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Thermochemical Process Development: From Mechanism to Scale-Up and Industrial Adoption

A Technical Framework for Sustainable Industrial Transformation

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Abstract

Sustainable industrial transformation is often presented through large system goals: hydrogen, circular economy, waste-to-X, electrification, carbon management, and net-zero manufacturing. In practice, these goals become industrially meaningful only when physical-chemical and thermochemical processes can operate reliably under variable feedstocks, strict emission limits, changing energy prices, product-quality requirements, safety constraints, and real plant integration conditions. This article argues that thermochemical knowledge remains a central enabling competence because it connects feedstock chemistry, reaction pathways, heat and mass transfer, reactor design, gas cleaning, emissions control, product specification, process integration, and scale-up evidence. The article covers combustion, pyrolysis, gasification, reforming, biochar production, syngas generation, hydrogen-related systems, waste valorization, and carbon-management pathways. It proposes a development logic built on problem definition, feedstock-envelope qualification, product-intent design, controlling-phenomena analysis, model-assisted uncertainty reduction, experimental validation, decision-quality piloting, and disciplined scale-up. The central message is that transformation technologies should not be judged by attractive labels or isolated laboratory effects, but by validated operating windows and complete flowsheet consequences. A process is industrially useful only when its benefit remains positive relative to a reference case after energy demand, emissions, separation burden, maintenance, reliability, uncertainty, product specification, and implementation constraints are considered.

Keywords: thermochemical conversion; process development; scale-up; waste-to-X; syngas; biochar; hydrogen; circular economy; industrial decarbonization; pilot validation; carbon management; industrial usefulness

1. Introduction: sustainability depends on process reliability

The transition toward sustainable industry is not a single technology substitution. It is a systems transformation in which energy supply, material flows, carbon management, process safety, product specifications, infrastructure, and economics must be made compatible. The International Energy Agency (IEA) describes clean energy technology markets as expanding rapidly but also subject to uncertainty in policy, trade, costs, and infrastructure. Its Energy Technology Perspectives 2026 notes that markets for clean energy technologies have grown strongly, while near-zero-emissions materials such as steel, cement, aluminium, and ammonia remain exposed to high cost premiums and policy dependence (IEA, 2026. This is an important signal for industrial R&D: scientific excellence alone is insufficient if the technology cannot survive the realities of scale, cost, regulation, and operation.

In practice, industrial decarbonization is not achieved by single technologies alone, but by robust process systems. Whether the objective is lower-carbon energy conversion, circular use of carbon-containing resources, waste valorization, fuel upgrading, or emissions reduction, the decisive challenge is often the same: translating a scientifically attractive concept into a stable, controllable, and scalable process. This requires attention to reaction pathways, transport phenomena, operating windows, feedstock variability, product quality, downstream treatment, and integration with existing industrial infrastructure. Without this process-level discipline, even technically promising solutions may remain difficult to operate, certify, finance, or scale.

The European policy direction reinforces this technical reality. The European Commission's Circular Economy Action Plan emphasizes waste prevention, product-life-cycle thinking, and keeping resources in the economy for as long as possible (European Commission, 2020). The Net-Zero Industry Act aims to accelerate EU manufacturing capacity for net-zero technologies, including hydrogen technologies, sustainable biogas and biomethane, storage technologies, and carbon capture-related technologies (European Commission, 2024a). Industrial carbon management, meanwhile, is explicitly framed around capturing, transporting, using, storing, and removing carbon dioxide from industrial and energy systems (European Commission, 2024b). These policy frameworks create demand for technologies, but they do not remove the engineering burden. The burden remains process development.

This work presents thermochemical process development as a bridge between scientific knowledge and industrial transformation. Its scope is international, with particular relevance to mature industrial regions where energy-intensive production, chemical processing, waste and water systems, transport infrastructure, and applied research capacities are closely interconnected. In such environments, hydrogen, circular economy, carbon management, and industrial decarbonization are not abstract policy themes; they become practical engineering challenges that require robust process understanding, scale-up discipline, and integration with existing industrial infrastructure.

The central thesis is simple: sustainable industrial transformation is decided at the interface between mechanism and scale. Mechanism explains why a process is scientifically plausible; scale determines whether it can operate repeatedly, safely, economically, and under non-ideal industrial conditions. Success at this interface depends on integrating fundamental process understanding with modeling, experimental validation, pilot-scale learning, operational robustness, environmental performance, and clear communication between research, engineering, and decision-making teams.

This paper is positioned as a technical framework article for thermochemical and physical-chemical process development. It combines established scientific principles, selected literature evidence, and industrial scale-up logic to define practical criteria for evaluating technology readiness, process usefulness, pilot validation, and sustainable industrial adoption.

2. Thermochemical platforms: more than energy conversion

Thermochemical processes are often described as energy-conversion routes, but this is too narrow. They can produce heat, power, syngas, hydrogen-containing gases, reducing gases, liquid intermediates, recovered carbon, biochar, activated-carbon precursors, mineral residues, destruction of hazardous organics, and chemical building blocks. The same reactor family may be useful for one product intent and unsuitable for another.

This distinction matters because product intent determines process design. A gasification system optimized for tar-minimized syngas is not the same process as a slow-pyrolysis system optimized for stable biochar, a fast-pyrolysis system optimized for liquid yield, or a reforming process optimized for hydrogen-rich gas. Temperature, heating rate, residence time, pressure, gas atmosphere, oxygen or steam addition, catalyst or sorbent selection, reactor hydrodynamics, solid handling, and downstream treatment all depend on the target product and its specification.

The technical literature supports this view. Reviews of biomass gasification show that feedstock type, operating parameters, tar formation and cracking, and modeling assumptions strongly influence gasification performance (Sikarwar et al., 2016). Fast-pyrolysis literature shows that product distribution and product upgrading requirements are inseparable from process design (Bridgwater, 2012). For municipal solid waste gasification, reactor type, process configuration, gas cleaning, environmental performance, and commercial readiness must be assessed together (Arena, 2012). Recent waste-conversion literature similarly treats pyrolysis, gasification, combustion, and related thermochemical routes as technology families whose usefulness depends on fuel characteristics, standards, emissions, and product pathways (Quan et al., 2026).

2.1 Feedstock variability is the first industrial reality

Laboratory work often begins with a representative sample. Industrial operation rarely has that luxury. Biomass, refuse-derived fuel, sewage sludge, mixed plastics, biogenic residues, oily waste, wastewater-derived solids, and industrial by-products differ in chemical composition and physical properties, including moisture, ash content, particle size, volatile matter, fixed carbon, chlorine, sulfur, nitrogen, alkali metals, heavy metals, and mineral phases. These differences influence heating behavior, devolatilization, gas composition, char reactivity, tar formation, slagging, fouling, corrosion, emission behavior, condensate or process-water formation, and product quality.

A serious development program should therefore treat feedstock variability as a design input rather than as a disturbance. The practical question is not whether one sample can be converted. The practical question is whether a defined feedstock envelope can be converted into acceptable products within safe, controllable, and economic limits. This requires feedstock characterization, controlled experiments, sensitivity analysis, impurity mapping, and model-supported identification of critical variables.

For biomass-to-biochar and heat systems, applied modeling work has shown how temperature, moisture, oxygen exposure, and residence time can shift biochar yield, gas formation, and conversion behavior. Such modeling is useful for process orientation and hypothesis generation, but it should be treated as an initial decision-support tool that requires experimental validation before being used as a design basis (Saylam, 2024a).

2.2 Product intent determines process architecture

Product quality is not an afterthought. It must be designed into the process. A sustainable process is not simply one that uses a renewable or residual feedstock. It is one that produces a defined, usable output with controlled environmental burden and credible life-cycle logic.

Biochar illustrates the point clearly. Surface area, porosity, pH, ash content, fixed carbon, volatile matter, contaminant content, H/C and O/C ratios, stability indicators, adsorption capacity, and application-specific performance may all matter. Studies of slow-pyrolysis biochar show that feedstock type, highest treatment temperature, and residence time influence final properties (Ronsse et al., 2013). Other work shows that pyrolysis temperature strongly affects biochar stability and carbonization indicators (Crombie et al., 2013; Keiluweit et al., 2010). A broad review also confirms that pyrolysis temperature and feedstock type affect pH, surface area, porosity, cation-exchange capacity, volatile matter, ash, and carbon content (Tomczyk et al., 2020).

The same logic applies to syngas and fuel or synthesis gas applications. A product gas intended for direct combustion, engine use, methanol synthesis, Fischer-Tropsch synthesis, hydrogen production, direct reduction, or fuel blending will require different limits for tar, sulfur species, chlorine species, particulates, nitrogen species, methane, CO_2, H_2/CO ratio, moisture, and trace contaminants. Process architecture must therefore start from the intended product specification and duty, not from the reactor name.

3. The scale-up gap: why promising concepts fail

Scale-up in thermochemical and reactive systems is rarely a linear enlargement exercise. The controlling physical and chemical phenomena change their relative importance with scale. Heat-transfer area-to-volume ratios change. Mixing and residence-time distributions change. Wall effects decline. Particle-particle interactions, entrainment, separation, and agglomeration become more important. Materials experience longer exposure to heat, corrosion, erosion, and cyclic stress. Control loops interact with plant inertia. Start-up, shutdown, feed interruptions, cleaning cycles, and off-design operation may dominate risk, even when steady-state laboratory performance looks attractive.

These changes explain why scale-up cannot be assessed only by asking whether the chemistry works. The question is whether the process has passed through development steps that expose the relevant industrial risks. Technology-readiness assessment therefore needs to be adapted to chemical and process industries. Buchner et al. (2019) argue that generic technology readiness level (TRL) scales require sector-specific criteria for chemical technologies, distinguishing idea, concept, proof of concept, preliminary process development, detailed process development, pilot trials, demonstration, commissioning, and production. This distinction protects both developers and decision-makers from premature claims of maturity.

Scale-up also requires preserving the relevant similarity, not every similarity. Geometric, kinematic, and dynamic similarity can all be important, but the decisive requirement is to preserve the controlling phenomena. If heat transfer controls the process, heat-transfer similarity matters. If equilibrium limits product composition, temperature, pressure, gas composition, and residence time matter. If kinetics controls conversion, reaction time, temperature history, and catalytic or mineral interactions matter. If tar cracking controls downstream operability, gas-phase residence time, temperature history, catalytic exposure, and quench behavior matter. If product carbon stability controls value, pyrolysis severity and post-treatment exposure matter. If fouling controls availability, impurity deposition and cleaning behavior matter. The scale-up question is always: which phenomena must mainly remain comparable for the decision to be valid?

3.1 The laboratory is for mechanisms; the pilot plant is for decisions

Laboratory experiments are indispensable for identifying reaction pathways, kinetic regimes, material behavior, initial operating windows, and failure modes. However, they are not, by themselves, proof of industrial feasibility.

Pilot plants and mini-plants should not merely replicate laboratory conditions at a larger scale. They should answer decision-critical questions: Which reactor concept is robust? Which variables dominate product quality? Which impurities create unacceptable risk? What is the real heat balance? Which downstream unit becomes the bottleneck? What maintenance pattern is likely? Which transients are manageable?

A well-designed pilot campaign generates decision-quality data. It should include material, carbon, and energy balances; steady-state operation; transient behavior; feedstock variation; gas-cleaning performance; tar and condensable mapping; catalyst or sorbent aging where relevant; emission data; residue quality; cleaning cycles; operator observations; uncertainty ranges; and product yield per unit of energy consumed.

The quality of the pilot question is often more important than the size of the pilot unit.

3.2 Tar, fouling, and downstream treatment are scale-up problems, not details

In gasification and many high-temperature waste-conversion systems, downstream treatment is often where technically attractive concepts become industrially difficult. Tar formation is a clear example. Devi et al. (2003) describe tar as a major problem in biomass gasification because it can condense as the gas cools, causing blockage and fouling of process equipment. They also distinguish between primary measures inside the gasifier and secondary hot-gas cleaning after the gasifier. This distinction is essential for scale-up: a reactor cannot be evaluated separately from the gas it produces and the equipment that must handle that gas.

The same logic applies to particulates, alkali metals, chlorine species, sulfur species, wastewater, condensates, ash, slag, and solid residues. A process that reaches high conversion but creates difficult wastewater, unstable tar, problematic solids, harmful emissions, undesired by-products, excessive cleaning frequency, corrosion risk, or weak product demand is not yet an industrial solution.

3.3 Industrial usefulness, not local activity

A frequent innovation error is to confuse local activity with industrial usefulness. Higher conversion, faster removal, stronger mixing, visible cavitation, higher heat transfer, or smaller droplets may prove that a technology creates an effect, but not that it improves the complete process. A reactor can increase conversion while worsening selectivity or separation. A mixer can improve contact while creating stable emulsions. A heat-recovery system can save energy while adding pressure drop, fouling, or cleaning frequency.

A more defensible approach is to evaluate a candidate process module relative to a defined reference case, using the same process boundary. The candidate is useful only when the useful benefit remains positive after energy demand, chemical use, pressure drop, separation burden, emissions, maintenance, product quality, reliability, uncertainty, and hard constraints are included. This is the logic behind an industrial usefulness window: the operating domain where a specifically defined technology configuration provides positive net contribution without transferring unacceptable burden elsewhere in the flowsheet (Saylam, 2026b).

4. Modeling and validation: the digital-physical development loop

Modeling is most valuable when it is treated as a disciplined dialogue with experiments, not as a substitute for them. In thermochemical systems, useful models can range from equilibrium calculations and mass-energy balances to reduced kinetic models, reactor-network models, CFD, CFD-DEM, population-balance models, detailed chemical-kinetic simulations, flowsheet models, techno-economic analysis, and life-cycle models. The appropriate model is not necessarily the most complex one. It is the simplest model that can support the decision with known assumptions and uncertainty.

For early screening, equilibrium and mass-energy models can identify theoretical limits and sensitivity to feedstock composition. For reactor development, kinetic and transport models can distinguish chemical limitation from heat-transfer or mass-transfer limitation. For scale-up, CFD and residence-time analysis can expose maldistribution, hot zones, dead zones, wall heat losses, particle segregation, or recirculation. For investment decisions, simplified models may be more valuable than highly detailed simulations if they are transparent, validated, and tied to operational variables.

Gasification modeling literature supports this hierarchy. Thermodynamic equilibrium models are useful for preliminary comparison and process studies, but they cannot give highly accurate predictions in all cases because gasifier design, kinetics, transport, and non-equilibrium effects matter. Kinetic models can be more detailed, but they require parameters that are often feedstock- and reactor-specific (Puig-Arnavat et al., 2010). For complex systems and processes, empirical and semi-empirical models built from experimental data can be very useful and, in some cases, may be the most practical available approach for representing behavior that is too complex, feedstock-specific, or poorly characterized for purely first-principles modeling (Aydin et al., 2017; Pradhan et al., 2019).

4.1 Validation must be purposeful

Validation is not the act of matching one curve. It is the process of demonstrating that a model is reliable enough for its intended use. A model used for concept ranking requires different evidence than a model used for safety margins, emission prediction, plant control, or investment decisions. Model credibility should therefore be defined by scope, assumptions, data quality, parameter identifiability, uncertainty, and known failure modes.

A practical development loop follows five steps: define the industrial decision; build the simplest model able to support that decision; identify the variables that dominate uncertainty; design experiments to test those variables; then update the model and repeat. This loop helps prevent two opposite errors: over-modeling without validation, and under-modeling where intuition is no longer reliable.

The same principle appears outside thermochemical systems. In advanced oxidation processes, intrinsic radical chemistry does not directly predict reactor performance because water-matrix scavenging, mass transfer, radiation attenuation, hydrodynamics, and energy demand reshape the apparent rate constant. A kinetic-process framework therefore treats the apparent first-order rate constant as an emergent system parameter, not as a pollutant property alone, thereby linking chemistry to reactor-scale behavior (Saylam, 2026a). The lesson is transferable: observable process performance is usually the coupled result of chemistry, transport, geometry, feed matrix, operating boundary conditions, and the wider process flowsheet.

4.2 Hybrid expertise is the innovation direction

The future of process development will not be purely mechanistic or purely data-driven. Physics-based models provide structure, constraints, and interpretability. Empirical, semi-empirical, and data-driven methods can detect patterns, drifts, anomalies, and correlations in pilot or plant data. Expert judgment connects these tools to chemical plausibility, materials behavior, control limits, operational reliability, and industrial consequences.

The strategic task for senior technical teams is to decide where model complexity creates value and where it creates false precision. A correct carbon balance tied to product specification may be more useful than an impressive simulation that cannot be validated. Conversely, a detailed CFD or kinetic model may be essential when local temperature, mixing, turbulence-chemistry interaction, particle behavior, or hot-spot formation determines safety and scale-up success.

5. Application fields for sustainable transformation

5.1 Waste-to-X and residual-resource valorization

Waste-to-X should not be used as a slogan for converting anything into anything. It is a disciplined resource-conversion problem. The first question is waste hierarchy and suitability: can the material be prevented, reused, mechanically recycled, biologically treated, chemically recycled, thermochemically converted, or safely disposed? The second question is product intent: energy, syngas, liquid intermediates, recovered carbon, mineral residues, or destruction of hazardous organics? The third question is system integration: where does the heat go, how are emissions treated, how are residues handled, and what is the carbon benefit?

Thermochemical conversion fits a circular-economy portfolio when it handles residual streams that cannot be better managed by higher-value routes, or when it enables recovery of energy, carbon, or materials that would otherwise be lost. This positioning is important because waste-to-X can be environmentally useful or environmentally weak depending on boundary selection, emissions, avoided disposal, product displacement, residue fate, and indirect inputs.

Applied waste-to-X analysis of wood waste compared three thermochemical cases: full syngas combustion, partial syngas combustion, and externally heated non-oxidizing gas driven by renewable energy. The comparison showed that biochar production alone does not automatically imply climate credibility. Direct CO_2 and NOx emissions, syngas use, heat supply, and indirect emissions associated with chemicals and materials must be included before carbon-credit potential can be claimed (Saylam, 2024b).

5.2 Biochar, pyrogenic carbon, and carbon-management logic

Biochar is a useful example because it connects thermochemical conversion, carbon stability, soil and material applications, waste management, pollutant adsorption, and carbon-removal markets. The technical value of biochar depends on properties; the climate value depends on durable carbon storage, sustainable biomass sourcing, system boundaries, avoided emissions, and monitoring, reporting, and verification. IPCC assessment work treats carbon dioxide removal as part of the mitigation portfolio while emphasizing durability, scale, and sustainability limits (IPCC, 2023). The State of Carbon Dioxide Removal reports similarly emphasize tracking where, how, and how much carbon is removed (Smith et al., 2024).

For process developers, biochar should be treated as a product, not as a residual solid. A plant designed for carbon removal may not be identical to a plant designed for activated-carbon precursors, soil amendment, construction materials, catalyst support, or wastewater treatment. Product intent changes feedstock acceptance, temperature, heating rate, residence time, oxygen exposure, gas management, post-treatment, certification, and quality-control requirements.

This is why carbon-credit claims require caution. A biochar process that combusts all co-produced gas for heat may be energy self-sufficient but still produce direct emissions (Saylam, 2024b). A process that preserves syngas for chemicals or fuels may improve carbon efficiency but requires downstream quality and economics. A process heated by renewable non-oxidizing gas may reduce direct emissions but requires credible energy sourcing and capital feasibility. The correct question is not whether biochar exists, but whether the integrated system produces durable carbon storage with acceptable emissions, product use, and verification.

5.3 Hydrogen-related and syngas systems

Hydrogen has become a central term in industrial decarbonization, but it is not a magic replacement molecule. Its role depends on application: reducing agent, chemical feedstock, energy carrier, storage vector, fuel, or intermediate toward ammonia, methanol, synthetic fuels, or direct-reduction gases. The IEA Global Hydrogen Review 2025 reports that low-emissions hydrogen remains below 1 percent of global production, although committed low-emissions projects have grown since 2020 (IEA, 2025). This mixed picture is important: hydrogen deployment is limited not only by chemistry but also by cost, infrastructure, offtake, policy, and project bankability.

Thermochemical expertise matters because hydrogen frequently interacts with reforming, gasification, syngas conditioning, methanation, Fischer-Tropsch synthesis, carbon capture, combustion stability, materials compatibility, and safety. For waste- and biomass-derived syngas, hydrogen-related development is not simply a question of producing H_2. It is a question of gas quality, gas cleaning, reforming duty, H_2/CO ratio adjustment, carbon handling, contaminants, compression, storage, and end-use requirements.

Transient combustion-based systems illustrate the broader principle that thermochemical outcomes are governed by operating window, temperature history, residence time, equivalence ratio, and reaction pathway, not by reactor name alone. Model-supported HCCI studies provide one example of this logic, while further validation would be required before such concepts could be considered industrially relevant syngas routes (Saylam, 2020).

5.4 Industrial clusters and hard-to-abate sectors

Hard-to-abate industries illustrate why process development must be embedded in industrial ecosystems. Steel, cement, chemicals, refineries, waste management, energy utilities, and transport infrastructure cannot decarbonize through isolated equipment changes alone. They require coordinated changes in feedstock supply, power and heat integration, hydrogen or syngas availability, carbon capture and transport, product certification, permitting, and investment timing.

For steel, hydrogen-compatible direct reduction is not only a furnace question. It requires ore quality, reducing-gas supply, electric melting, grid capacity, hydrogen infrastructure, CO_2 accounting, product certification, and investment confidence. For chemicals, the same principle applies to methanol, ammonia, synthetic fuels, carbon-containing intermediates, and circular carbon routes. Thermochemical process development therefore becomes most valuable when it is connected to regional infrastructure and industrial cluster logic.

6. A practical adoption framework

Sustainable process innovation needs a framework that is technical enough for engineers and simple enough for decision-makers. The framework below is designed for thermochemical and physical-chemical technologies from early concept to industrial adoption. It is not a rigid sequence; development is iterative. However, skipping one layer usually transfers risk to a later, more expensive stage.

The central principles are straightforward: define the industrial problem before selecting the technology; define the feedstock envelope and product specification early; identify controlling phenomena; quantify the operating window through targeted experiments and models; validate under realistic disturbances; integrate environmental, safety, and economic constraints before scale-up; and communicate results in the language of decisions: risk reduced, performance proven, cost range narrowed, emissions controlled, product specification met, and next investment justified.

6.1 Decision framework for process-development teams

The following framework summarizes the main decision layers that can guide thermochemical and physical-chemical process development from early problem definition to industrial integration.

Table 1. Decision framework for thermochemical process-development teams.

Development stage	Dominant question	Minimum evidence needed	Decision outcome
Problem framing	What industrial problem is worth solving?	Waste/resource map, product need, regulatory driver, stakeholder value, reference case.	Proceed only if the problem is real, valuable, and technically addressable.
Concept screening	Which route is chemically and thermodynamically plausible?	Mass and energy balances, equilibrium limits, literature data, preliminary risk map.	Select the smallest set of credible routes.
Laboratory validation	Which phenomena control performance?	Feedstock characterization, kinetic data, product analysis, impurity effects, reproducibility.	Define operating window and critical variables.
Model-assisted development	Which uncertainties dominate scale-up?	Validated simple models, sensitivity analysis, uncertainty ranges, heat/mass-transfer assessment.	Design targeted pilot experiments.
Pilot campaign	Can the process operate under realistic variation?	Material balance, carbon balance, emission data, transients, residue quality, maintenance observations.	Reduce technical risk and refine design basis.
Demonstration and integration	Can the system work as part of an industrial site?	Utility integration, control concept, HSE review, logistics, product certification, economic model.	Prepare investment-grade decision package.

The framework is intended as a practical screening and development tool. Its purpose is not to replace detailed engineering design, but to ensure that each development stage produces evidence strong enough to justify the next investment step.

6.2 Metrics that matter

A transformation technology should be evaluated by a balanced set of metrics. Technical metrics include conversion, selectivity, yield, energy efficiency, product specification, operating flexibility, durability, emissions, and availability. Environmental metrics include greenhouse-gas balance, circularity, pollutant transfer, residue use or disposal, water use, and carbon permanence where relevant. Economic metrics include capital intensity, operating cost, energy cost exposure, feedstock cost or gate fee, revenue stability, certification cost, and offtake reliability. Implementation metrics include safety, permitting, supply chain, operator competence, maintainability, and compatibility with existing infrastructure.

This balanced-metric approach is consistent with the concept of an industrial usefulness window, in which a technology configuration is judged relative to a defined reference case and a complete process boundary rather than by isolated local performance indicators alone (Saylam, 2026b).

These metrics should not be used only at the end. They should guide the entire development program. A process that achieves excellent conversion but creates difficult wastewater, problematic solids, unstable tar, high maintenance demand, weak product demand, or weak certification logic is not yet an industrial solution.

6.3 Evidence filters for technology claims

Technology claims should be assessed according to the strength of the supporting evidence and the completeness of the process boundary. The following table contrasts common weak evidence with stronger evidence suitable for industrial decision-making.

Table 2. Evidence filters for technology claims in process-development assessment.

Claim type	Weak evidence	Stronger evidence
Conversion claim	Single feed sample, ideal conditions, no closed balance.	Reproducible conversion with material and carbon balances across the defined feedstock envelope.
Product-quality claim	Yield reported without specification.	Yield plus composition, contaminants, stability, certification path, and application test.
Energy claim	Core reactor energy only.	Delivered energy including drying, compression, pumping, oxygen/steam, recirculation, cooling, and cleaning.
Emission claim	CO_2 or pollutant measured only at the main stack.	Direct and indirect emissions, residues, wastewater, pollutant transfer, and avoided-burden assumptions.
Scale-up claim	Laboratory effect assumed transferable.	Pilot data under transients, realistic feed variability, cleaning cycles, and validated scale-up variables.
Economic claim	Revenue assumed from generic product value.	Product specification, offtake route, certification cost, operating availability, and sensitivity analysis.

These evidence filters help distinguish promising technical effects from validated process performance. They are especially useful when comparing early-stage thermochemical concepts, pilot results, and scale-up claims.

7. The human and organizational dimension

Industrial process development is a technical discipline, but it is performed by organizations. Many failures occur because scientific teams, engineering teams, operators, HSE experts, business units, regulators, investors, and customers work with different definitions of success. Researchers may optimize novelty or conversion. Engineers may prioritize reliability and maintainability. Managers may focus on cost, schedule, and market risk. Regulators focus on emissions and safety. Customers focus on consistent product quality. These views are not contradictory, but they must be integrated early.

A senior technology-development function is therefore partly scientific and partly translational. It converts complex physical-chemical understanding into process options, testable hypotheses, risk maps, pilot programs, validation plans, decision packages, and implementation logic. This translational role is especially important in sustainable technologies because the systems are often new, cross-sectoral, infrastructure-dependent, and exposed to public credibility risk.

Two mistakes should be avoided. The first is technology push: starting with a favored reactor, catalyst, or concept and searching for a market later. This produces elegant prototypes without adoption. The second is premature commercial optimism: presenting early experimental success as near-industrial readiness. Both mistakes can be reduced by clear problem framing, chemical-industry-specific TRL thinking, realistic pilot validation, transparent risk communication, and reference-based metrics.

The alternative is disciplined innovation. It should be ambitious in purpose but conservative in evidence. It should welcome novel ideas while requiring mass balances, energy balances, safety analysis, emissions data, product specifications, uncertainty ranges, maintainability logic, and integration thinking. In industrial transformation, credibility is itself a form of innovation.

8. Conclusion

Thermochemical knowledge remains a core competence for sustainable industrial transformation because many pathways to lower-carbon, circular, and resource-efficient industry are still governed by physical chemistry, reaction engineering, heat and mass transfer, material transformation, emissions control, and process integration. Hydrogen, waste-to-X, biochar, syngas, circular carbon, catalytic upgrading, process intensification, and carbon management all depend on the ability to move from mechanism to scale.

The most effective development approach is neither purely academic nor purely operational. It combines scientific depth with industrial pragmatism: define the problem, understand the feedstock envelope, specify the product, identify controlling phenomena, model with purpose, validate experimentally, pilot for decisions, and scale only when the operating window and residual risks are sufficiently known.

The strongest industrial question is not whether a technology can create an effect. The stronger question is whether a specifically defined process configuration remains useful inside a complete flowsheet after energy demand, emissions, separation burden, reliability, product quality, uncertainty, economics, and implementation constraints are included. This shift from technology enthusiasm to decision-quality evidence is the practical bridge from thermochemical knowledge to sustainable industrial process development.

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