizes extremely high temperatures, ranging from 1500 °C to 5500 °C, and in some cases up to 14,000 °C, achieved through ionized gases (plasma) generated using air, O_2, steam, CO_2, N_2, or their mixtures. This environment allows for the near-complete conversion of waste into a synthesis gas (syngas) primarily composed of hydrogen (H_2) and carbon monoxide (CO), with conversion efficiencies reaching up to 99.99% (Sanlisoy and Carpinlioglu, 2017).

The syngas produced can serve multiple roles, such as a clean fuel for heat and power generation or as a chemical feedstock for producing hydrogen, methanol, ammonia, or synthetic hydrocarbons (Agon et al., 2016). Plasma gasification or plasma assisted gasification stands out by minimizing the formation of tars, chars, and harmful emissions such as dioxins and furans, ensuring cleaner outputs and better environmental compliance (Mazzoni and Janajreh, 2017).

A key benefit of plasma technology is its adaptability to diverse feedstocks without limitation to organic or inorganic composition. This makes it particularly suitable for sustainable waste management and renewable energy production. Studies have demonstrated the successful gasification of a broad spectrum of feedstocks (Gimžauskaitė et al., 2022), highlighting plasma's versatility and environmental advantages.

Despite its energy-intensive nature, the external energy supplied via plasma allows for more precise control over syngas composition. Compared to traditional gasification, which often results in syngas contaminated with CO_2, methane, and tars, plasma technology yields cleaner syngas suitable for high-grade applications (Hrabovsky, 2011). Nevertheless, pre-treatment of the feedstocks such as drying, crushing, and homogenization remains critical to ensure optimal efficiency and reliability in plasma gasification systems. Therefore, a comprehensive SWOT analysis is essential to evaluate the strengths, weaknesses, opportunities, and threats of plasma-assisted gasification, particularly in its application to biomass and waste-to-energy systems.

Overview of Conversion Technologies

Plasma, the fourth state of matter, is a fully or partially ionized gas characterized by equal densities of positive and negative charges, resulting in a quasi-neutral state with no internal electric field (Sipra et al., 2018). It is generated by supplying external electrical energy to neutral, reducing, or oxidizing gases, leading to ionization through electron collisions. Key plasma parameters include temperature, pressure, and charge concentration. Thermal or "quasi equilibrium" plasmas are most commonly used in gasification processes, typically generated at pressures above 10 kPa using DC/AC, radio frequency, or microwave energy sources, with temperatures ranging from 2000 to 20,000 K (Dave and Joshi, 2010). High-pressure arc discharge plasmas exhibit thermal equilibrium among ions, electrons, and neutral particles, facilitating efficient energy transfer through collisions (Schutze et al., 1998). Plasma can be produced by electric arcs, microwaves, lasers, RF induction, or by heating gases at high temperatures (Sikarwar et al., 2020). For detailed technical specifications, reference should be made to Deliverable D2.3.

Plasma Gasification SWOT Analysis

The SWOT analysis was developed through a structured and evidence-based approach (Table 17). Key information was sourced from two primary channels: expert competences and finding collected performing EU (TWIN-PEAKS, GIFFT) and National Lithuanian (INODUMTECH, BIOMETANAS) research projects and further supported by an in-depth review of scientific literature on plasma gasification technologies. Each insight was categorized into one of the four dimensions—Strengths, Weaknesses, Opportunities, and Threats (SWOT).

Plasma-assisted gasification remains an emerging and highly promising waste-to-energy technology, currently situated around TRL 6–8 depending on configuration and application. Unlike traditional gasification, it leverages extremely high-temperature plasma (1500–5,000 °C) to decompose biomass or biowastes into clean syngas with minimal residues (Sanlisoy and Carpinlioglu, 2017, Ibrahimoglu and Yilmazoglu, 2020). This allows for the treatment of complex feedstocks, including RDF, sewage sludge, and biomass or its waste fractions otherwise unsuitable for conventional pathways (Gimžauskaitė et al., 2022). Syngas produced is high in H_2 and CO, enabling downstream conversion to fuels and chemicals such as methanol, ammonia, or hydrogen (Agon et al., 2016)

However, the technology faces key weaknesses. High electricity demand limited commercial deployment, electrode erosion, and complex feedstock preparation remain significant challenges. Social awareness and acceptance are also limited, partly due to the novelty and perceived risks of plasma processes.

Opportunities are considerable. Plasma's ability to handle diverse waste types supports circular economy goals and aligns well with EU Green Deal and RED III objectives. Emerging modular systems, integration, and policy incentives for waste valorisation could accelerate adoption (Vedraj Nagar, 2024). Nevertheless, high CAPEX, regulatory uncertainty, and competition from established low-carbon alternatives present ongoing threats.

Table 17 SWOT Analysis of Plasma Gasification of Biomass and Biowaste

PLASMA GASIFICATION		
	Success Factors	**FAILURE FACTORS**
INTERNAL	**STRENGTHS** (S1) High Conversion Efficiency: Plasma gasification achieves feedstock conversion rates up to 99.99%, thanks to extreme operational temperatures, enabling efficient breakdown of complex organic and inorganic compounds (Sanlisoy, 2017; Ibrahimoglu, 2020). (S2) Cleaner Syngas Production: Produces low-tar, compositionally controlled syngas suitable for advanced energy and fuel applications (Hrabovsky, 2011; Agon et al., 2016). (S3) Environmental Performance: Minimizes generation of pollutants like dioxins, furans, NOx, and SOx; reduces landfill demand and enables vitrified slag recovery (Mazzoni, 2017; Gimžauskaitė et al., 2022). (S4) Versatile Feedstock Use: Capable of processing a wide variety of waste types including biomass, biowaste, RDF, sludge, glycerol, etc. (Gimžauskaitė et al., 2022).	**WEAKNESSES** (W1) High Energy Demand: Requires substantial initial electrical energy input to generate plasma, making operational costs high (Varshney, 2022; Gun et al., 2022). (W2) Limited Commercial Deployment: Most systems remain at TRL 7–8, with very few fully commercial installations worldwide (Kaushal, 2024; Nagar, 2024). (W3) Electrode Erosion: DC arc systems suffer from electrode wear, especially under oxidative gas conditions, affecting durability and maintenance frequency.
EXTERNAL	**OPPORTUNITIES** (O1) Decarbonization Pathways: Potential to support EU Green Deal and RED III goals through clean hydrogen and synthetic fuel production (Gimžauskaitė et al., 2022). (O2) Circular Economy Integration: Converts waste to valuable outputs (e.g., methanol, NH_3, hydrocarbons), aligning with zero-waste strategies. (O3) Modular Plant Development: Advances in modular reactor design offer scalability and adaptability for decentralized waste management (Nagar, 2024). (O4) Emerging Markets: Growing interest in waste valorisation in developing economies and for hard-to-treat waste streams like medical or plastic waste.	**THREATS** (T1) High Capital Investment: higher than other thermal WtE technologies. (T2) Public Awareness & Acceptance: Limited societal familiarity with plasma technology may result in community resistance or underutilization. (T3) Policy and Regulatory Uncertainty: Lack of targeted incentives or clear policy support for plasma-specific technologies may hinder adoption. (T4) Technology Risk: Insufficient process understanding and control can affect long-term reliability, particularly in large-scale or mixed-waste operations.

Plasma-assisted gasification emerges as a promising, though still maturing, technology for sustainable waste-to-energy conversion. Its unique ability to process diverse feedstocks with near-complete conversion, while producing clean syngas and reusable by-products, offers clear advantages over conventional thermochemical routes. However, high energy demand, limited commercialization, and policy uncertainties remain critical barriers. The SWOT and comparative analyses highlight plasma's strategic role in future energy systems, particularly when integrated with circular economy pathways. Targeted R&I, cost reduction, and supportive EU frameworks will be essential to advance plasma gasification toward scalable deployment and climate-aligned applications.

D SUPERCRITICAL WATER GASIFICATION

Author: Elanur Adar Yazar

This part gives a structured SWOT analysis of supercritical water gasification (SCWG) for making hydrogen energy and treating waste. Table 18 shows the SWOT Matrix for SCWG.

Table 18 SWOT Matrix for Supercritical Water Gasification

Supercritical water gasification process		
	Success Factors	**Failure Factors**
INTERNAL	**STRENGTHS** (S1) Very energy-efficient and able to make clean hydrogen-rich energy (S2) Processing of flexible feedstocks, such as wet wastes (S3) Low emissions and a lot of room for integration into a circular economy (S4) Short time to react compared to many thermal processes	**WEAKNESSES** (W1) High costs of capital and running a business (W2) The technology isn't mature enough yet, and the market isn't ready for it yet (TRL 6–7) (W3) Very high pressure and temperature that make it necessary to use special equipment (W4) Problems with corrosion, salt buildup, and system plugging; needs a lot of maintenance
EXTERNAL	**OPPORTUNITIES** (O1) The world is asking for more clean hydrogen and renewable energy. (O2) Circular economy drivers and stricter environmental rules that encourage more advanced ways to turn waste into energy (O3) Public-private R&D partnerships, pilot projects, and funding to make things more scalable and last longer (O4) The ability to turn difficult wet feedstocks into something useful, which cuts down on the need for landfills	**THREATS** (T1) There is a lot of competition from well-known energy and gasification technologies. (T2) Changes in the market and economic risks because of high costs (T3) Few government incentives and unclear rules are making it hard for people to adopt. (T4) People think that high-risk technology is bad and that it won't be accepted by society.

Supercritical Water Gasification (SCWG) is a new and cutting-edge technology that turns waste biomass into hydrogen energy. Gasification happens above the supercritical point of water (374 °C, 22.1 MPa) with this technology. When water is in a supercritical state, it has special properties that make it a good solvent and reactive agent. This means that materials with a lot of moisture, like sewage sludge, food waste, and black liquor, can be gasified quickly and easily without having to dry them out first (Adar et al., 2020; Huang et al., 2024; Ochieng & Sarker, 2025). These benefits set SCWG apart from other thermochemical methods and make it a good choice for the circular economy and making clean/hydrogen energy.

The best things about SCWG are that it uses a lot of energy and makes a clean, hydrogen-rich synthesis gas (S1). The reaction happens quickly and in a closed system (S4), which cuts down on the production of tar and other harmful emissions. This makes it a good candidate for use in the circular economy (S3). The best thing about it is that it can handle wet and hard-to-dispose-of waste (S2). Even with these benefits, it has big problems with operations and money. The process's high-pressure and high-temperature conditions make it expensive to set up and run (W1). Corrosion and the buildup of inorganic salts in some parts of the process (especially the reactor) are caused by harsh operating conditions. This leads to system blockages and high maintenance costs (W3, W4) (Schulenberg, 2025). Because of the hard operating conditions and these problems, the process is only at a pilot scale (TRL 6–7), which means that there isn't much demand for it on the market (W2).

SCWG has a lot of chances to grow because of things outside of its control. This technology is becoming more important because more people want clean hydrogen energy (O1) and environmental regulations are getting stricter (O2). Funding and partnerships for research and development between the public and private sectors (O3) can help fix the problems with this technology, especially its high cost. Also, treating or getting rid of wet or liquid waste on-site (O4) can help cities and businesses save space in landfills and/or reduce the load on wastewater treatment plants.

Along with the problems that come with SCWG, the fact that there are better and cheaper technologies like biogas and pyrolysis (T1) also makes it hard for this process to enter the market. This expensive technology is sensitive (T2) because of economic risks and changes in the market, which also makes it hard for investors to get involved. SCWG has its own problems, but the fact that there are advanced and cheap technologies like biogas and pyrolysis (T1) that are already on the market makes it even harder for this process to get into the market. This expensive technology is sensitive (T2) because of economic risks and changes in the market, which makes it hard for investors to get involved. The technology is also slow to catch on because the government doesn't offer enough incentives (T3) and the public doesn't accept it because of the high risk (T4).

In conclusion, SCWG is a "high risk, high reward" process that could quickly and with little pollution turn wet, dangerous waste into hydrogen energy. It is very important for industrial waste treatment, municipal sludge disposal, and niche applications that focus on the circular economy that it can handle wet materials, is very efficient, has a short reaction time, and produces clean hydrogen gas. To boost SCWG's market share and TRL level, more research and development is needed to fix its problems with corrosion, salt precipitation, and high costs. To get more people to buy the technology, we need new materials science, new reactor designs that cut costs, and policies that help. From a strategic point of view, this technology can be commercialized more quickly to make hydrogen energy and get rid of expensive waste.

4.2.3. Pyrolysis Technologies

Author: Marta Trninić

Pyrolysis represents a process of thermal degradation that takes place without the presence of oxygen, during which organic matter is converted into gaseous products, liquid bio-oil, and solid bio-char. Developing pyrolysis technology requires careful optimization of reactor design, feedstock pretreatment, operating temperature, and other process parameters to obtain the targeted distribution of products. In this section, attention is given to the main engineering aspects and design principles that ensure an effective pyrolysis system, with emphasis on maximizing energy recovery and enhancing overall efficiency.

Pyrolysis technologies are commonly classified according to heating rate and vapor residence time, including slow, intermediate, fast, flash, and hydrothermal pyrolysis. Each subtype offers distinct advantages depending on feedstock characteristics, operating parameters, and targeted end-use pathways such as biochar, bio-oil, syngas, or specialty chemicals.

The five principal categories are:

1. Slow pyrolysis

Characterized by low heating rates and long residence times (hours). Optimized for biochar production, this method allows thorough carbonization of biomass. It is simple, robust, and suitable for decentralized applications, but yields limited bio-oil and syngas.

2. Intermediate pyrolysis

Operates at moderate heating rates and residence times (seconds to minutes). Balances biochar and bio-oil yields, offering flexibility for combined product streams. Suitable for medium-scale setups and adaptable to various feedstocks.

3. Fast Pyrolysis

Uses high heating rates and short vapor residence times (typically <2 seconds). Maximizes bio-oil yield, making it ideal for liquid fuel production. Requires finely ground feedstock and precise temperature control. Commonly implemented in fluidized bed reactors.

4. Flash Pyrolysis

An intensified form of fast pyrolysis with ultra-rapid heating and residence times in milliseconds. Produces high-quality vapours for chemical synthesis or advanced fuels but demands sophisticated reactor design and feedstock pre-treatment.

5. Hydro Pyrolysis

Conducted in aqueous environments under high pressure and moderate temperatures. Converts wet biomass without drying, yielding bio-crude, gases, and aqueous organics. Ideal for sludge, algae, and high-moisture feedstocks, with potential for integration into biorefinery platforms

Each subtype offers distinct advantages depending on:

- Feedstock characteristics (moisture, particle size, ash content, heterogeneity).
- Operating parameters (temperature, heating rate, residence time, pressure).
- Targeted end-use pathways (biochar, bio-oil, syngas, bio chemicals).

The main characteristics of pyrolysis technologies are presented in this comprehensive review D2.3.

1.1.1.1. Pyrolysis SWOT Analysis

The following section provides a SWOT analysis organized around the design and operational features of various gasifier types, emphasizing their core advantages, limitations, implementation prospects, and potential challenges.

A SLOW PYIROLYSIS

The SWOT Matrix for slow pyrolysis is presented in Table 19.

A comprehensive SWOT analysis of slow pyrolysis for biomass conversion reveals several critical aspects:

Slow pyrolysis is a mature and well-characterized thermal conversion process that excels in producing biochar—a stable, carbon-rich material with wide-ranging environmental and agronomic benefits. Its primary strength lies in the high yield of biochar (S1), which is increasingly recognized as a tool for soil amendment and long-term carbon sequestration (S2) (Akinpelu et al., 2023, Nachenius et al., 2013, Cai et al., 2020, Bhattacharyya et al., 2024). With a high energy density and multifunctional applications—as a fuel, catalyst, or adsorbent—biochar offers both ecological and industrial value (S3) (Bhattacharyya et al., 2024, Mohanty et al., 2024).

Compared to other pyrolysis methods, slow pyrolysis operates at lower energy input levels (S4), making it suitable for decentralized or resource-constrained settings. Its ability to treat diverse biomass waste streams (S5) aligns well with circular economy principles and regenerative agriculture, especially as climate policies begin to favour carbon-negative technologies (S5). With a Technology Readiness Level (TRL) of 7–9, it is widely studied and field-tested, offering a reliable platform for scale-up and integration (S4).

Table 19 SWOT Matrix for Slow Pyrolysis

SLOW PYROLYSIS		
	Success Factors	**Failure Factors**
INTERNAL	STRENGTHS (S1) High yield of biochar (S2) Biochar ideal for soil amendment and long-term carbon sequestration (S3) High energy density of biochar; usable as fuel, catalyst, adsorbent (S4) Lower energy input compared to other pyrolysis methods (S5) Versatile treatment of diverse biomass waste (S4) Mature technology (TRL 7–9), widely studied and field-tested. (S5) Strong alignment with circular economy and regenerative agriculture principles.	WEAKNESSES (W1) Long residence times reduce throughput and and scalability (W2) High moisture content requires energy-intensive drying pre-treatment (W3) Emissions of toxic gases (e.g., PAHs, VOCs) in industrial setups require mitigation (W4) Feedstock variability affects biochar quality and consistency (W5) Limited public awareness of biochar benefits and certification schemes
EXTERNAL	OPPORTUNITIES (O1) Rising demand for sustainable agriculture and soil amendments (O2) Global push for carbon-negative technologies and net-zero targets (O3) Certification schemes (e.g., EBC) promoting quality and sustainability (O4) EU and global climate policies increasingly recognize biochar as a carbon sink. (O5) Waste valorisation and circular economy initiatives (O6) Conversion of low-value waste into high-value products	TREATS (T1) Regulatory gaps in biochar classification and land application standards (T2) Competition from other biomass conversion technologies (T3) Environmental and economic challenges from toxic emissions and energy use (T4) Technical complexity in scaling due to biomass variability and pyrolysis conditions (T5) Risk of airborne metal(loid) particles from contaminated biomass during pyrolysis (T6) Public skepticism toward thermal waste treatment. (T7) Limited financial incentives for biochar deployment in some regions

However, several technical and perceptual barriers remain. Long residence times limit throughput and scalability (W1), while high moisture content in feedstocks necessitates energy-intensive drying (W2) (Akinpelu et al., 2023). Industrial setups may emit toxic gases such as PAHs and VOCs (W3), requiring robust mitigation strategies to meet environmental standards (T3)

(Javaid et al., 2024). Additionally, feedstock variability can affect biochar consistency (W4), and public awareness of its benefits and certification schemes (e.g., EBC) remains limited (W5).

Despite these challenges, the landscape is evolving. The rising demand for sustainable agriculture (O1) and the global push for net-zero targets (O2) create fertile ground for biochar deployment (Fambri et al., 2024, Peters et al., 2015). Certification schemes (O3, O4)) and waste valorisation initiatives (O5) offer pathways to improve quality assurance and market trust (Garcia et al., 2022, EBC, 2022). Moreover, the conversion of low-value waste into high-value biochar (O6) supports both economic and environmental goals.

Yet, slow pyrolysis must navigate several external threats. Regulatory gaps in biochar classification and land application (T1) can hinder adoption, while competition from other biomass technologies (T2) may divert investment (Javaid et al., 2024, Raza et al., 2021). Technical complexity in scaling (T4) and risks from contaminated biomass (T5) require careful feedstock management and reactor design (Akinpelu et al., 2023, Suriapparao and Vinu, 2017, Hussain Tahir and Shimizu, 2024). Finally, public scepticism toward thermal waste treatment (T6) and limited financial incentives (T7) may slow deployment unless addressed through policy and outreach.

In conclusion, slow pyrolysis offers a powerful method for sustainable waste management and carbon sequestration through biochar production, but its success hinges on overcoming challenges related to product diversification, process optimization, and market development amidst strong competition from alternative biomass conversion pathways.

B INTERMEDIATE PYIROLYSIS

The SWOT Matrix for intermediate pyrolysis is presented in Table 20.

A comprehensive SWOT analysis of intermediate pyrolysis reveals its distinct advantages, limitations, and strategic positioning within the bioenergy landscape.

Intermediate pyrolysis occupies a unique niche in the biomass conversion landscape, offering a balanced output of bio-oil, biochar, and syngas (S1) that supports diversified applications across energy, agriculture, and materials (Dasari and Gumtapure, 2019, Tinwala et al., 2015, Parvari et al., 2025). Its moderate residence times enable greater control over product distribution (S2), while less stringent feedstock requirements compared to fast pyrolysis (S3) make it more adaptable to heterogeneous biomass streams (Alperen Tozlu et al., 2024).

The process generates co-products that enhance energy efficiency and soil health (S4), and its compatibility with biorefinery integration (S5) positions it well for future circular economy models. With a Technology Readiness Level (TRL) typically between 5 and 7 (Alperen Tozlu et al., 2024), intermediate pyrolysis is emerging from pilot-scale experimentation into early commercialization, offering a flexible platform for innovation and hybridization

Table 20 SWOT Matrix for Intermediate Pyrolysis

INTERMEDIATE PYROLYSIS		
	Success Factors	**Failure Factors**
INTERNAL	STRENGTHS (S1) Balanced product output: bio-oil, biochar, syngas (S2) Moderate residence times allow better control over product distribution (S3) Less stringent feedstock requirements than fast pyrolysis (S4) Co-products enhance energy efficiency and soil applications. (S5) Suitable for integration into biorefineries and hybrid systems.	WEAKNESSES (W1) No maximum yield of any single product compared to specialized methods; trade-offs in output ratios. (W2) Raw bio-oil still requires upgrading for fuel applications (high viscosity, corrosiveness, instability, high oxygen content) (W3) Upgrading bio-oil adds complexity and cost (W4) Reactor sensitivity and control complexity hinder scale-up (W5) High capital and operational costs for scale-up (W6) TRL varies (typically 5–7); not yet widely commercialized (W7) Limited public visibility compared to fast pyrolysis or gasification
EXTERNAL	OPPORTUNITIES (O1) Rising demand for renewable energy and sustainable products (O2) Waste valorisation and circular economy alignment (O3) Catalytic pyrolysis innovations improve bio-oil quality (O4) Advanced technologies (e.g. microwave-assisted pyrolysis) enhance efficiency and scalabilit (O5) Potential for integrated biorefineries combining multiple conversion technologies (O6) EU RED III and similar frameworks support waste-to-energy integration.	TREATS (T1) Competition from more mature or specialized technologies (T2) Biomass feedstock cost and supply chain uncertainties (T3) Lack of standardized policies for intermediate pyrolysis outputs (T5) High capital and operational costs for pilot-scale deployment. (T6) Environmental compliance challenges in mixed-output systems.

However, its generalist nature presents trade-offs. Unlike specialized methods, intermediate pyrolysis does not maximize yield for any single product (W1), which can complicate market positioning (Afraz et al., 2024, Parvari et al., 2025). The raw bio-oil produced still requires significant upgrading due to its high oxygen content, viscosity, and instability (W2, W3), adding cost and technical complexity (Dada et al., 2021, Shamsul et al., 2017). Reactor sensitivity and control challenges further hinder scale-up (W4), while capital and operational costs remain high (W5). Public visibility is also limited compared to more established technologies like fast pyrolysis or gasification (W7), which may affect stakeholder engagement and funding.

Despite these challenges, intermediate pyrolysis is well-aligned with current policy and market trends. The rising demand for renewable energy and sustainable products (O1) and the push for waste valorisation (O2) create fertile ground for deployment (Tinwala et al., 2015). Catalytic innovations (O3) and advanced reactor designs such as microwave-assisted pyrolysis (O4) offer pathways to improve efficiency and product quality. Its suitability for integrated biorefineries (O5) allows for co-processing with fermentation, gasification, or anaerobic digestion—maximizing resource utilization and policy alignment under frameworks like EU RED III (O6) (Dada et al., 2021, Cai et al., 2024, Choudhary et al., 2025, Kaiqi Shi et al., 2011, Buelvas et al., 2024, Qiu et al., 2024).

Externally, intermediate pyrolysis must navigate competition from more mature technologies (T1) and biomass supply chain uncertainties (T2) (Afraz et al., 2024, Foong et al., 2020, Narayana Sarma and Vinu, 2023). The lack of standardized policies for its mixed outputs (T3) can hinder investment and regulatory approval, while environmental compliance in multi-output systems (T6) requires robust monitoring and adaptive design (Makepa et al., 2023). High deployment costs (T5) remain a barrier, especially in regions with limited financial incentives or infrastructure (Akinpelu et al., 2023).

C FAST PYIROLYSIS

The SWOT Matrix for fast pyrolysis is presented in Table 21.

A detailed SWOT analysis reveals its strategic position within the bioenergy sector.

The paramount strength of fast pyrolysis lies in its high efficiency in producing bio-oil, with yields often reaching up to 75% on a dry biomass basis (S1) (Reza et al., 2023). This biooil, can serve as a renewable liquid fuel or as a feedstock to produce various chemicals, significantly reducing reliance on fossil fuels (S2) (Cai et al., 2024, Wang et al., 2022). The process benefits from rapid heating and short residence times, which minimize secondary reactions and maximize liquid output (S3) (Tozlu Alperen et al., 2024).

Its versatile feedstock adaptability—including agricultural residues, woody biomass, and municipal biowaste (S4)—supports waste valorisation and circular economy principles (S5) (Tozlu Alperen et al., 2024, Choudhary et al., 2025). The high energy density of bio-oil facilitates economical storage and transport (S6), while co-produced syngas and biochar enhance energy efficiency and environmental value (S7) (Hornung et al., 2022, Dada et al., 2021). With a Technology Readiness Level (TRL) of 6–8, fast pyrolysis has reached commercial-scale demonstrations, offering a relatively mature platform for deployment (S8) (Alperen Tozlu et al., 2024).

Table 21 SWOT Matrix for Fast Pyrolysis

	FAST PYROLYSIS	
	Success Factors	Failure Factors
INTERNAL	STRENGTHS (S1) High bio-oil yield (up to 75% dry biomass basis) (S2) Bio-oil usable as renewable fuel or chemical feedstock (S3) Rapid heating and short residence times minimize secondary reactions (S4) Versatile feedstock adaptability (agricultural, woody, municipal biowaste) (S5) Waste valorisation and alignment with circular economy principles (S6) High energy density of bio-oil enables economical storage and transport (S7) Co-produced syngas and biochar enhance energy and environmental value (S8) TRL 6–8; several commercial-scale demonstrations exist	WEAKNESSES (W1) Poor raw bio-oil quality: high oxygen content, viscosity, corrosiveness, instability (W2) Upgrading processes are costly and technically demanding. (W3) Stringent feedstock requirements: low moisture, small particle size (W4) Extensive pre-treatment increases energy use and operational costs (W5) Complex reactor design and precise control hinder scale-up (W6) Biomass variability affects bio-oil quality and yield (W7) Public perception of bio-oil is underdeveloped compared to biodiesel or ethanol
EXTERNAL	OPPORTUNITIES (O1) Global push for decarbonizing transport and chemicals (O2) Catalytic pyrolysis innovations improve bio-oil quality (O3) Integration into biorefineries expands product diversity (O4) Regulatory incentives for advanced biofuels under EU RED III.	TREATS (T1) Competition from other biomass conversion technologies (e.g., gasification, intermediate pyrolysis) (T2) Biomass feedstock cost and supply chain instability (T3) Regulatory uncertainty around bio-oil classification and emissions (T4) High capital expenditure for reactors and upgrading units (T5) Emissions (e.g., VOCs) require strict monitoring and mitigation. (T6) TRL gaps in catalytic variants may slow adoption.

However, several technical and perceptual challenges remain. The raw bio-oil typically exhibits high oxygen content, corrosiveness, and instability (W1), requiring costly and technically demanding upgrading processes (W2) (Tozlu Alperen et al., 2024). The process demands stringent feedstock specifications—low moisture and fine particle size (W3)—which necessitate extensive pre-treatment, increasing energy use and operational costs (W4) (Tozlu Alperen et al., 2024). Complex reactor designs and the need for precise control hinder scalability (W5), while biomass variability affects product consistency (W6). Public perception of bio-oil remains underdeveloped compared to more familiar biofuels like biodiesel or ethanol (W7), which may limit market acceptance.

Despite these weaknesses, fast pyrolysis is well-positioned to capitalize on emerging technological and policy opportunities (Bridgewater, 2004, Bridgewater, 2012, Gerdes et al., 2001). Catalytic pyrolysis innovations (O2) offer promising routes to improve bio-oil quality and reduce upgrading burdens (Choudhary et al., 2025, Wang et al., 2022). Integration into biorefineries (O3) enables co-processing with other conversion technologies, expanding product diversity and improving economic viability (Buelvas et al., 2024, Hornung et al., 2022). Regulatory frameworks such as EU RED III (O4) increasingly support advanced biofuels, offering incentives and market access for pyrolysis-derived products.

Externally, fast pyrolysis faces competition from other biomass conversion technologies, including gasification and intermediate pyrolysis (T1). Biomass feedstock costs and supply chain instability (T2) pose operational risks, while regulatory uncertainty around bio-oil classification and emissions (T3) may hinder investment and deployment. The capital intensity of reactor systems and upgrading infrastructure (T4) remains a barrier, particularly in emerging markets. Emissions of volatile organic compounds (VOCs) require strict monitoring and mitigation (T5), and TRL gaps in catalytic variants may slow adoption despite promising lab-scale results (T6).

D FLASH PYIROLYSIS

The SWOT Matrix for flash pyrolysis is presented in Table 22.

A comprehensive SWOT analysis highlights its unique position and challenges in the bioenergy landscape.

Flash pyrolysis represents the frontier of rapid biomass conversion, distinguished by its ultra-fast reaction times and high throughput (S1). Within seconds, it can generate high yields of bio-oil (S2), making it a compelling option for distributed energy systems and mobile applications (Akinpelu et al., 2023). Its compact, modular reactor design (S3) enables decentralized deployment (S4), particularly in settings where conventional infrastructure is limited or impractical. The process accommodates a wide range of feedstocks (S5) and produces syngas as a co-product, which can be used to offset internal energy demands (S6). These attributes make flash pyrolysis a strong fit for on-site waste-to-energy solutions (S7) and circular economy models (O6).

Despite its promise, flash pyrolysis faces several technical and developmental challenges. The raw bio-oil produced is typically of low quality, with high oxygen content, corrosiveness, and instability (W1), necessitating costly upgrading processes (W2) that increase complexity and reduce economic viability. The process requires intensive feedstock pre-treatment—drying and grinding—which adds to operational burdens (W3). Its reactor systems are highly sensitive, demanding precise control over temperature and residence time (W4), and biomass variability can lead to inconsistent product quality (W5) (Choudhary et al., 2025, Alperen Tozlu et al., 2024). With a Technology Readiness Level (TRL) of 4–6, flash pyrolysis remains in early-stage development (W6) and suffers from low public awareness and limited policy recognition (W7), which may hinder adoption.

Table 22 SWOT Matrix for Flash Pyrolysis

FLASH PYROLYSIS		
	Success Factors	**Failure Factors**
INTERNAL	STRENGTHS (S1) Ultra-fast conversion and high throughput. (S2) High bio-oil yield in seconds. (S3) Compact, modular reactor design. (S4) Potential for decentralized and mobile deployment. (S5) Versatile feedstock processing. (S6) Co-produced syngas improves energy efficiency. (S7) Strong fit for on-site waste-to-energy applications	WEAKNESSES (W1) Poor raw bio-oil quality: high oxygen content, viscosity, corrosiveness, instability (W2) Costly upgrading processes increase complexity and reduce economic viability (W3) Intensive feedstock pre-treatment (drying, grinding) (W4) Reactor sensitivity and complexity hinder scale-up (W5) Biomass variability affects biooil consistency and process control (W6) TRL 4–6; still in early-stage development. (W7) Low public awareness and limited policy recognition.
EXTERNAL	OPPORTUNITIES (O1) Demand for decentralized waste-to-energy solutions (O2) Advances in microreactor and modular pyrolysis systems. (O3) Integration into biorefineries expands product diversity (O4) Emerging catalyst technologies to improve bio-oil quality. (O6) Growing interest in circular economy and local energy autonomy (O7) Potential inclusion in future regulatory frameworks for distributed bioenergy.	TREATS (T1) Competition from other biomass conversion technologies (e.g., gasification, fast pyrolysis) (T2) Regulatory gaps and lack of standards for flash pyrolysis bio-oil (T3) Feedstock variability and scalability challenges (T4) High capital costs for precision reactor systems (T5) Potential emissions require monitoring and mitigation (T6) TRL limitations may deter investors and delay commercialization. (T7) Public scepticism toward emerging thermal technologies

Nonetheless, the technology is well-aligned with emerging market and policy opportunities. The demand for decentralized waste-to-energy solutions is growing rapidly (O1), especially in urban and remote contexts. Advances in microreactor and modular pyrolysis systems (O2) offer pathways to improve scalability and reduce capital intensity. Integration into biorefineries (O3) can diversify product streams and share infrastructure, while emerging catalyst technologies (O4) promise to enhance bio-oil quality and reduce upgrading costs (Choudhary et al., 2025, Cai et al., 2024). The broader momentum toward local energy autonomy and circular economy principles (O6) further supports flash pyrolysis as a flexible, site-adaptable solution. Its potential inclusion in future regulatory frameworks for distributed bioenergy (O7) could unlock incentives and accelerate commercialization (Makepa et al., 2023).

Externally, flash pyrolysis must navigate competition from more mature technologies such as fast pyrolysis and gasification (T1) and contend with regulatory gaps in bio-oil classification and emissions standards (T2) (Buelvas et al., 2024). Feedstock variability and scalability challenges (T3) remain significant, especially in heterogeneous waste streams. The high capital costs of precision reactor systems (T4) and the need for continuous emissions monitoring (T5) add further complexity (Makepa et al., 2023). TRL limitations may deter investors and slow market entry (T6), while public scepticism toward emerging thermal technologies (T7) underscores the need for transparent communication and demonstrable environmental benefits.

The pyrolysis spectrum offers a diverse set of technologies for biomass conversion, each with distinct strengths, limitations, and strategic fit. Understanding their comparative profiles is essential for aligning deployment choices with environmental goals, policy frameworks, and market dynamics.

Slow pyrolysis is the most mature and biochar-focused pathway, operating at low temperatures and long residence times. Its primary strength lies in producing high yields of stable biochar, which is increasingly valued for soil amendment and long-term carbon sequestration. With a Technology Readiness Level (TRL) of 7–9, it is well-suited for agricultural and carbon-negative applications. However, its low throughput, energy-intensive drying requirements, and emissions challenges limit scalability. Public awareness remains modest, though certification schemes and climate policies are beginning to recognize its value. Slow pyrolysis thrives where soil health, carbon markets, and circular agriculture intersect.

Intermediate pyrolysis offers a balanced output of bio-oil, biochar, and syngas, making it a flexible option for integrated biorefineries. Its moderate residence times and feedstock tolerance support waste valorisation, while catalytic and microwave-assisted innovations promise improved efficiency. With a TRL of 5–7, it is emerging from pilot-scale development but faces challenges in product consistency, reactor sensitivity, and public visibility. Policy support is still evolving, and environmental compliance in mixed-output systems requires careful design. Intermediate pyrolysis is best positioned where multi-product flexibility and hybrid integration are strategic priorities.

Fast pyrolysis is the most commercially advanced liquid-fuel pathway, delivering high bio-oil yields in seconds. It benefits from rapid conversion, versatile feedstock processing, and several commercial-scale demonstrations (TRL 6–8). Its bio-oil can serve as a renewable fuel or chemical feedstock, though its poor raw quality necessitates costly upgrading. Reactor complexity and feedstock pre-treatment add operational burdens, and public perception of bio-oil remains underdeveloped. Nonetheless, fast pyrolysis aligns well with decarbonization goals, advanced biofuel incentives, and biorefinery models—especially when catalytic innovations and digital optimization are applied.

Flash pyrolysis represents the cutting edge of modular, high-speed conversion. With ultra-fast reaction times and compact reactor designs, it is ideal for decentralized and mobile deployment. It accommodates diverse feedstocks and produces syngas for internal energy use, making it attractive for on-site waste-to-energy systems. However, its TRL remains low (4–6), and it faces significant hurdles in bio-oil quality, reactor sensitivity, and public/policy recognition. Advances in microreactor systems, catalyst development, and CFD-based optimization could unlock its potential, especially in urban, remote, or circular economy contexts.

In summary, each pyrolysis type offers a distinct strategic value:

1. Slow pyrolysis excels in biochar and carbon sequestration.
2. Intermediate pyrolysis offers flexibility and integration potential.
3. Fast pyrolysis leads in bio-oil yield and commercial readiness.
4. Flash pyrolysis promises agility and modularity for decentralized systems.

Selecting the optimal pathway depends on feedstock availability, desired outputs, infrastructure readiness, and alignment with regulatory and climate objectives. Together, these technologies form a complementary toolkit for advancing the bioeconomy.

4.2.4. Torrefaction Technologies

Author: Marta Trninić

Torrefaction is a thermal pre-treatment technique applied to biomass at moderate temperatures, typically between 200 and 300 °C, in an oxygen-deprived or inert environment. It aims to improve the fuel properties of raw biomass, making it more suitable for energy applications such as co-firing, gasification, and industrial heating. The process enhances energy density, reduces moisture content, and transforms biomass into a hydrophobic as bio-char. Despite its technical advantages, torrefaction faces several commercialization hurdles.

The SWOT matrix presented in Table 23 synthesizes these insights to provide a strategic snapshot of torrefaction’s current position in the bioenergy landscape.

Table 23 SWOT Matrix for Torrefaction

TOREFFACTION		
	Success Factors	**Failure Factors**
INTERNAL	STRENGTHS (S1) Enhanced fuel properties: increased calorific value (21–23 MJ/kg), reduced moisture, and hydrophobic behavior improve combustion and storage (S2) Improved grindability: up to 95% reduction in milling energy; particle shape becomes coal-like, aiding pneumatic feeding (S3) Compatibility with coal-fired power plants: torrefied biomass can be co-fired with minimal retrofitting (S4) Reduced biological degradation: longer shelf life and lower risk of microbial spoilage during storage	WEAKNESSES (W1) High capital and operational costs due to complex reactor design and process control requirements (W2) Inconsistent product quality due to feedstock variability and process sensitivity (W3) Pelletization challenges: higher energy demand and need for binders to achieve durable pellets (W4) Limited commercial deployment: most technologies remain at pilot or demonstration scale
EXTERNAL	OPPORTUNITIES (O1) EU Green Deal, Fit for 55, and REPowerEU promote biomass as part of the renewable energy mix, supporting torrefaction adoption Rising demand for low-carbon fuels and climate-neutral energy solutions supports torrefaction adoption (O2) Integration with other processes (e.g., pyrolysis, gasification, ironmaking) enhances economic and energy efficiency (O3) Development of ISO standards and safety certifications enables global trade of torrefied biomass (O4) Valorisation of waste biomass supports circular bioeconomy and reduces greenhouse gas emissions (O5) The growing public support for renewables creates momentum for policy, investment, and innovation — including torrefaction as a cleaner, coal-replacing biofuel.	TREATS (T1) Dust explosion risks: torrefied biomass dust is classified as St-1 (moderately explosive), requiring strict safety measures (T2) Regulatory uncertainty: lack of clear classification under REACH and IMO hinders international transport (T3) Feedstock variability: seasonal and geographic differences affect process efficiency and product consistency (T4) Skepticism toward biomass fuels — especially regarding land-use change, deforestation, and biodiversity loss — can lead to public resistance, stricter regulations, or exclusion from green energy incentives

Torrefaction offers several notable strengths that position it as a promising biomass upgrading technology. First, it significantly enhances fuel properties (S1), increasing the calorific value of biomass to 21–23 MJ/kg while reducing moisture and improving hydrophobicity — all of which contribute to better combustion performance and storage stability (Chen et al., 2021, Marcel Cremers et al., 2015). The process also improves grindability (S2), as the breakdown of hemicellulose makes the material brittle and easier to mill, reducing energy consumption by up to 95% and producing coal-like particles suitable for pneumatic feeding systems (Marcel Cremers et al., 2015). Importantly, torrefied biomass is compatible with existing coal-fired power plants (S3), allowing for co-firing with minimal infrastructure modifications. Additionally, its reduced biological degradation (S4) means longer shelf life and lower risk of microbial spoilage during transport and storage (Chen et al., 2021).

However, torrefaction faces several weaknesses that hinder its broader adoption. The technology requires precise temperature control and robust reactor design, resulting in high capital and operational costs (W1) (Chen et al., 2021). Product consistency is another challenge (W2), as variations in feedstock moisture and composition can lead to uneven torrefaction outcomes (Marcel Cremers et al., 2015). Pelletization is particularly demanding (W3), with torrefied biomass requiring more energy and often binders to form durable pellets (Marcel Cremers et al., 2015). Moreover, commercial deployment remains limited (W4), with most systems still operating at pilot or demonstration scale and struggling to attract large-scale investment (Chen et al., 2021).

Despite these challenges, torrefaction is well-aligned with emerging opportunities. EU climate policy frameworks — including the Green Deal, Fit for 55, and REPowerEU — actively promote biomass as part of the renewable energy mix (O1), offering regulatory and financial support for torrefaction technologies (Chen et al., 2021).The process can also be integrated with other thermochemical systems such as pyrolysis, gasification, and ironmaking (O2), enhancing energy efficiency and economic viability (Chen et al., 2021). Ongoing development of ISO standards and safety certifications (O3) will facilitate international trade and improve market confidence 【 (Marcel Cremers et al., 2015). Torrefaction also enables the valorisation of agricultural and forestry residues (O4), supporting circular bioeconomy goals and reducing greenhouse gas emissions (Chen et al., 2021). Furthermore, growing public support for renewable energy (O5) creates momentum for torrefaction, especially when positioned as a sustainable, coal-replacing solution — though this requires transparent sourcing and sustainability assurance (Chen et al., 2021).

On the threat side, safety risks must be carefully managed. Torrefied biomass dust is classified as St-1 (moderately explosive), posing hazards during handling and storage (T1) (Marcel Cremers et al., 2015). Regulatory ambiguity (T2), particularly regarding REACH and IMO classifications, complicates logistics and may delay market entry (Marcel Cremers et al., 2015).. Feedstock variability (T3) — due to seasonal and geographic differences — can affect process control and product consistency (Chen et al., 2021).Lastly, public skepticism toward biomass fuels (T4), especially concerning land-use change and biodiversity impacts, may lead to stricter regulations or reduced support unless sustainability is clearly demonstrated (Chen et al., 2021).

Torrefaction holds significant potential as a bridge technology in the global shift toward low-carbon energy systems. Its ability to upgrade biomass into a stable, energy-dense fuel aligns well with industrial needs and climate goals. However, realizing this potential requires targeted investment in reactor design, feedstock flexibility, safety protocols, and regulatory frameworks.

To move forward, stakeholders must focus on:

1. Demonstrating consistent product quality at commercial scale
2. Establishing clear international standards for transport and trade
3. Leveraging torrefaction within integrated bioenergy systems

With coordinated effort across research, policy, and industry, torrefaction can evolve from a promising concept into a robust pillar of sustainable energy infrastructure.

4.3. Physicochemical Conversion

Author: Marta Trninić

As it is described in Deliverable D2.3 (Alperen Tozlu et al., 2024), physicochemical conversion technologies represent a core set of processes within waste biorefinery systems, enabling the transformation of biomass and organic waste into energy carriers and high-value compounds through mechanical, chemical, and thermal means (Alperen Tozlu et al., 2024). These technologies—including mechanical processing, extraction, transesterification, supercritical methods, and hydrolysis—play complementary roles in unlocking the resource potential of waste streams (Alperen Tozlu et al., 2024). Their relevance spans multiple disciplines, from bioenergy and chemical engineering to environmental science and industrial biotechnology.

In light of growing global efforts to advance circular bioeconomy models and meet sustainability targets, physicochemical conversion technologies offer both strategic advantages and implementation challenges. A structured SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis provides a critical framework to assess their technical capabilities, economic feasibility, and alignment with policy and market drivers. This analysis supports academic inquiry, informs decision-making, and guides future research and innovation in sustainable waste valorisation.

4.3.2. Transesterification Process

Authors: Kenan Dalkılıç

The transesterification process (TP) is the physicochemical conversion of the triglycerides (fats and oils) and alcohol (ethanol, methanol) mixtures into fatty acid methyl esters (FAME) via a catalyst under certain conditions (Asfaw et al., 2025, Naseef et al., 2025). The resultant product is called biodiesel, which shows similar physicochemical properties to the fossil fuel-based diesel (Oyekunle et al., 2023). Biodiesel offers numerous benefits such as high combustion efficiency (high cetane number), high flash point (> 130 ^{o}C) which makes it safe for storage and vehicle transportation, excellent lubricity, low net emissions, and low viscosity (Naseef et al., 2025, Oyekunle et al., 2023). Biodiesel can be produced from edible crop plants, namely palm, soybean, corn, sunflower, and rapeseed, and non-edible oils such as jatropha curcas, pongamia pinnata, jojoba, castor, tobacco, sea mango, candle nut, rubber, mahua, cotton, and so on. When using these oils and animal fats to produce biodiesel, the transesterification process is applied with different catalysts.

Other technologies, such as emulsification, pyrolysis, supercritical fluid extraction, and hydrothermal liquefaction, can be applied to generate biodiesel from various feedstocks and materials (Naseef et al., 2025, Rajak et al., 2025). Compared to other techniques, the transesterification process has its own strengths, weaknesses, opportunities, and threats (SWOT) derived from the characteristics of the process and other external factors. The SWOT analysis of the transesterification process is summarized in the table below, with operational parameters and important features.

Table 24 SWOT Matrix for Transesterification

Transesterification		
	Success Factors	**Failure Factors**
Internal	STRENGTHS (S1) The transesterification process (TP) can be used for biodiesel production, which can replace fossil fuel-derived diesel production, and it can support the climate change goals (Asfaw et al., 2025, Amani et al., 2022) (S2) The feedstocks used for biodiesel production are easily accessible all around the world at any time (Akram et al, 2022) (S3) Waste cooking oils and animal fats can be used as a feedstock for biodiesel production in the TP, serving for waste management and valorisation (Akram et al, 2022) (S4) Algal biomass is a good alternative for biodiesel production by TP (Akram et al, 2022, Aamir et al., 2022) (S5) Low energy requirements. Relatively lower temperatures (30-80oC) are needed for the reactions (alkali, acidic, and enzymatic catalysis) (Naseef et al., 2025) (S6) Biodiesel, is promoted and encouraged by several countries with the regulations and policies (Aamir et al., 2022) (S7) Using 3rd generation feedstocks (WCO and animal fats) doesn't compete with edible feedstocks and doesn't require agricultural land (Akram et al, 2022, Aamir et al., 2022)	WEAKNESSES (W1) High cost of biodiesel production by TP compared to petroleum-based diesel production (Amani et al., 2022, Aamir et al., 2022) (W2) Scarcity and price increase for edible feedstocks used in TP (Aamir et al., 2022, Ambat et al., 2018) (W3) Dependent on the feedstocks, which cost 70-80 % of the overall production process (Ambat et al., 2018) (W4) Lower biodiesel performance and higher requirement of alcohol when applying plant seeds as the oil source (2nd generation) (Aamir et al., 2022) (W5) Soap formation and free fatty acids usually affect the process performance (Aamir et al., 2022, Devarajan et al., 2022) (W6) A pretreatment is needed before using waste cooking oils and animal fats for biodiesel production (Akram et al., 2022) (W7) Using algal biomass for biodiesel production requires extra processes such as drying and extracting, which in turn increases the production costs (Aamir et al., 2022) (W8) 95 % of worldwide biodiesel production is achieved by utilizing edible vegetable oils (Akram et al., 2022)

	(S8) Heterogeneous catalysis: higher catalytic performance, environmental acceptability, and easy recyclability (Ambat et al., 2018) (S9) The downstream process is simpler and cheaper compared to homogeneous catalysts (Naseef et al., 2025) (S10) Very fast reaction at mild conditions and less energy-intensive in the case of a base-catalyzed process (Akram et al., 2022) (S11) Easy separation of catalysts and reuse (Akram et al, 2022) (S12) Catalysts such as CaO, NaOH and KOH are relatively cheap and widely available (Akram et al, 2022) (S13) Supercritical alcohol transesterification is an alternative method to the catalytic processes, and it is simple and efficient (Yu et al., 2025) (S14) Many flow regimes (batch, semi-batch, semi-continuous) and reactor types are available according to feedstock and feeding rate.	(W9) Disturbance of the process occurs when a high number of free acids is present in the feedstock (Kant et al., 2021, Devarajan et al., 2022) (W10) Difficulty in the recovery of catalysts, downstream treatment requirements, and their high cost in homogeneous catalytic TP (Naseef et al., 2025) (W11) Low stability and high price of heterogeneous catalysts (Naseef et al., 2025, 9]. (W12) Supercritical alcohol transesterification requires high pressure (40-70 MPa) and temperature (300-400 oC), resulting in a high cost of energy input (Aamir et al., 2022) (W13) Slow reaction when using enzymes and the acid catalysts (Amani et al., 2022) (W14) High cost of production due to high pressure and temperature when heterogeneous and enzyme catalysts are used (Kalita et al., 2022)
External	**OPPORTUNITIES** (O1) Transesterification is the most applied method for biodiesel due to the required characteristics of the product. The technology and the feedstock alternatives can be improved to increase the application of TP (Amani et al., 2022) (O2) Efficient reactor designs (Tabatabaei et al., 2019) (O3) The potential to decrease the cost of catalysts and find new catalysts (O4) Biomass-derived heterogeneous catalysts are cheap, sustainable, eco-friendly, non-toxic, efficient, and can be applied instead of conventional catalysts (Naseef et al., 2025) (O5) Enzymes such as lipase or microbial cell enzymes can be used as biocatalysts instead of homogeneous and heterogeneous catalysts (Nayab et al., 2022) (O6) The enzymes can be regenerated to be used more than once. No need for recovery of biocatalysts due to cost-intensive production (Nayab et al., 2022) (O7) Funding opportunities for renewable energy and waste to sustainable technologies are available due to the renewable energy policies (Kant et al., 2021) (O8) New technologies regarding the production of alcohol from renewable sources. (O9) The lower blend rate that is being used presently (3-5%) can be increased, and this serves the climate change actions (Kant et al., 2021)	**TREATS** (T1) The possibility of an increase in the production cost of alcohol due to the depletion of fossil fuels (natural gas) and the catalysts used in biodiesel production (Tabatabaei et al., 2019) (T2) Developments on the biodiesel production of other technologies (pyrolysis, emulsification, and hydrothermal liquefaction) have the potential to replace the TP. (T3) Possible impacts of oil feedstock production on tropical forests and biodiversity and threat to food security and prices (Tabatabaei et al., 2019) (T4) Net GHGs from direct or indirect land-use (Tabatabaei et al., 2019) (T5) Water consumption in the process and the downstream process in the case of water scarcity (Tabatabaei et al., 2019)

5. COMPARATIVE SWOT ANALYSIS

Author: Marta Trninić

This section presents a comprehensive comparative assessment of the biomass waste biorefinery technologies analysed in previous chapters, focusing on their strategic positioning across multiple key dimensions—technical, environmental, economic, regulatory, and social. By integrating and synthesizing the individual SWOT analyses for each technology, overarching cross-cutting strengths and weaknesses that extend beyond individual process boundaries are identified.

Unique selling points (USPs), based on SWOT analysis, are emphasized, highlighting differentiation in operational efficiency, scalability, product specificity, and adaptability to diverse feedstocks. At the same time, critical risks and challenges are evaluated, including technical barriers, capital intensity, environmental impacts, and regulatory uncertainties that may limit deployment and wider adoption.

By systematically mapping these factors, the analysis supports strategic prioritization of technologies with the greatest potential impact and alignment with sustainability objectives. Furthermore, it provides a foundation for developing a coherent roadmap (D2.5) that leverages the complementary strengths of biochemical, thermochemical, and physicochemical pathways to foster a resilient and future-ready biorefinery sector.

5.1. Cross-Cutting Strengths and Weaknesses

Author: Marta Trninić

The following synthesis highlights recurring strengths and weaknesses observed across multiple biorefinery technologies. These cross-cutting factors represent **systemic opportunities and challenges that critically influence the overall feasibility and scalability of sustainable bio-based solutions.** To support integrated decision-making and alignment with policy objectives, the analysis is organized along five key dimensions: technical, environmental, economic, regulatory, and social.

The key strengths and weaknesses of different biorefinery technologies, organized by dimension, are summarized in Tables 25-27. Table 25 presents the cross-cutting strengths and weaknesses for biorefinery technologies in general.

Table 25 Cross-cutting strengths and weaknesses for Biochemical Technologies (Authors: İlgi Karapinar, Umar Muazu Yunusa)

Dimension	Strengths	Weaknesses
Technical	Ability to utilize diverse renewable feedstocks; mild operating conditions; potential for integration with other processes (e.g., dark + photofermentation).	Low yields and productivity; process sensitivity to pH, temperature, and oxygen; scale-up challenges such as mass transfer and light/heat distribution.
Environmental	Lower carbon footprint; waste valorization; co-production of useful by-products reduces environmental burden	Feedstock variability affecting process performance; potential generation of wastewater or by-products that require treatment.
Economic	Co-product generation can enhance profitability; potential for decentralized energy production; use of low-cost or waste substrates reduces input costs.	High capital and operational costs for bioreactors, pretreatment, and downstream purification; economic feasibility sensitive to market prices of biofuels
Regulatory	Alignment with renewable energy and carbon reduction policies; potential eligibility for government incentives or green funding	Regulatory uncertainty in emerging biofuels markets; lack of standardized guidelines for new biochemical processes.
Social	Supports local energy production and energy security; promotes sustainable practices and circular economy; job creation in rural or industrial areas	Low public and stakeholder awareness of biochemical fuels; acceptance may be limited by unfamiliarity or perceived risks

Table 26 Cross-cutting strengths and weaknesses for Thermochemical Technologies

Dimension	Strengths	Weaknesses
Technical	High feedstock flexibility including diverse biomass waste, scalable for large volumes.	Requires robust handling of heterogeneous waste streams, high temperature/pressure demands, potential catalyst deactivation due to contaminants.
Environmental	Converts various biomass wastes into syngas, bio-oil, and char, promoting waste valorisation.	Potential emissions (tar, particulates), management of ash and other residues, energy intensive.
Economic	Suitable for large-scale waste valorisation, potential for co-generation and multiple products.	Significant capital expenditure, feedstock variability impacts process stability and costs.
Regulatory	Alignment with renewable energy and waste reduction targets, incentives for waste-based fuels.	Emission limits and permitting complexity can delay deployment.
Social	Supports waste management infrastructure, creates employment in waste handling and energy sectors.	Community concerns related to air quality and safety, requires ongoing stakeholder engagement.

Table 27 Cross-cutting strengths and weaknesses for biorefineries technologies

Dimension	Common Strengths	Common Weaknesses
Technical	Robust and scalable processes, high product specificity, flexibility in feedstock utilization.	Limited scalability, sensitivity to feedstock variability, complex feedstock pretreatment.
Environmental	Potential for GHG reduction, efficient waste valorisation, alignment with circular economy goals.	Uncertain LCA outcomes, emission control challenges, variable energy demands.

Economic	Efficient use of feedstocks, valorisation of low-cost residues; potential for rural development	High CAPEX/OPEX, operational complexity, low market competitiveness vs. fossil alternatives
Regulatory	Supportive EU frameworks (RED III, Fit for 55), increasing regulatory support for bio-based solutions.	Fragmented standards, regulatory uncertainties; prolonged approval timelines; costs of compliance and certification.
Social/Stakeholder	Positive public perception, job creation potential, rural development, fosters stakeholder engagement and social acceptance.	Limited public awareness, potential resistance to new technologies, need for skilled workforce.

6. LINK TO ROADMAP DEVELOPMENT (D2.5)

The stakeholder-driven SWOT analysis presented in this report provides the foundation for the strategic planning activities in D2.5. The identified strengths, weaknesses, opportunities, and threats will be systematically translated into actionable strategies using the TOWS framework. In parallel, the D2.5 roadmap will incorporate a dedicated GAP analysis to identify regulatory, technological, and awareness-related barriers to large-scale deployment.

By linking the evidence-based insights from D2.4 with the targeted measures in D2.5, the WIRE COST Action will ensure that proposed actions are grounded in stakeholder realities and strategically aligned with EU policy objectives—ultimately supporting the sustainable and competitive integration of these technologies into advanced biorefineries.

CONCLUSION

This report has brought together the perspectives of researchers, technology providers, and policy stakeholders to assess the strengths and weaknesses of key biomass conversion technologies. Through a structured SWOT analysis, it highlights not only the technical and operational characteristics of each pathway, but also the broader conditions shaping their deployment—regulatory frameworks, market dynamics, and societal expectations.

The findings confirm that while many technologies are mature and well-understood, their integration into biorefineries is often hindered by fragmented data, uneven policy support, and limited coordination across sectors. At the same time, opportunities are emerging—from EU climate targets and circular economy strategies to growing interest in bio-based products and carbon-negative solutions.

By capturing these insights, the report lays the groundwork for the strategic roadmap developed in D2.5. It ensures that future actions—whether in research, investment, or regulation—are informed by real-world experience and aligned with stakeholder needs. Above all, it reinforces the importance of collaboration, transparency, and shared learning in advancing Europe’s renewable carbon transition.

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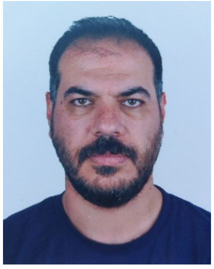

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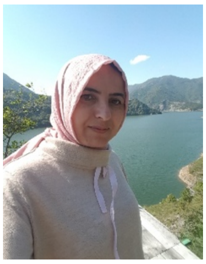

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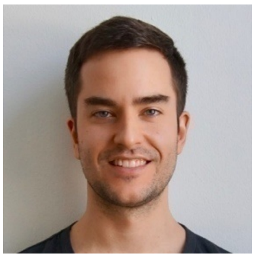

Short Biography: Dr. Jaime Moreno García has published over 50 articles in international journals (JCR) on Microbiology, Food Science, and Biofuels, along with 90 contributions to scientific congresses. He has participated in numerous funded research projects and received prestigious fellowships (FPU, Fulbright), as well as five awards for research and entrepreneurship, including the Extraordinary Doctoral Thesis Award 2017/2018 from the University of Córdoba. He has conducted research at leading institutions like UNIS (Norway), UC Davis (USA), Sassari (Italy), and Umeå (Sweden). Currently, he is an Associate Professor at the University of Córdoba, a Fulbright-Spain Commission evaluator, and Associate Editor of Microbial Cell Factories.

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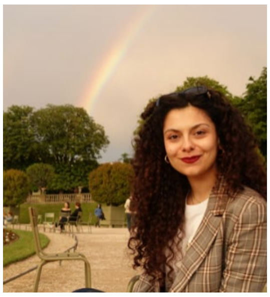

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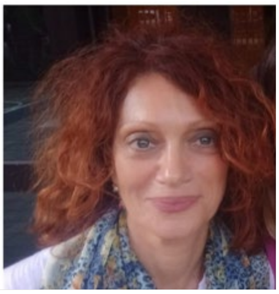

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ANNEXES

1. Stakeholder Questionnaire

Waste biorefinery technologies for accelerating sustainable energy processes

BIOREFINERY TECHNOLOGY STAKEHOLDER QUESTIONNAIRE

For Industrial technology providers and Research and Technology Organizations (RTOs)

Purpose of the Questionnaire

This anonymous questionnaire is designed to support the strategic analysis of conversion technologies within the scope of **WIRE COST ACTION CA 20127**. The collected responses will be used exclusively for conducting **SWOT and TOWS analyses**, which will inform the development of a **roadmap for sustainable technology deployment**.

NOTE: Please complete one questionnaire per biomass conversion technology. This ensures clarity and consistency in the analysis.

The questionnaire consists of **five thematic sections**, aimed at capturing insights from both **industrial technology providers** and **research and technology organizations (RTOs)**: Stakeholder Profile, Technology-Specific Assessment, Strategic Alignment & Outlook, Gap Analysis – Importance vs. Satisfaction, Additional Comments.

Thank you for taking the time to complete this questionnaire.
Your insights are invaluable for shaping a shared vision of sustainable biorefinery technologies.

By contributing your experience and perspective, you are helping to build a roadmap that reflects real needs, fosters innovation, and strengthens collaboration between industry and research.

Section 1: Stakeholder Profile
1. Type of Stakeholder ☐ Industry ☐ Research Laboratory 2. Role in Biorefinery Value Chain ☐ Technology Developer ☐ Operator ☐ Researcher ☐ Other 3. Years of Experience in the Field ☐ Less than 5 years ☐ 5–10 years ☐ More than 10 years 4. Country/Region of Operation

Section 2: Technology Identification and Development Stag

For each technology you are familiar with (e.g., anaerobic digestion, pyrolysis, transesterification, gasification, hydrothermal liquefaction), please complete the following.

Please complete one questionnaire per biomass conversion technology. This ensures clarity and consistency in the analysis.

5. Which technology are you assessing?

☐ Combustion
☐ Gasification
☐ Pyrolysis
☐ Torrefaction
☐ Anaerobic digestion
☐ Fermentation
☐ Hydrothermal carbonization
☐ Electrochemical processes
☐ Physicochemical extraction
☐ Other:

NOTE: If you select gasification, pyrolysis, anaerobic digestion, or other conversion pathways, please specify the relevant subtype or configuration (e.g. downdraft gasification, fast pyrolysis, mesophilic digestion, supercritical CO_2 extraction etc).

6. What is the current Technology Readiness Level (TRL)?

☐ TRL 1 (Basic principles observed)	☐ TRL 4 (Technology Validated in Lab)	☐ TRL 7 (System Prototype Demonstrated)
☐ TRL 2 (Technology concept formulated)	☐ TRL 5 (Technology Validated in Relevant Environment)	☐ TRL 8 (System Completed and Qualified)
☐ TRL 3 (Experimental proof of concept)	☐ TRL 6 (Technology Demonstrated in Relevant Environment)	☐ TRL 9 (Actual System Proven)

7. What are the **key strengths** of these technologies in your view? (*e.g., efficiency, feedstock flexibility, low emissions, clean energy, modularity, integration with local systems*)

8. What are the **main weaknesses** or limitations of these technologies? (*e.g., feedstock quality issues, cost, scalability, regulatory barriers, technological immaturity*)

9. What are the **most critical technical challenges** that need to be addressed?

Section 3: Deployment and Implementation Challenges
10. What **emerging opportunities** could support wider deployment of biorefinery technologies? (*e.g., circular economy, market demand, innovation*)
11. Are there any policy or regulatory gaps that could limit or delay deployment?
12. What external threats, other than policy or regulatory issues, could hinder adoption or implementation? (e.g., public perception, competing technologies, market trends)
13. What kind of **support mechanisms** (funding, standards, partnerships) would accelerate adoption?

Section 4: Strategic Alignment & Future Outlook
14. What is the **potential for market uptake in the next 5–10 years**? ☐ High ☐ Medium ☐ Low 15. What are the **most promising application sectors for the products** obtained from these technologies? ☐ Transport

☐ Agriculture
☐ Chemicals
☐ Energy
☐ Other

16. Would you recommend this **technology for further investment and scaling**? Why or why not?

Section 5: Gap Analysis – Importance vs. Satisfaction

Please rate the following factors based on:

1. *Importance: How critical are these factors for successful deployment of biorefinery technologies?*

Satisfaction: Estimate the level of satisfaction regarding the current status, based on your personal understanding.

Likert Scale Definitions

Importance Scale:
1 = Not important
2 = Slightly important
3 = Moderately important
4 = Important
5 = Very important

Satisfaction Scale
1 = Very dissatisfied
2 = Dissatisfied
3 = Neutral
4 = Satisfied
5 = Very satisfied

Factor	Importance (1–5)	Satisfaction (1–5)	Suggested action for improvement (if satisfaction ≤2 or importance ≥4)
Availability of skilled workforce			
Access to sustainable feedstock			
Level of establishment of feedstock supply chains			

Supportive policy and regulation			
Technology maturity and reliability			
Funding and investment mechanisms			
Market demand and end-user acceptance			
Collaboration across value chain actors			
Availability of both physical facilities (pilot/demo/commercial plants) and enabling environment (regulatory, financial, and market support) necessary for scaling up biorefinery technologies.			
Public awareness and perception			

Section 6: Additional Comments
17. Please provide any additional insights, examples of best practices or challenges, case studies, or relevant data related to biorefinery implementation. 18. Interested in follow-up workshops? ☐ Yes ☐ No