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IMPROVING BIO-BASED INDUSTRIES LIFE CYCLE SUSTAINABILITY

Industry CAse studies anaLysis to IMprove EnviROnmental performance and sustainability of bio-based industrial

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Theory of Change & Key Levers | 04.06.25

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Building Blocks of our Theory of Change

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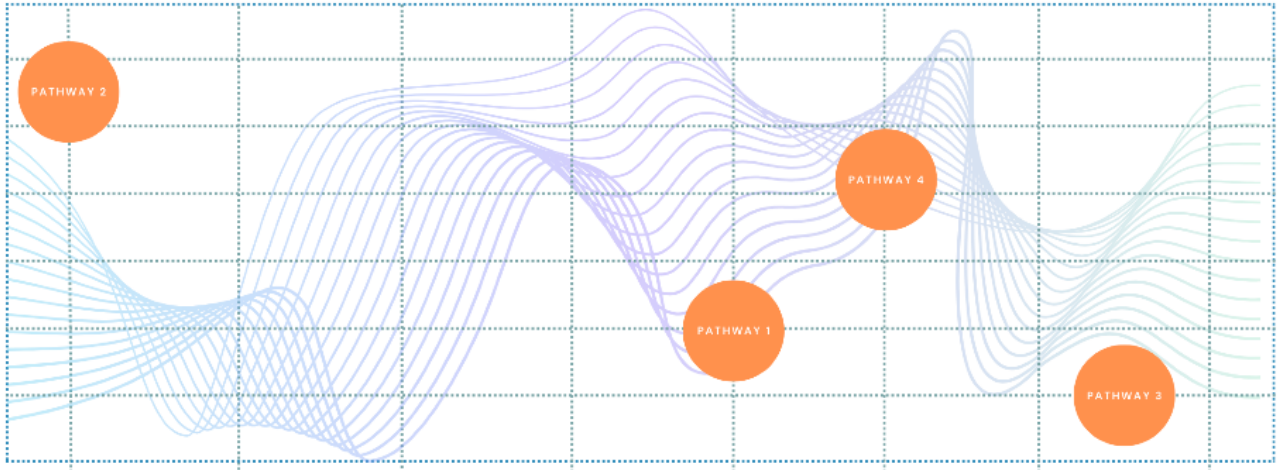
Theory of Change Diagram

Goal
To enhance sustainability in the bio-based industries

Objective 1	Objective 2	Objective 3	Objective 4	Objective 5
Identify Main Barriers and Incentives	Define Reference Case Studies and Identify Levers to Improve Life Cycle Sustainability	Improve Existing Sustainability Assessment Methodologies	Develop a Multi-Objective Optimization Framework (MOO)	Provide Feasible Solutions with Better Sustainability Performance
IR1 Improved Data Collection and Identification of Sustainability Gaps	**IR2** Detailed Case Studies with Sustainability Levers	**IR3** Enhanced Sustainability Assessment Methodologies	**IR4** Development of a MOO Framework for Industrial Processes	**IR5** Feasible Solutions for Improved Sustainability Performance

Levers of Change

- LifeCycle Thinking
- Methodological Advancements
- Data Management
- MOO of Industrial Processes
- Sectorial and Cross-Sectorial Solutions



Output 1	Output 2	Output 3	Output 4	Output 5	Output 6	Output 7	Output 8
Enhanced Methodologies	Protocols for Data Collection	Identification of Hotspots and Sustainability Gaps	Case Studies	MOO for Bio-Based Sectors	Feasible Solutions	Policy Recommendations	Stakeholder Engagement

Partner Contributions

- Expertise in LCA and LCSA
- Data Collection and Analysis
- Industry Knowledge
- MOO Development
- Solution Collaboration
- Guidelines and Policy Formulation
- Stakeholder Engagement

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Multi-Scale Bioeconomy Transformation

Reference to Gilberthorpe and Papyrakis (2015) advocating for an integrated approach at micro, meso, and macro levels.

Micro Scale
Facilities maximize biomass value through cascading applications

Meso Scale
Value chain networks create regional ecosystems through collaborative partnerships that prevent burden-shifting

Macro Scale
Policy frameworks and market incentives reward absolute sustainability outcomes

Key Insight: Simultaneous transformation across all scales prevents rebound effects and ensures genuine environmental impact progress

Figure 1. Bio-based Sectors: A Three-tier Perspective on Global Dynamics - Macro, Meso, and Micro, declined from the "Key challenges for the EU's sustainability transition" shared in the report *"Strategic foresight report 2023, European Commission / Sustainability and people's wellbeing at the heart of Europe's open strategic autonomy"*

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Vision for Regenerative Bio-Based Industries

Our Vision for 2035

EU bio-based industries lead the global circular transformation, delivering products that regenerate **natural capital** while ensuring equitable prosperity. We've moved beyond efficiency gains to create systems where **material flow adds value** - from cascading biomass applications to industrial symbiosis networks.

This transformation succeeds through **integrated action** across all scales, preventing the **rebound effects** that historically undermined sustainability.

By connecting facility innovations with regional value chains and supportive policies, we ensure saved resources translate to genuine environmental benefits, not displaced impacts.

From Theory to Impact: Our Four Pathways

Pathway 1 - Regenerative Optimization

The CALIMERO project exemplifies regenerative optimization by leveraging case studies across five bio-based sectors to identify critical process improvements. In the construction industry, the project addresses the lack of standardization in LCSA and PEF applications that limits effectiveness in comparing environmental impacts. For the woodworking sector, optimization focuses on reducing hotspots related to green wood processing and fossil-based adhesives, which account for nearly all environmental impacts. Through multi-disciplinary workshops involving 12 consortium partners from industry and academia, the project facilitates knowledge exchange to optimize value chains, such as transitioning to circular economy models in construction and implementing closed-loop strategies for material recovery. These empirical approaches drive systemic shifts toward reduced environmental footprints while maintaining economic viability.

From Theory to Impact: Our Four Pathways

Pathway 2 - Integration and Transparency

The integration of novel characterization factors represents a pillar of CALIMERO's transparency pathway, with the development of ProScale H and E characterization factors for 52+ substances, UseTox CFs for eco and human toxicity, and critically assessment tools that enhance data utilization across the bio-based value chain. The project's LCSA framework creates feedback loops by linking environmental, social, and economic indicators through integrated assessment tools, such as the dynamic carbon footprint methodology that captures temporal emissions profiles and the criticality assessment framework that evaluates supply chain vulnerabilities. These simulation tools and analytical capabilities enable transparent communication of sustainability performance, as demonstrated through the detailed guidelines for PEF and PEFCR implementation that facilitate industry-wide adoption of standardized assessment methodologies.

From Theory to Impact: Our Four Pathways

Pathway 3 - Collaboration and Adaptive Governance

The project reinforces collaboration between traditionally siloed sectors, creating synergies that unlock sustainable innovations. Notable examples include the biochemical industry utilizing tall oil from pulp and paper operations as a bio-based alternative to fossil-derived carboxylic acids, and the construction sector potentially incorporating pulp ash waste to substitute up to 10% of concrete components. Through stakeholder engagement across the value chain CALIMERO develops adaptive governance frameworks that respond to evolving EU regulations like the Circular Economy Action Plan and the Strategy for Sustainable and Circular Textiles. This collaborative ecosystem accelerates the transition to bio-based alternatives while ensuring compliance with environmental standards.

From Theory to Impact: Our Four Pathways

Pathway 4 - Balancing the Bio-Based Demand

The project addresses the critical balance between bio-based demand growth and environmental stewardship through innovative methodologies that quantify trade-offs, including biodiversity impact assessments using spatial connectivity modeling and ecosystem services evaluation frameworks. By developing dynamic carbon accounting methods that distinguish between biogenic and fossil carbon flows, CALIMERO enables transparent tracking of actual climate benefits while the criticality assessment tool identifies potential supply constraints that could limit sustainable bio-based expansion. The integration of Life Cycle Costing indicators with environmental assessments provides the financial transparency needed to incentivize responsible market development, ensuring that bio-based growth occurs within ecological boundaries while maintaining economic viability through evidence-based decision-making tools.

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From Theory to Impact: Potential Success Indicators
(long-term)

Zero fossil-based adhesives in woodworking products through complete transition to bio-based alternatives.

Baseline (2024): Bio-based adhesives comprise < 1% of the woodworking adhesive market (global wood adhesives market ≈ USD 8 billion in 2024, bio-based < 1% share).
Reference: https://www.grandviewresearch.com/industry-analysis/wood-adhesives-market

Plausible pathway: Assume bio-adhesives grow from < 1% in 2024 to 25% by 2030, 50% by 2035, and 100% by 2040 driven by R&D advances in lignin and soy-based formulations, supportive EU regulations, and industry commitments. The global bio-adhesives market is projected to expand at a CAGR of 8.6% - 10% through 2030, suggesting potential to scale rapidly.
Reference: https://www.alliedmarketresearch.com/wood-adhesives-market-A10827

Textile industry water consumption reduced by 50% through low-impact dyeing technologies and water-efficient processes.

Baseline (2020): Average water use for EU textile processing ≈ 200 L/kg of textile (wet processes); agriculture of cotton alone uses up to 5 000 - 15 000 L/kg fiber, culminating in 9 m^3 per person-year of consumed textiles.
References: Kärkkäinen, E., & Heikkilä, P. (2024). Textile production water use and textile wastewaters: Literature Review. Telaketju.
https://telaketju.turkuamk.fi/telavaluen-tuloksia/tekstiiliteollisuuden-jano-valmistusprosessien- vedenkulutus-ja-jatevesien-laatu/
https://www.eea.europa.eu/en/topics/in-depth/textiles

Plausible pathway: By 2030, 80% of EU mills adopt at least one low-impact dyeing method (e.g., cold-pad-batch, enzymatic pretreatment, digital spray), each demonstrating 40% - 75% water savings. Trials show 50% average reduction; combined with process optimization (heat recovery, closed-loop rinse water), sector-wide water use can fall by 50% by 2030.
References:
https://www.sciencedirect.com/science/article/abs/pii/S095965262402362X
https://fashionunited.com/statistics/global-fashion-industry-statistics/european-union

Pulp and paper industry energy intensity decreased from 5% - 6% to 3% of global industrial energy use through closed-loop systems.

Baseline (2022): Pulp & paper accounted for approximately 5%-6% of global industrial final energy consumption.
References: https://www.globalefficiencyintel.com/pulp-and-paper-industry
https://www.sciencedirect.com/science/article/pii/S1364032122005950

Plausible pathway: Assume 70% of EU mills implement best-practice heat recovery, electrification, and biomass cogeneration by 2035, cutting absolute energy demand by 30% (to 4.2 % of global industrial energy). By 2040, 90%+ integration of closed-loop water/energy systems could achieve a further 20% cut (to 3%)- supported by studies estimating up to 2.1 -2.4 EJ per year savings via these measures.
References:
https://www.sciencedirect.com/science/article/pii/S2666787240000369
https://www.engieimpact.com/insights/financing-decarbonization-pulp-paper

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From Theory to Impact: Potential Success Indicators
(long-term)

Paper recycling rates increased from 79% (2023) to ≥ 90% across all EU member states.

Baseline (2023): EU paper recycling rate = 79.3% (all paper & board).
References:https://www.paperforrecycling.eu/press-release-european-recycling-rate-increased-to-72-in-2019-2-2/
https://www.eurosac.org/media/news/eprc-monitoring-report-2023

Plausible pathway: Harmonized separate collection, deposit-return expansion, and upgraded decontamination boost rate by 2% - 3% per year. States currently < 80 % improve faster (3% year), those > 80% improve at 1% - 2% per year, enabling all to reach ≥ 90 % by 2030 (e.g., packaging stream targets hit 90% by 2030 in several countries).

Construction industry achieves 10% material substitution with industrial waste streams (e.g., pulp ash in concrete)

Baseline (2024): On average, pulp ash is not systematically used; pilot studies show up to 5% - 10% cement replacement feasible.
References:
https://www.sciencedirect.com/science/article/abs/pii/S2214785323015523
https://www.mdpi.com/1996-1944/12/17/2766

Plausible pathway: By 2030, assume 60% of major concrete producers incorporate pulp ash at 10% replacement - enabled by updated EU concrete standards, certified SCM supply chains, and demonstrated long-term performance (10% pulp ash mix yields + 15% compressive strength, acceptable durability).
References: https://onlinelibrary.wiley.com/doi/10.1155/2022/8880196

Cross-sectoral industrial symbiosis partnerships increase from isolated cases to 30% of production volume.

Baseline (2022): Formal industrial symbiosis covers around 10% of production volume in sectors like paper, chemicals, and metals
References: https://www.mattech-journal.org/articles/mattech/full_html/2021/04/mt210042/mt210042.html

Plausible pathway: With rollout of EU industrial symbiosis platforms (from 2025 onward), regulatory incentives, and digital by-product marketplaces, by 2035 over 50% of medium-large-scale facilities engage in formal symbiosis agreements - together utilizing 30% of combined production volume. Pilot studies suggest up to 20% of material flows can be symbiotic under enabling policies.
References: https://www.scalerproject.eu/wp-content/uploads/2020/06/D3.5_SCALER_Quantified-potential-of-industrial-symbiosis-in-Europe_v1.0.pdf
https://www.mdpi.com/2071-1050/13/16/9159

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Key Levers for Systemic Change
10 Leverage Clusters Driving Transformation

Regulatory Context • Civil Society • Location Factors • Forces • Mindset • Innovation • Evidence-Based Data • Cooperation • Processes • Business Models

Critical Barriers Identified

• Fragmented data collection systems • Regulatory misalignment across EU states
• Technology stuck at low readiness levels • IP protection limiting collaboration
• Weak incentives for circular practices

Three Strategic Recommendations

AI-Enhanced Data Systems - Automated collection and analysis
Integrated Impact Models - Combining social, economic, environmental variables
Rebound Risk Metrics - Measuring unintended consequences

Cross-Sector Opportunities

Bio-based adhesives • Energy efficiency networks • Waste-to-value chains

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Policy Recommendations: Enabling Regenerative Transformation
Five Critical Policy Interventions

1. Integration Over Isolation
Merge circular economy and bioeconomy strategies - only 20 of 76 countries currently integrate both

2. Cascading Innovation Support
Enable multi-stage value extraction from biomass: from textiles to energy to soil optimization

3. Rebound Prevention Protocols
Embed assessment tools in all policies - 75% of studies ignore circular economy rebound effects

4. Inclusive Governance
Engage farmers, SMEs, informal workers, community knowledge drives equitable transformation

Moving Forward Together
Success requires abandoning fragmented interventions for coordinated multi-level strategies. By aligning biodiversity preservation with regenerative economics across all scales, we create the conditions for true sustainability within planetary boundaries.

From linear to circular, from efficiency to regeneration, from theory to transformation