Interreg CENTRAL EUROPE

Co-funded by the European Union

GreenChemForCE

Deliverable D.3.1.2 STRATEGY DOCUMENT

Activity 3.1. Recovery of precious metals used as homogeneous catalyst

Interreg Central Europe project CE0200857 GreenChemForCE

Version 1

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Contents

1. Introduction and Purpose of the Strategy

1.1. Background and Project Context

The GreenChemForCE project was established to support the transition of the chemical industry in Central Europe towards more sustainable, resource-efficient, and environmentally responsible production systems.[1-3] The project promotes the implementation of circular approaches within chemical manufacturing and aims to reduce the environmental impacts associated with industrial processes, raw material consumption, waste generation, and emissions. Its activities are organised around three principal thematic areas: sustainable management of plastics, carbon dioxide management in industry, and greener production of fine chemicals.

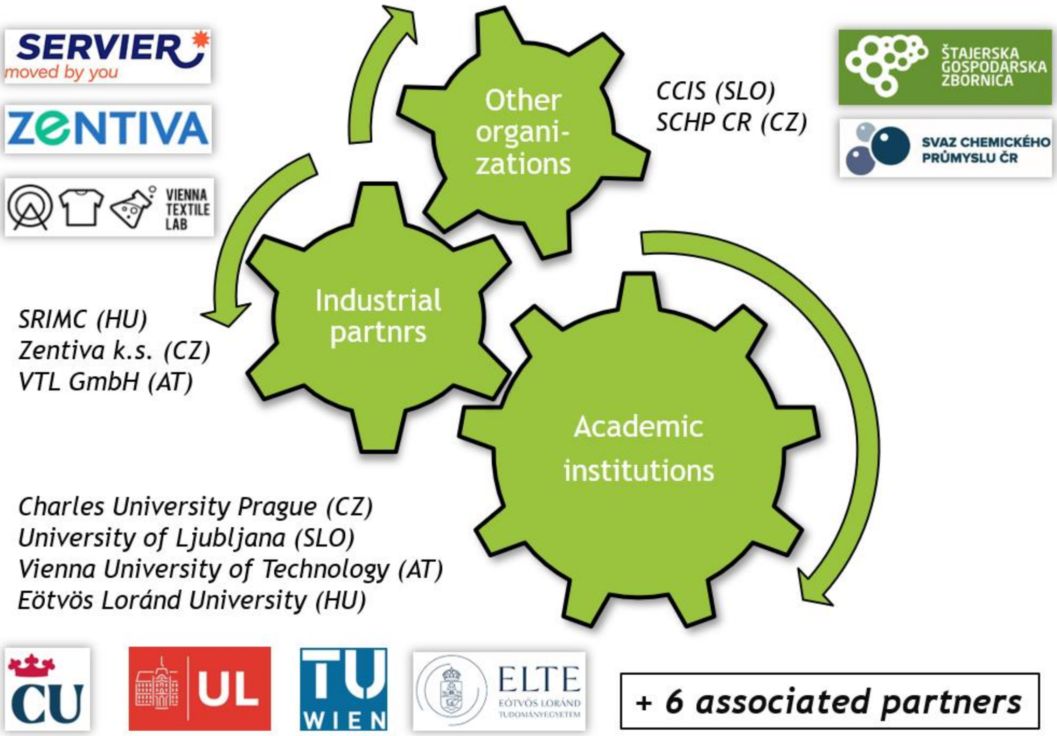


Fig 1: GreenChemForCE project

The GreenChemForCE consortium brings together academic institutions, industrial partners, and sectoral organizations from the Czech Republic, Austria, Hungary, and Slovenia. The participating partners represent a broad spectrum of expertise ranging from pharmaceutical and fine chemical production to catalysis, process engineering, plastics recycling, and industrial sustainability. Through this cross-border structure, the project seeks to strengthen regional cooperation, accelerate technological innovation, and support the implementation of greener industrial practices across Central Europe. Within this framework, the project combines analytical activities, pilot actions, and strategic development in order to create long-term pathways towards a more sustainable chemical sector.

Within the structure of GreenChemForCE, Work Package 3 (WP3) focuses on streamlining processes for the production of fine chemicals and active pharmaceutical ingredients (APIs). The work package addresses sustainability challenges associated with fine chemical and pharmaceutical manufacturing, particularly those related to solvent use, transition metal catalysis, process efficiency, and waste generation. A major objective of WP3 is to identify and support technological approaches capable of reducing the environmental footprint of chemical production while preserving industrial applicability and economic feasibility.

The analytical activities performed within Deliverable D.3.1.1 established a baseline assessment of key sustainability challenges connected to the production of fine chemicals in Central Europe. Particular attention was dedicated to solvent consumption, solvent recovery, the use of precious and transition metals in catalysis, and the environmental and strategic implications associated with their supply and recovery. The analysis further examined renewable feedstocks, catalyst circularity, and opportunities for greener synthetic methodologies relevant to pharmaceutical and fine chemical manufacturing. While renewable carbon sources and alternative feedstocks are also extensively addressed within WP2, particularly through the analytical activities and pilot actions focused on CO_2 management and utilization, the topic is equally relevant to WP3. Renewable feedstocks can serve as sustainable building blocks for fine chemical synthesis and as sources of renewable solvents and reaction media. Given this strong thematic overlap and their importance for reducing dependence on fossil-derived raw materials, renewable feedstocks are therefore discussed within this strategy as a cross-cutting topic linking both WP2 and WP3.

Building upon this analytical foundation, the present Strategy Document (Deliverable 3.1.2) translates the identified challenges and opportunities into a broader strategic framework for sustainable fine chemical production in Central Europe. The Strategy is aligned with major European policy initiatives, including the European Green Deal,[4] the Circular Economy Action Plan,[5] the Critical Raw Materials Act,[6] and the Transition Pathway for the Chemical Industry.[7] These frameworks collectively emphasize resource efficiency, circular material use, reduced dependence on hazardous substances and fossil feedstocks, and the development of resilient industrial value chains capable of supporting the long-term sustainability and competitiveness of the European chemical industry.

2. Key Analytical Findings

The analytical activities performed within WP3 of the GreenChemForCE identified several interconnected sustainability challenges associated with the production of fine chemicals and pharmaceuticals in Central Europe. The analysis focused primarily on two critical resource streams that strongly influence the environmental footprint, economic resilience, and long-term sustainability of chemical manufacturing: transition and precious metals used in catalytic systems, and organic solvents used throughout production workflows.

The findings demonstrate that these two areas represent not only major environmental burdens, but also strategic vulnerabilities connected to resource availability, regulatory pressures, and industrial competitiveness. At the same time, the analysis identified significant opportunities for improving circularity, reducing waste generation, and implementing greener process technologies within the Central European chemical sector.

2.1. Precious Metals as a Strategic Sustainability Challenge

The analysis confirmed that platinum group metals (PGMs), particularly palladium, platinum, rhodium, ruthenium, and iridium, remain indispensable for modern pharmaceutical and fine chemical synthesis. Their catalytic properties enable highly selective and efficient transformations including hydrogenation, oxidation, hydroformylation, and carbon-carbon coupling reactions that are fundamental to contemporary chemical manufacturing.

At the same time, the study highlighted a growing structural vulnerability associated with these metals. Global PGM supply remains highly geographically concentrated, with over 96% of reserves located primarily in South Africa and Russia, while more than 80% of global production originates from these two countries alone (Fig. 2, A). This creates significant geopolitical and economic risks for European chemical industries, particularly in Central Europe, where domestic primary production is essentially absent. The Czech Republic, Austria, Hungary, and Slovenia therefore remain strongly dependent on imports and external supply chains.

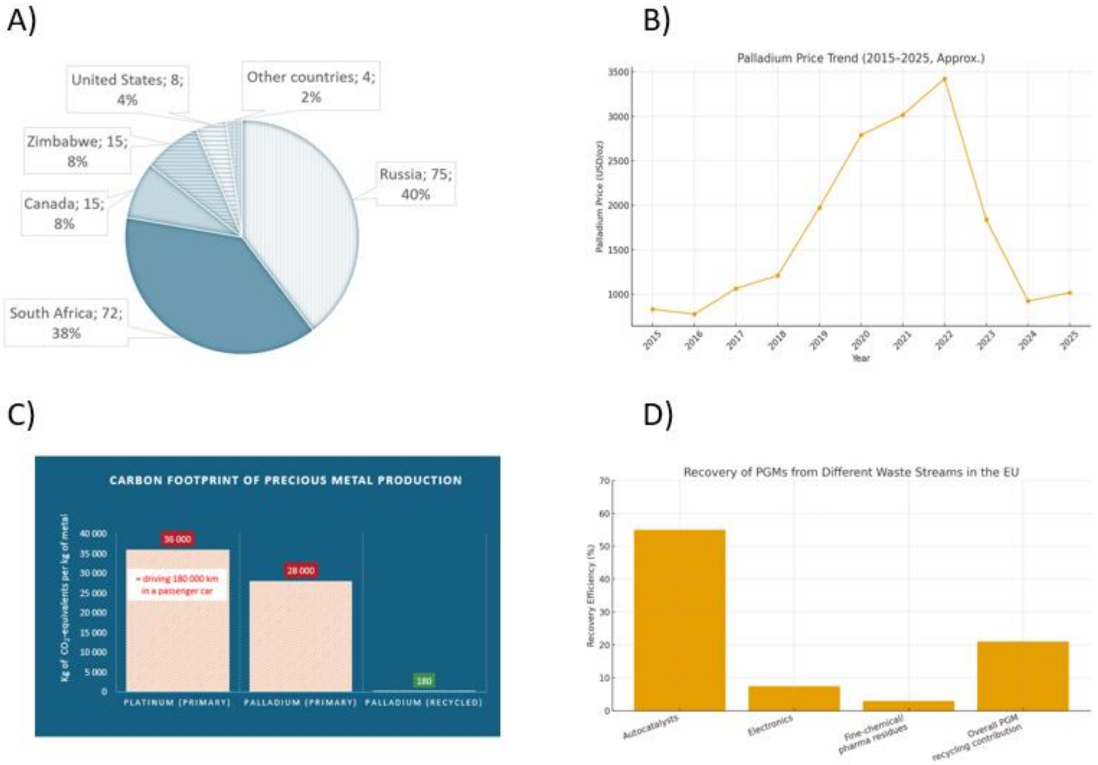


Fig 2: A) Sources of palladium by country. B) Volatility of palladium prices. C) Carbon footprint of primary vs. secondary metals. D) Recovery rates of PGMs.

The analysis further demonstrated that increasing industrial demand, especially from green technologies, renewable energy systems, fuel cells, and advanced catalysis, is expected to intensify pressure on PGM supply in the coming years. Simultaneously, the market exhibits substantial price volatility. Palladium prices, for example, experienced a dramatic growth–collapse cycle over the last decade, reaching historical maxima above 3,000 USD per ounce before sharply declining again (Fig. 2, B). Such fluctuations create considerable economic uncertainty for fine chemical and pharmaceutical manufacturers relying on homogeneous catalytic systems.

A major analytical finding concerns the environmental footprint associated with precious metals. The report demonstrates that primary mining of PGMs belongs among the most carbon-intensive industrial activities worldwide. Estimated lifecycle emissions reach approximately 18,000–36,000 kg CO_2-equivalent per kilogram of platinum and roughly 28,000 kg CO_2-equivalent per kilogram of palladium (Fig. 2, C). Even recycling processes, while substantially more sustainable than primary extraction, remain environmentally demanding due to their energy and reagent intensity.

Nevertheless, the comparison between primary and secondary sourcing clearly demonstrates the strategic importance of recycling and recovery technologies. Recovery from secondary streams significantly reduces lifecycle emissions while simultaneously improving resource security and reducing dependence on geopolitically sensitive suppliers. The analysis therefore identifies catalyst recovery and circular use of transition metals as one of the principal sustainability priorities for the fine chemical sector in Central Europe.

An additional important finding concerns the inefficiency of current recovery systems. While certain waste streams, particularly automotive catalysts, already achieve relatively high recovery rates, fine chemical and pharmaceutical residues remain severely underutilized. Current estimates suggest that recovery efficiencies from pharmaceutical and fine chemical waste streams remain below 5%, despite the high intrinsic value of the contained metals. This represents a substantial untapped opportunity for improving circularity and reducing losses of critical raw materials (Fig. 2, D).

The SWOT analyses performed for the Czech Republic, Austria, Hungary, and Slovenia further revealed a common structural pattern across the region. All participating countries possess well-developed pharmaceutical or chemical sectors and strong academic or industrial research capacities. However, they simultaneously share:

- dependence on imported PGMs,
- limited domestic recovery infrastructure,
- vulnerability to geopolitical supply disruptions,
- and exposure to volatile raw material prices.

At the same time, the analysis identified important opportunities. EU legislation related to circular economy and critical raw materials increasingly supports investment into recovery technologies, recycling infrastructure, and sustainable catalysis. This creates favorable conditions for the development of regional recovery systems and cross-border cooperation mechanisms within Central Europe.

Overall, the analysis demonstrates that precious metal management can no longer be treated solely as a procurement issue. Instead, catalyst circularity must become an integral component of sustainable process design and industrial strategy.

2.2. Solvent Use as a Dominant Source of Environmental Burden

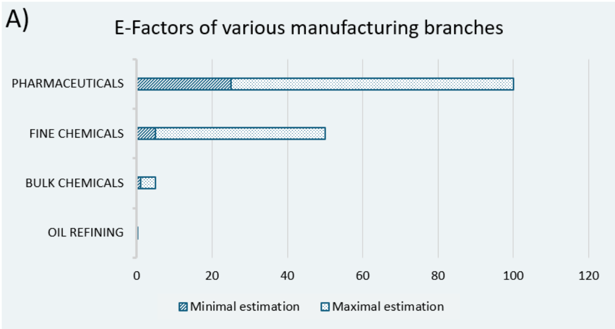
The second major analytical area focused on solvent management within fine chemical and pharmaceutical manufacturing. The analysis confirmed that solvent use represents one of the largest contributors to environmental burden, waste generation, and process inefficiency in the chemical industry.

The report highlights that solvents are indispensable for numerous industrial operations, including:

- synthesis,
- extraction,
- purification,
- crystallization,
- and product formulation.

However, the overwhelming majority of commonly used solvents remain fossil-derived and are frequently associated with toxicity, volatility, occupational risks, or poor environmental profiles.

A particularly significant analytical finding concerns the disproportionate role of solvents within pharmaceutical manufacturing. While the pharmaceutical sector produces relatively small quantities of final products compared to bulk chemical industries, solvent consumption per unit of product is extremely high. The analysis confirms that solvents account for approximately 56% of the total mass input during active pharmaceutical ingredient (API) manufacturing, with water contributing an additional 32%.



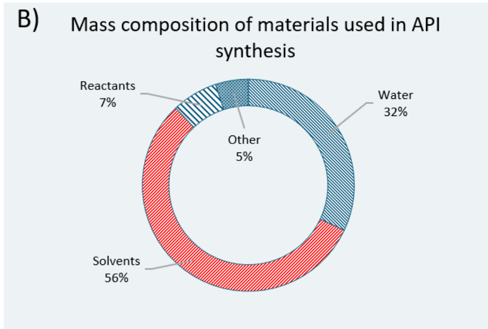


Fig 3: A) E-factors for various branches of chemical production B) Waste composition associated to API production.

This leads to very high E-factors for pharmaceutical production compared to other industrial sectors. Whereas oil refining exhibits E-factors around 0.1 and bulk chemicals around 1-5, pharmaceutical production often reaches values between 25 and 100 depending on the process complexity. The analysis therefore identifies solvent consumption as one of the dominant contributors to waste generation and lifecycle emissions in fine chemical production.

The report further emphasizes that solvent-related emissions constitute a substantial fraction of the total greenhouse gas emissions of the chemical industry. According to referenced EPA estimates, solvent emissions associated with industrial activity may account for approximately 62% of total chemical-sector emissions.

Another important analytical finding concerns the growing regulatory pressure associated with hazardous solvents. European legislation under REACH, the Industrial Emissions Directive, and worker-protection frameworks increasingly restricts or phases out problematic solvents (e.g. dichloromethane, trichloroethylene, perchloroethylene, and dimethylformamide).

This creates a dual challenge for industry:

- maintaining process performance and regulatory compliance,
- while simultaneously transitioning toward greener solvent systems.

At the same time, the report highlights a critical technological limitation: some problematic solvents, especially dipolar aprotic solvents, remain difficult to replace because of their unique physicochemical properties and broad applicability in synthetic chemistry. Their substitution therefore represents not only a regulatory issue but also a major scientific and technological challenge for green chemistry.

2.3. Renewable Feedstocks and Renewable Carbon Sources

Another important analytical finding concerns the strong dependence of the chemical industry on fossil-based raw materials. Current estimates indicate that approximately 97% of industrial chemicals and chemical feedstocks originate from fossil resources, including petroleum, natural gas, and coal-derived intermediates. This structural dependence creates long-term sustainability challenges related not only to greenhouse gas emissions, but also to resource depletion, supply security, and vulnerability to geopolitical and economic instability.

The transition toward renewable feedstocks therefore represents one of the key long-term directions for sustainable chemical manufacturing. Within the context of fine chemical and pharmaceutical production, renewable carbon sources may include:

- biomass-derived platform molecules,
- bio-based solvents,

- renewable alcohols and carbonyl compounds,
- waste-derived intermediates,
- and carbon dioxide-derived building blocks.

The analysis highlights that the integration of renewable feedstocks into fine chemical synthesis remains technologically challenging due to the high purity requirements, strict regulatory standards, and complex synthetic pathways associated with pharmaceutical manufacturing. Nevertheless, renewable carbon utilization is increasingly becoming a strategic priority within green chemistry and industrial sustainability frameworks.

This topic is closely interconnected with the objectives of WP2, which focuses on carbon dioxide management and carbon circularity in industry. Significant overlap exists between both work packages, particularly in areas related to:

- renewable carbon utilization,
- replacement of fossil-derived feedstocks,
- circular carbon economy,
- and development of sustainable catalytic transformations.

At the same time, WP3 addresses these aspects from a more process-oriented and synthetic chemistry perspective, specifically in relation to the preparation of fine chemicals, pharmaceutical intermediates, and active pharmaceutical ingredients (APIs). In this context, renewable feedstocks are not considered solely as alternative raw materials, but as part of a broader transformation toward greener and more circular synthetic methodologies.

Particular importance is attributed to renewable solvents and biomass-derived building blocks already emerging in pharmaceutical synthesis, including compounds such as Cyrene, γ-valerolactone, 2-methyltetrahydrofuran, furfural derivatives, and oxalic acid-derived synthons. These materials demonstrate that renewable carbon integration can increasingly provide technically feasible alternatives to conventional fossil-derived reagents and solvents while simultaneously reducing lifecycle environmental impacts.

The analysis therefore identifies renewable feedstock integration as an important long-term strategic direction for sustainable fine chemical production in Central Europe. However, the report also emphasizes that successful implementation will require further development of catalytic methodologies, process optimization, industrial validation, and cross-disciplinary cooperation between carbon-management initiatives and synthetic chemistry research.

2.4. Strategic Implications for WP3

The analytical findings can be viewed through three overarching sustainability principles:

- waste prevention,
- circularity,
- resource responsibility.

These principles provide a common framework for addressing the major challenges identified within WP3. Excessive solvent consumption contributes significantly to waste generation and environmental emissions, highlighting the need for waste prevention through improved process design and solvent management. The limited recovery and reuse of transition metals in API synthesis demonstrates a lack of circularity for critical raw materials, emphasizing the importance of catalyst recovery and resource recirculation. At the same time, the continued reliance on fossil-derived feedstocks and solvents reflects insufficient resource responsibility, underscoring the need for greater integration of renewable carbon sources and renewable materials. In this context, the analytical outcomes of WP3 provide a critical foundation for the subsequent strategic framework of the GreenChemForCE, supporting the long-term objective of establishing a more resilient, circular, and environmentally sustainable fine chemical sector in Central Europe.

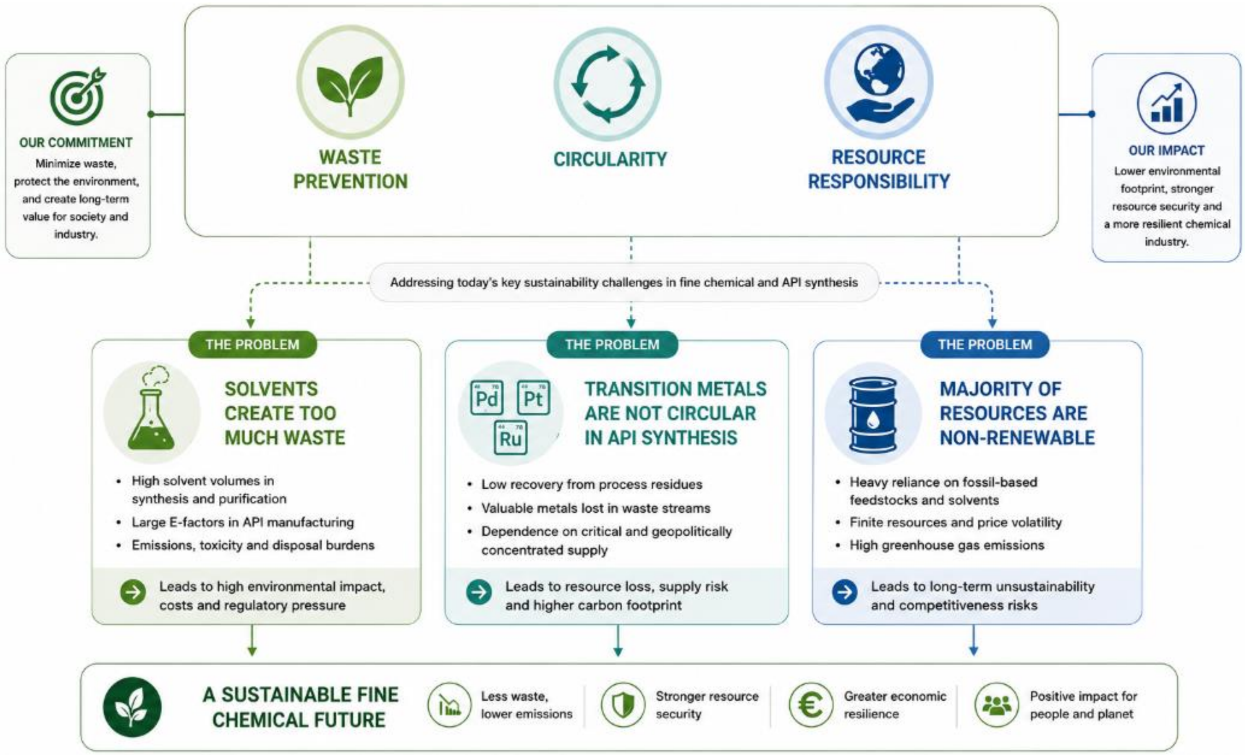


Fig 4: Key sustainability concepts and their connection on the analytical outcome

3. Strategic Framework of WP3

The analytical activities performed within WP3 identified three principal technological directions representing the core sustainability challenges associated with fine chemical and pharmaceutical production in Central Europe:

- transition metals and catalyst circularity,
- solvent management,
- and renewable feedstocks and renewable carbon integration.

These technological areas form the main thematic focus of WP3 and reflect the key environmental, economic, and strategic issues identified within the analysis report.

3.1. Main Technological Directions

3.1.1. Transition Metals and Catalyst Circularity

This technological direction focuses on the sustainable use, recovery, recycling, and circular management of transition and precious metals used in homogeneous catalysis, particularly platinum group metals (PGMs) such as palladium, platinum, rhodium, ruthenium, and iridium.

3.1.2. Solvent Management

This technological direction addresses solvent use within fine chemical and pharmaceutical manufacturing, including solvent selection, solvent replacement, solvent recovery and recycling, reduction of solvent consumption, and implementation of greener solvent systems.

3.1.3. Renewable Feedstocks and Renewable Carbon Sources

This technological direction focuses on the gradual integration of renewable feedstocks and renewable carbon sources into fine chemical and pharmaceutical synthesis, including biomass-derived building blocks, renewable solvents, and renewable carbon-containing reagents.

The topic is closely interconnected with WP2 activities focused on carbon management and carbon circularity, while WP3 specifically addresses these aspects in relation to fine chemical and API production.

3.2. Strategic Pillars of the WP3 Strategy

To support the implementation of these technological directions, the WP3 Strategy is structured around four interconnected strategic pillars:

1. Regulatory framework and governance
2. Regional collaboration
3. Educational pillar
4. Technological pillar

These pillars are not independent components but mutually interconnected elements of the Strategy. Effective implementation of sustainable fine chemical production requires simultaneous interaction between technological development, regulatory support, regional cooperation, and educational capacity building. The pillars therefore function as complementary and interdependent components of a unified strategic framework for the transition towards greener and more sustainable chemical manufacturing in Central Europe.

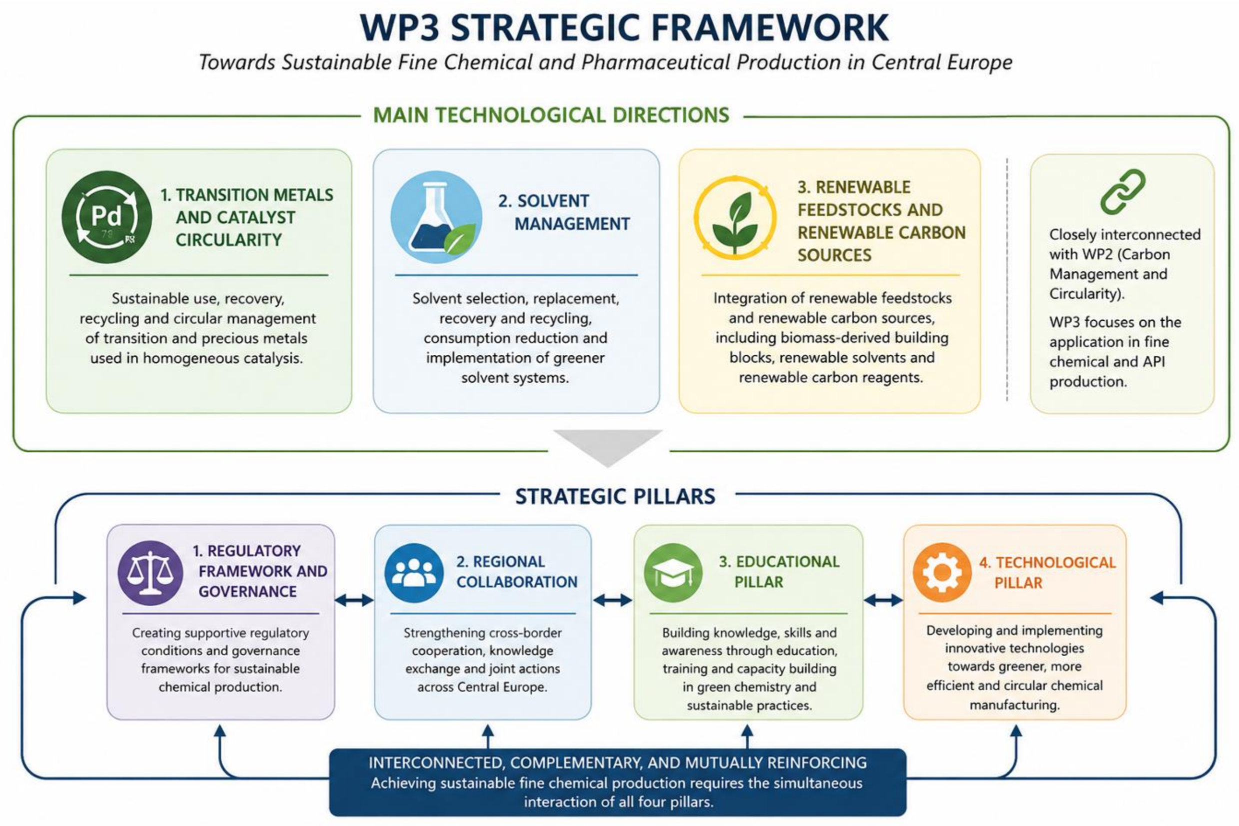


Fig 5: Strategic framework

4. Regulatory Framework and Governance

4.1. Dual Regulatory Approach to Solvent Regulation in the European Union

Within the European regulatory framework, solvents are regulated through two complementary approaches. In some regulatory frameworks, solvents are treated as a distinct technological and industrial category, particularly in legislation focused on industrial emissions, volatile organic compounds (VOCs), and solvent-intensive industrial activities, such as the Industrial Emissions Directive (IED). In parallel, solvents are also regulated as ordinary chemical substances under broader chemical legislation, including REACH and CLP regulations, where the primary focus is placed on intrinsic hazard properties such as toxicity, carcinogenicity, flammability, environmental impact, and occupational exposure risks. Consequently, solvent regulation in the EU combines process- and emission-oriented approaches with substance- and hazard-oriented chemical regulation, creating an interconnected but partially fragmented regulatory landscape.

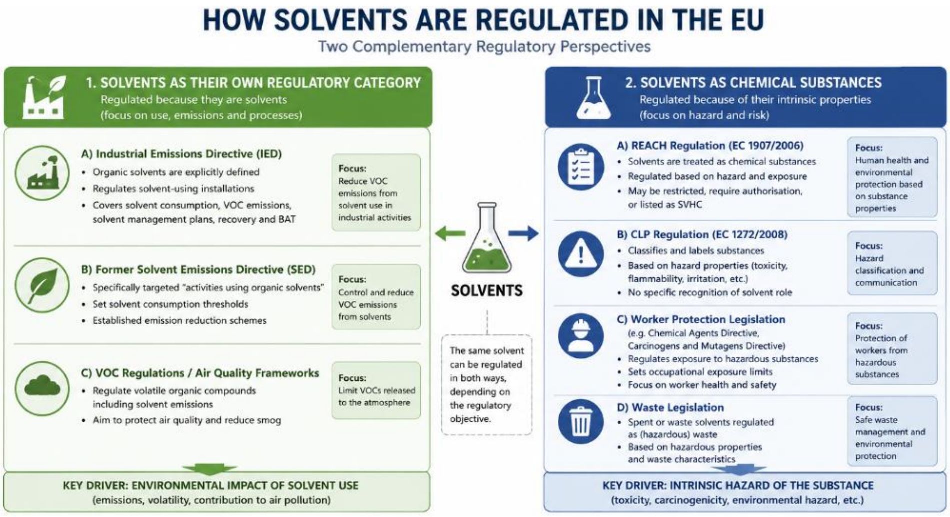


Fig 6: Solvent regulations

4.2. Towards Integrated and Preventive Solvent Management

Although the current European regulatory framework provides extensive control over solvent-related emissions, hazardous properties, occupational exposure, and waste management, these approaches primarily address the consequences of solvent use rather than solvent use itself at the process-design level. Existing legislation is therefore largely focused on managing emissions, toxicity, environmental release, and worker safety once solvents have already been incorporated into industrial workflows.

From a long-term sustainability perspective, a more integrated and preventive approach is needed. Rather than relying predominantly on end-of-pipe control and substance restriction, solvent management should increasingly be based on "green-by-design" principles, where sustainability considerations are incorporated already during process development and technology selection. At the same time, sustainability transition within fine chemical and pharmaceutical manufacturing must remain technologically feasible, economically realistic, and progressively implemented. The Strategy therefore supports balanced regulatory approaches that acknowledge industrial realities and technological limitations while simultaneously creating a clear long-term direction towards greener and more sustainable chemical production.

Key strategic directions include:

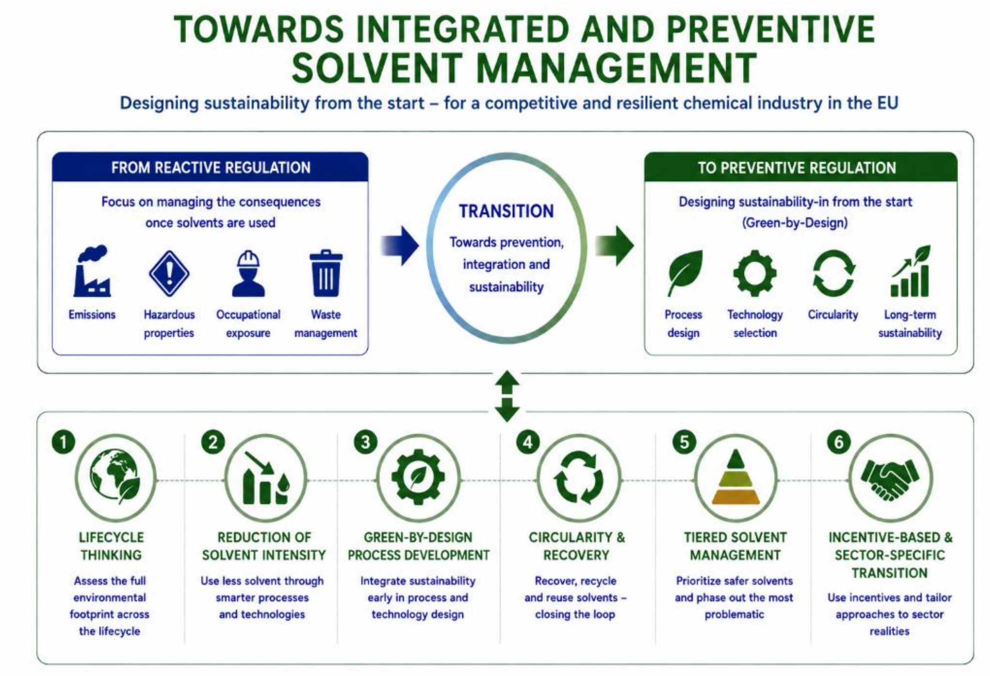


Fig 7: Strategic key aspects for regulatory considerations.

- **Lifecycle-oriented assessment (LCA):** Sustainability evaluation should extend beyond intrinsic solvent toxicity and include the overall environmental footprint associated with solvent production, use, recovery, and disposal. Assessment should consider greenhouse gas emissions, energy demand, waste generation, recyclability, solvent recovery efficiency, and overall process performance, enabling more balanced evaluation of solvent systems. This is particularly important because certain replacement solvents may appear environmentally favorable from a hazard perspective while simultaneously exhibiting higher lifecycle impacts elsewhere in the production chain.
- **Solvent circularity and recovery**: Future solvent management should increasingly support circular approaches based on solvent recovery, recycling, and closed-loop solvent systems. Improved circularity may substantially reduce raw material consumption, waste generation, lifecycle emissions, and dependence on virgin solvent production. The Strategy therefore supports gradual implementation of solvent recovery targets, solvent recycling benchmarks, and reporting obligations related to solvent intensity and recovery efficiency.
- **Reduction of solvent intensity**: Since solvents often represent the dominant material input in pharmaceutical and fine chemical manufacturing, sustainability efforts should also focus on reducing total solvent consumption. This may include process intensification, continuous-flow technologies, reduction of purification steps, improved reaction efficiency, and development of solvent-minimized synthetic methodologies. The objective is not solely replacement of problematic solvents, but broader reduction of solvent demand throughout manufacturing workflows.
- **Tiered solvent management systems**: Solvent selection should increasingly distinguish between preferred, transitional, and problematic solvents. Such an approach would support gradual substitution of hazardous solvents while simultaneously acknowledging current technological limitations and maintaining industrial feasibility. Rather than relying on immediate prohibition, tiered systems may support mandatory justification for use of higher-risk solvents, periodic reassessment, and gradual tightening of regulatory expectations linked to technological readiness of available alternatives.

- **Regulatory recognition of green-by-design process development**: Sustainability considerations should increasingly become integrated directly into process development and industrial decision-making. This includes implementation of solvent selection guides, lifecycle-based process evaluation, solvent circularity assessment, and sustainability documentation already during early-stage development. In pharmaceutical manufacturing particularly, sustainability-oriented process design should ideally be incorporated already during initial technology development and process selection stages.
- **Incentive-based regulations**: The Strategy supports incentive-driven sustainability transition based on innovation support, pilot programmes, public–private partnerships, and industrial collaboration rather than relying exclusively on restrictive measures.
- **Sector-specific transition**: Fine chemical and pharmaceutical manufacturing possess fundamentally different characteristics compared with bulk chemical production, including higher purity requirements, more complex synthetic routes, lower production volumes, and inherently higher solvent intensity. Sustainability expectations should therefore reflect these sector-specific realities.

Together, these approaches support a transition from reactive solvent regulation towards more integrated, preventive, and sustainability-oriented solvent management compatible with both environmental objectives and industrial realities.

5. Regional Collaboration: Strategic Objectives

Regional collaboration represents one of the central enabling mechanisms for the transition towards more sustainable fine chemical and pharmaceutical production in Central Europe. The sustainability challenges associated with solvent use, transition metal management, and dependence on fossil-based feedstocks are highly interconnected across the region and frequently exceed the capacities of isolated institutions, companies, or national systems. Effective implementation of sustainable technologies therefore requires coordinated cooperation between scientific institutions, industrial stakeholders, infrastructure providers, and public-sector organizations.

Within WP3, regional collaboration is approached through two complementary strategic objectives. The first objective focuses on transfer of knowledge, technological know-how, and validated industrial practices supporting implementation of greener and more circular production approaches. The second objective focuses on development of regional logistics systems and shared infrastructure enabling circular material management, resource recovery, and integration of renewable feedstocks across interconnected industrial value chains.

The Strategy further recognizes that sustainable transformation cannot be achieved through isolated stakeholder groups operating independently. For this reason, the proposed collaborative framework is based on strong integration between academia, industry, and public and sectoral organizations. Such an interconnected approach enables simultaneous development, validation, implementation, coordination, and dissemination of sustainable technologies and strategic methodologies throughout the Central European chemical sector.

5.1. Regional Collaboration and Stakeholder Integration

Within WP3, regional collaboration serves as an enabling mechanism supporting the transition towards more sustainable fine chemical and pharmaceutical production in Central Europe. The Strategy identifies two principal objectives of regional collaboration:

- **Knowledge development, transfer, and dissemination of best practices**
- **Development of regional logistics and circular infrastructure**

Successful implementation of these objectives requires strong integration between:

- academia and research institutions,
- industrial stakeholders,
- and public and sectoral organizations.

The Strategy therefore supports a collaborative “triple-helix” framework connecting scientific research, industrial implementation, and public-sector coordination across the region.

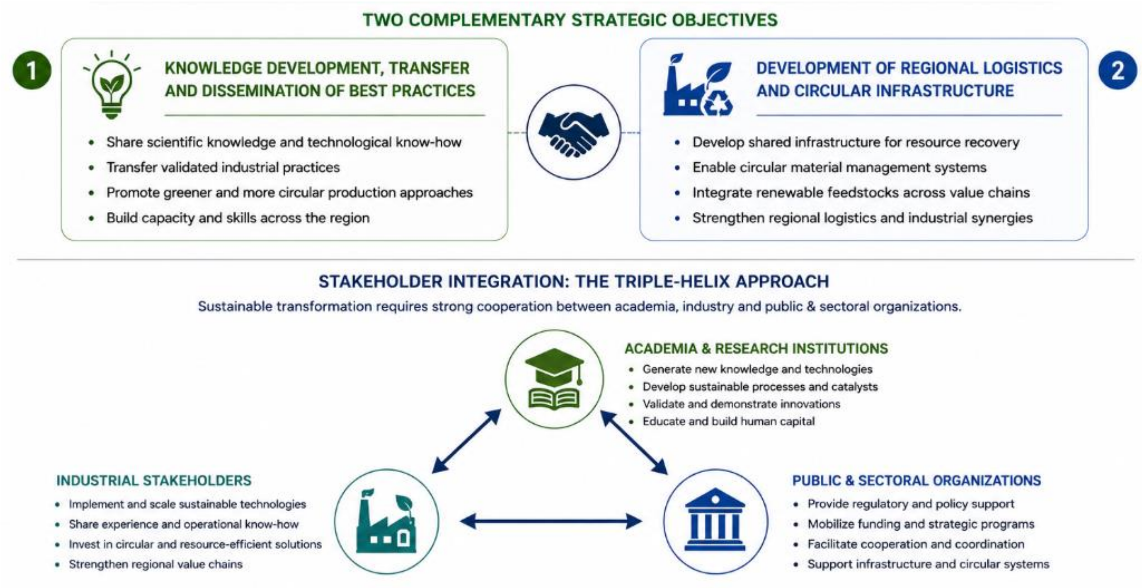


Fig 8: Top: two principal objectives of regional collaboration, bottom stakeholder integration.

5.1.1. Knowledge Development, Transfer, and Dissemination of Best Practices

One of the major benefits of regional collaboration is acceleration of knowledge exchange between academia, industry, technology providers, and regional stakeholders. This includes transfer of:

- validated sustainable methodologies,
- solvent selection approaches,
- lifecycle assessment methodologies,
- recovery technologies,
- and industrial implementation experience.

In the context of **solvent management**, knowledge transfer is particularly important for implementation of greener solvents, solvent recovery systems, and solvent-minimized processes, where industrial adoption is often limited by implementation risk and regulatory complexity rather than lack of available technologies.

For **renewable feedstocks**, regional cooperation may facilitate multidisciplinary exchange between chemistry, biotechnology, biomass processing, and industrial manufacturing sectors, supporting development and implementation of renewable-carbon-based synthetic methodologies.

In the area of **transition metals**, collaboration may support dissemination of recovery technologies, catalyst circularity approaches, and best practices related to reduction of critical raw material consumption.

Key stakeholders involved in this process include:

- universities and research institutions,
- pharmaceutical and fine chemical companies,
- solvent and material producers,

- engineering and technology providers,
- industrial associations,
- and regional innovation platforms.

Strategic recommendations include:

- establishment of regional knowledge-sharing platforms and expert networks,
- organization of cross-border workshops, pilot demonstrations, and industrial case-study dissemination,
- harmonization of sustainability assessment methodologies across participating institutions,
- strengthening collaboration between academia and industry during technology validation,
- and support for multidisciplinary cooperation across chemistry, engineering, biotechnology, and industrial manufacturing sectors.

5.1.2. Development of Regional Logistics and Circular Infrastructure

The second major objective of regional collaboration is development of regional logistics systems and infrastructure supporting circular material management across Central Europe.

In the context of **transition metals**, regional integration may enable establishment of economically viable recovery and recycling systems through aggregation of material streams across multiple industrial stakeholders and countries. Shared infrastructure may improve recovery efficiency, reduce dependence on imported critical raw materials, and strengthen regional resilience.

For **solvent management**, regional logistics and infrastructure may support centralized solvent recovery systems, recycling capacities, and development of circular solvent-management networks capable of reducing waste generation and virgin solvent consumption. Nevertheless, implementation should be guided by life-cycle assessment (LCA) and techno-economic evaluation, since the sustainability benefits of centralized recycling may vary depending on transportation distances, solvent characteristics, recovery efficiencies, and the feasibility of on-site recycling solutions.

Within the area of **renewable feedstocks**, regional collaboration may support development of interconnected supply chains for biomass-derived and renewable-carbon-based materials, including coordination between feedstock production, processing, transport, and industrial utilization.

Implementation of these activities requires involvement of:

- industrial manufacturers,
- recycling and waste-management companies,
- logistics providers,
- technology and engineering companies,
- public institutions and regulatory bodies,
- regional innovation agencies,
- and chemical industry associations.

Strategic recommendations include:

- support for development of regional recovery and recycling infrastructure, based on LCA,
- strengthening cross-border circular material flows,
- establishment of shared pilot and demonstration facilities,
- support for regional supply chains based on renewable and recycled resources,
- promotion of coordinated logistics systems enabling efficient transport and utilization of secondary and renewable raw materials,
- and strengthening cooperation between industrial stakeholders and public-sector organizations responsible for regional development and sustainability policy.

5.2. GreenChemForCE as an Illustrative Example of Regional Collaboration

The GreenChemForCE (GCF) consortium represents an illustrative example of the regional collaboration principles described within this Strategy. Through cooperation between universities, research institutions, industrial partners, and sectoral organizations across Central Europe, the consortium demonstrates how coordinated cross-border collaboration may support development and implementation of sustainable technologies within the chemical sector.

Within WP3, the activities of the consortium are primarily focused on generation of scientific and technological know-how and its subsequent transfer into industrial practice. The collaboration framework therefore emphasizes not only development of innovative methodologies, but also their validation, dissemination, and practical implementation under industrially relevant conditions.

The consortium integrates stakeholders representing multiple segments of the innovation ecosystem, including:

- academia and research organizations,
- pharmaceutical and fine chemical companies,
- and industrial and sectoral organizations.

This interconnected structure enables effective exchange of expertise across the principal technological directions of WP3, particularly:

- sustainable solvent management,
- transition metal recovery and catalyst circularity,
- and integration of renewable and biomass-derived feedstocks.

An important aspect of the collaboration is the direct connection between knowledge generation and industrial implementation. Research activities performed within academic institutions are continuously evaluated and validated in cooperation with industrial partners, enabling assessment of technological feasibility, process robustness, scalability, and sustainability performance under realistic manufacturing conditions.

In the area of solvent management, the consortium supports dissemination and implementation of greener solvent systems, and solvent-minimized synthetic methodologies. Within transition metal management, the collaboration contributes to development of catalyst recovery strategies and circular approaches aimed at reducing dependence on critical raw materials, and process intensification by a development of transformations with low catalytic loadings. In the context of renewable feedstocks, the consortium supports exploration of renewable-carbon-based synthetic approaches and integration of biomass-derived materials into chemical manufacturing workflows, as well as utilization of biocatalytic transformations for API replvant reactions and productions of dyes.

The GreenChemForCE consortium therefore demonstrates how regional collaboration may function as a practical mechanism for:

- accelerating knowledge transfer,
- reducing implementation barriers,
- strengthening industrial-academic cooperation,
- and supporting gradual transition towards a more sustainable, circular, and resilient chemical sector in Central Europe.

6. Green Chemistry Education and Research in Central Europe: A Comparative Overview

6.1. Introduction

The strategic educational and research framework presented here is aligned across all Work Packages of the GreenChemForCE project and is formulated in a consistent manner within all three strategic reports. In this version, particular emphasis is placed on Green Chemistry approaches related to the circular management of carbon dioxide and broader decarbonization strategies.

Green Chemistry is becoming an increasingly important component of modern chemical education and research, driven by the global transition toward sustainability, circular economy principles, and low-carbon technologies. Universities across Europe are incorporating these concepts into their academic and research structures through various approaches, ranging from dedicated degree programmes to research-oriented activities and sustainability-focused curricular elements. The main objective of this strategic pillar is to strengthen the educational dimension of Green Chemistry—particularly at the academic level—with a specific emphasis on the Central European region. To support this objective, an action plan has been developed across the academic institutions participating in the GreenChemForCE project. This includes comparing existing levels of expertise and educational approaches among the participating universities, promoting cross-border exchange of knowledge, and supporting curriculum development at institutions where Green Chemistry integration remains limited. In this way, the proposed approach fulfils the objectives of the InterregCE programme.

This overview presents four institutional models represented by TU Wien (in collaboration with the University of Vienna and BOKU University), Eötvös Loránd University, the University of Ljubljana, and Charles University in Prague. Within each institutional model, the final subsection specifically addresses aspects related to the sustainable production of advanced chemicals, including active pharmaceutical ingredients (APIs). The analysis indicates that TU Wien represents the most advanced and structurally developed model of Green Chemistry integration, followed by the University of Ljubljana and Eötvös Loránd University, while Charles University currently demonstrates only limited and largely indirect engagement with the field. Based on these findings, an action plan aimed at strengthening and systematizing Green Chemistry education and research at Charles University is proposed.

6.2. Approaches in academic education in Central Europe

6.2.1. Dedicated Green Chemistry Degree Programmes (Vienna Model)

a) Masters's Programme

The joint Master's programme in Green Chemistry offered by TU Wien, the University of Vienna, and BOKU represents a fully structured and interdisciplinary educational model.

<u>Programme Motivation and Goals</u>

The programme is designed in response to the transformation of the chemical industry from fossil-based systems toward sustainable, circular processes. It positions chemistry as a key contributor to environmental solutions.

Graduates are trained to:

- Design energy- and resource-efficient processes
- Evaluate environmental impacts using Life Cycle Assessment (LCA)
- Integrate chemistry with biotechnology and process engineering

Curriculum Structure

(120 ECTS, 4 semesters, English-taught) combines expertise from all three universities and includes:

- Core subjects (50–60 ECTS)
- Electives (20–30 ECTS)
- Soft skills (10 ECTS)
- Master’s thesis (30 ECTS)

Core Modules (Selection)

- Green Synthesis & Catalysis: Modern synthetic methods, photochemistry, and electrochemistry.
- Sustainable Polymers & Materials: Developing biodegradable or highly recyclable plastics.
- Renewable Raw Materials: Chemistry of biomass, CO2 as a feedstock, and the utilization of waste streams.
- Process Engineering & Technology: Scaling up processes ("scale-up") with a focus on green parameters.
- Sustainability Assessment: Tools for the ecological and economic evaluation of chemical processes.

Special Features

- Interdisciplinary enrolment across three institutions
- Strong industry collaboration in Vienna
- Innovation-driven “Benign by Design” philosophy

b) PhD Programme

The corresponding PhD programme (180 ECTS, 3 years) focuses on original research aimed at decarbonizing the chemical industry. Key research areas include:

- Advanced catalysis
- Circular chemical processes
- Green solvents (e.g., ionic liquids, deep eutectic solvents)
- Biorefinery concepts

Doctoral candidates typically work on funded research projects and contribute to scientific publications while engaging in international collaborations.

c) Vienna model in the context of WP3.

At TU Wien, University of Vienna, and BOKU University, Green Chemistry is integrated into education and research through a multidisciplinary approach connecting sustainable organic synthesis, catalysis, process engineering, and environmental assessment. The programmes emphasize the development of environmentally responsible chemical processes and modern synthetic methodologies aligned with sustainability principles.

- Advanced catalysis, including development of metal-free and bio-based catalysts
- Modern synthetic methodologies involving photochemistry and electrochemistry
- Research into green solvents, such as ionic liquids and deep eutectic solvents
- Utilization of renewable feedstocks and conversion of agricultural or industrial waste into high-value chemicals
- Integration of circular economy principles into chemical process development
- Emphasis on resource-efficient and energy-saving synthetic processes

- Application of Life Cycle Assessment (LCA) for environmental impact evaluation
- Connection between synthetic chemistry, biotechnology, and process engineering within sustainable chemical production
- Focus on environmentally benign and industrially relevant chemical technologies

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6.2.2. Integrated Curriculum Approach (Ljubljana Model)

At University of Ljubljana, Faculty of Chemistry and Chemical Technology (UL FKKT), Green Chemistry is broadly embedded across teaching, research, and industry collaboration.

a) Curriculum Integration

Green Chemistry concepts are incorporated at all levels:

- **Bachelor level**: Introduced within environmental chemistry, process engineering, and industrial chemistry courses
- **Master level**: Advanced topics include:
  - Green reaction engineering
  - Sustainable catalysis
  - Alternative solvents
  - Process intensification and flow chemistry
  - Microreactor and microfluidic technologies

Recent curriculum modernization initiatives have further strengthened sustainability-focused and interdisciplinary modules.

b) Research-Based Education

Students actively engage in research areas such as:

- CO_2 capture and utilization
- Polymer recycling and circular materials
- Biomass valorization
- Green oxidant production
- Intensified chemical processes

Research groups in catalysis, reaction engineering, environmental chemistry, and microprocess engineering play a central role in education.

c) Student Involvement and Scale

- 250–300 BSc students
- 120–150 MSc students
- 60–80 PhD students
- More than 50% exposed to Green Chemistry concepts

Students participate in:

- Thesis projects
- National and international research programmes (e.g., Horizon Europe, Interreg)
- Industry collaborations

d) Industry and Lifelong Learning

UL FKKT emphasizes knowledge transfer through:

- Micro-credential programmes
- Professional training modules
- Industry-focused case studies (e.g., hydrogen peroxide production, polymer recycling)

e) Ljubljana model in the context of WP3.

- Integration of Green Chemistry concepts across BSc, MSc, and PhD study programmes
- Focus on sustainable catalysis, green reaction engineering, and environmentally friendly process design
- Emphasis on process intensification, flow chemistry, and microreaction technologies
- Application of microstructured and microfluidic reactor systems for safer and more resource-efficient synthesis
- Research on sustainable reaction media and environmentally benign catalytic systems
- Integration of renewable feedstocks, biomass valorization, and circular chemical processes

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6.2.3. Research-Driven Green Chemistry Education (Budapest Model)

At Eötvös Loránd University, Green Chemistry is primarily integrated through research rather than formal coursework.

a) Curriculum Integration

Currently, there are no dedicated Green Chemistry courses at the BSc, MSc, or PhD levels. Instead, sustainability concepts are introduced through:

- Laboratory work
- Research projects
- Applied thesis topics

b) Research and Thesis Opportunities

Students can engage in Green Chemistry through thesis work, particularly within the Catalysis and Organic Synthesis Research Group. Research areas include:

- Sustainable catalysis (e.g., micellar catalysis)
- Environmentally benign synthetic methodologies

c) Student Participation

Engagement is highly specialized:

- Approximately 2–3% of MSc students of the Chemistry institute are involved in Green Chemistry topics.

d) Institutional Perspective

This model reflects a strong research foundation but limited curricular visibility. It offers flexibility and depth in specialized topics, while indicating potential for future expansion into formal coursework.

e) Budapest model in the context of WP2.

At Eötvös Loránd University, activities related to Green Chemistry are primarily focused on sustainable organic synthesis and catalysis research carried out within the Catalysis and Organic Synthesis Research

Group. The institutional involvement is research-oriented and centered mainly on thesis-level laboratory work.

- Sustainable catalysis
- Micellar catalysis
- Environmentally benign synthetic methodologies
- Organic synthesis under Green Chemistry conditions.

6.2.4. Limited Institutional Presence of Green Chemistry (Prague Model – Charles University)

a) Green chemistry aspects at CU

At Charles University, Green Chemistry currently has only a limited and largely indirect presence within the academic structure. Unlike more integrated or curriculum-based models, there are no dedicated Green Chemistry courses in the official study programmes, and even closely related subjects—such as environmental chemistry—are not systematically included in the core course list for chemistry students. Engagement with sustainability concepts therefore depends almost entirely on research activities. However, these are typically centered on general catalysis, organic synthesis, or materials chemistry without an explicit Green Chemistry focus or dedicated laboratory infrastructure. The absence of specialized research groups or laboratories oriented specifically toward Green Chemistry further reduces its visibility as a distinct field. As a result, while students may encounter isolated elements of sustainable chemistry within broader research contexts, there is no coherent educational or institutional framework that supports Green Chemistry as a defined area of study.

b) Prague model in the context of WP3.

- Catalysis and catalytic synthetic methodologies
- Electrochemistry and electrochemical approaches in synthesis
- Sustainable organic synthesis
- Utilization of non-fossil-based feedstocks as synthetic building blocks
- Recent expansion of Green Chemistry-related activities through InterregCE-supported collaborations and projects

6.2.5. Comparative Insights

These three institutional approaches illustrate distinct strategies for integrating Green Chemistry:

- **Vienna model**: Fully structured, interdisciplinary degree programmes with strong industry links
- **Ljubljana model**: Broad curricular integration combined with strong research and industry engagement
- **Budapest model**: Research-driven specialization with limited formal coursework
- **Prague model**: Limited institutional presence of Green Chemistry, research-driven specialization with limited formal coursework

6.3. Action Plan for Introducing Green Chemistry at Charles University

The introduction of Green Chemistry should follow a focused, stepwise approach that builds on existing strengths while gradually establishing a visible institutional framework.

1. Mapping of Existing Expertise

The initial step involves identifying and consolidating existing expertise across current courses and research groups. Particular attention should be given to areas such as catalysis, organic synthesis, materials chemistry, and process chemistry where Green Chemistry principles are already implicitly present.

This mapping will:

- Reveal internal capacity for teaching and supervision
- Enable coordination between departments
- Provide a foundation for curriculum development

Time frame: The mapping of the expertise has been already conducted as a part of the strategy development process.

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2. Establishment of a Dedicated Green Chemistry Course (Including CO_2 Circularity and Decarbonization Component)

A single specialized course in Green Chemistry should be introduced at the Master's level. This course will serve as the central educational component, providing a comprehensive foundation in Green Chemistry while incorporating thematic modules aligned with specific research areas.

One of these modules will focus on CO_2 circularity and decarbonization, addressing the role of chemistry in reducing greenhouse gas emissions and enabling carbon-neutral processes.

Within this framework, the modules should address:

- Introduction to Green Chemistry and the 12 Principles
- Sustainable Reaction Design, Atom Economy, E-factors
- Modern Catalytic Methods in Organic Synthesis
- Green Solvents and Solvent Selection Strategies
- Flow Chemistry and Continuous Processing
- Electrochemistry and Photochemistry in Synthesis
- Renewable Feedstocks and Bio-Based Chemicals
- Sustainable Polymer and Materials Chemistry
- Industrial Green Chemistry and Process Scale-Up
- Environmental Metrics, Life Cycle Assessment, and Chemical Process Sustainability

Time frame: The preparation of the course content will start during the duration of the project. It is expected that the curse will be launched in the academic year 2027/2028.

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3. Establishment of a Green Chemistry Research Laboratory (Including Green Chemistry as a Core Research Area)

To strengthen both research and educational activities in sustainable chemistry, a dedicated Green Chemistry laboratory should be created as a long-term institutional platform covering multiple areas of environmentally responsible chemical research. A major part of the laboratory activities will focus on sustainable synthetic methodologies and modern approaches relevant to organic synthesis and advanced chemical production.

The planned research activities will include:

- Mechanochemical methodologies for solvent-minimized organic synthesis
- Catalytic processes and development of modern catalytic transformations
- Application of green and alternative solvents in synthetic chemistry
- Utilization of renewable and biomass-derived feedstocks in organic synthesis
- Electrochemical methods for sustainable synthesis and catalytic applications
- Design of energy-efficient and low-impact synthetic procedures

In addition to these directions, the laboratory will support broader Green Chemistry themes, including sustainable synthesis, renewable raw materials, circular chemistry, and environmentally benign chemical technologies.

Time frame: Laboratory establishment will begin during the project implementation period through gradual development of infrastructure, instrumentation, and research activities. The laboratory is envisioned as a permanent institutional platform that will continue operating after the completion of the project, ensuring long-term sustainability of the activities.

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4. Development of Thesis Opportunities

Green Chemistry-oriented thesis projects should be progressively introduced at all educational levels, including Bachelor's, Master's, and PhD programmes. This approach will help create a continuous connection between education and active research activities.

Green Chemistry will form one of the principal thematic directions within the laboratory, enabling students to participate in projects related to sustainable synthesis, renewable feedstocks, catalytic methodologies, and environmentally responsible chemical technologies. Through these activities, students will gain direct involvement in both fundamental and applied research topics addressing current sustainability challenges in chemistry.

Time frame: Initial thesis activities have already started, with Bachelor's and Master's students currently involved in projects focused on biomass-derived components and renewable feedstocks. In parallel, new PhD topics have been introduced in areas connected with sustainable synthesis and renewable resource utilization. Further expansion of thesis opportunities will continue throughout the project duration and beyond, supporting long-term integration of research and education in Green Chemistry.

6.4. Expected Milestones

Milestone 1: Mapping of Existing Expertise (Involved Partners: PP1)

- Already completed within the strategy preparation phase

Milestone 2: Establishment of Basic Laboratory Infrastructure (Involved Partners: PP1)

- Allocation of laboratory facilities and essential equipment
- Identification of key Green Chemistry research themes
- Initiation of pilot-scale research activities
- Target: End of 2026

Milestone 3: Implementation of Research Activities (Involved Partners: PP1)

- Launch of research directions related to sustainable synthesis and renewable feedstocks
- Integration of research activities into teaching and student training
- Target: Beginning of 2027

Status: Additional financial support has already been obtained for related research activities through the Marie Curie grant Charleston, involving collaboration between PP1 (CU) and PP4 (SRIMC).

Milestone 4: Preparation of Green Chemistry Course for M.Sc. and Ph.D. Students (Involved Partners: PP1)

- Preparation of course structure and syllabus
- Inclusion of Green and Sustainable Chemistry modules
- Institutional approval procedure
- Target: Completion during 2027

Milestone 5: Introduction of Green Chemistry Course (Involved Partners: PP1)

- Incorporation of the course into the study curriculum
- Target: Academic year 2027/2028 or 2028/2029

Milestone 6: Expansion of Student Thesis Activities (Involved Partners: PP1)

- Introduction of Bachelor's, Master's, and PhD research topics
- Active student participation in ongoing research projects
- Establishment of interdisciplinary supervision framework

Status: ongoing — initial students are already involved in the activities and PhD research topics have been introduced.

7. Technological Pillar

7.1. Introduction to the Technological Pillar

The technological pillar focuses on development, validation, and implementation of technologies enabling transition towards more sustainable, circular, and resource-efficient fine chemical and pharmaceutical production. The Strategy recognizes that sustainable transformation requires both systemic technological change and practical implementation of concrete technological solutions across industrial workflows.

The technological pillar is therefore structured around strategic technological transformation areas representing key sustainability objectives within WP3. Within each area, specific enabling technologies and process approaches are identified as priorities for future development and implementation.

At the same time, the Strategy recognizes that implementation of novel technologies should not be evaluated solely on the basis of individual parameters such as intrinsic toxicity or regulatory classification. Technologies that appear environmentally favorable in one aspect may simultaneously generate increased environmental burden elsewhere in the process lifecycle, for example through higher energy demand, more complex manufacturing, reduced recyclability, or increased resource consumption.

For this reason, lifecycle-oriented assessment (LCA) should represent one of the central evaluation principles within the technological pillar. Sustainability evaluation should consider the complete lifecycle of technologies, materials, solvents, catalysts, and feedstocks, including:

- raw material sourcing,
- manufacturing footprint,
- energy demand,
- process efficiency,
- recyclability and recovery potential,
- waste generation,
- and end-of-life treatment.

The Strategy therefore emphasizes that implementation of novel technologies should be accompanied by comprehensive lifecycle-based validation to ensure that technological innovations provide genuine overall sustainability benefits rather than isolated improvements limited to individual process parameters. This approach is particularly important within solvent management, catalyst circularity, and renewable feedstock integration, where apparent "green" alternatives may not always result in lower total environmental impact when evaluated across the full lifecycle.

The technological pillar thus supports not only development of innovative technologies, but also establishment of scientifically robust validation frameworks enabling realistic assessment of their environmental, technological, and industrial sustainability performance.

7.2. Enabling technologies for gradual shift towards greener solvent management

7.2.1. Strategic transformation objective for solvent use

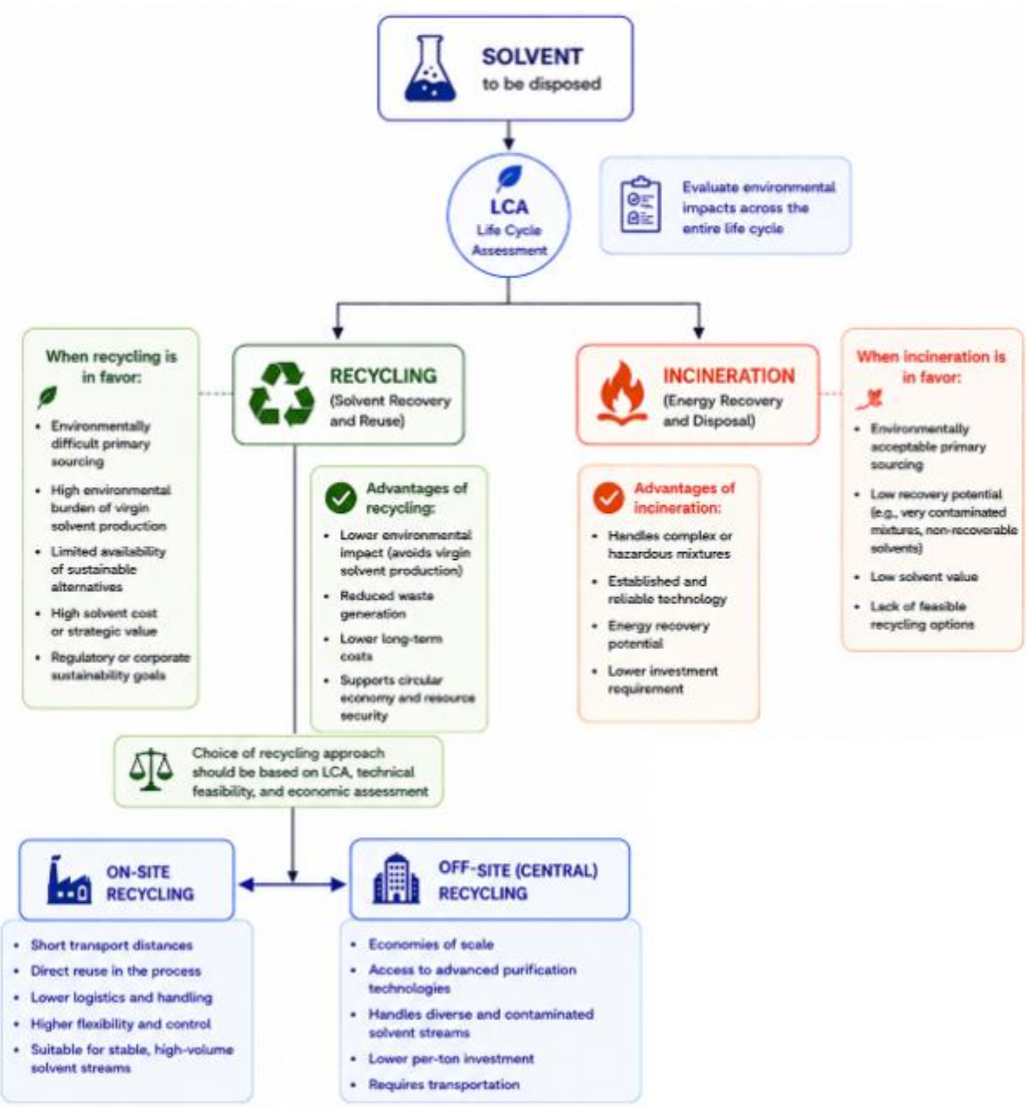
Reduction of the environmental impact associated with solvent use through improved solvent circularity, reduction of solvent intensity, and implementation of safer and more sustainable solvent systems is the main objective of the Strategy. The Strategy recognizes that solvents represent one of the dominant contributors to waste generation and lifecycle emissions within fine chemical and pharmaceutical manufacturing.[8] Technological development should therefore focus not only on solvent substitution itself, but also on broader optimization of solvent management across the entire process lifecycle.

At the same time, implementation of novel solvent technologies should be validated using lifecycle-oriented assessment (LCA) methodologies to ensure that apparent environmental benefits are not offset by increased impacts elsewhere in the production chain.[9-11]

7.2.2. Solvent Recovery and Circular Solvent Management

The Strategy recognizes solvent recovery as one of the most technologically realistic and industrially feasible approaches for reducing environmental impact in pharmaceutical and fine chemical manufacturing. Solvent recovery and recycling should be considered the preferred management route whenever it provides a lower overall environmental impact than disposal. Numerous life-cycle assessment (LCA) studies have demonstrated that recycling frequently outperforms incineration because it reduces the demand for virgin solvent production, which often represents one of the dominant contributors to lifecycle emissions.[9-12] In addition to lowering environmental impacts, solvent recycling can reduce waste generation, improve resource efficiency, and contribute to the development of more circular production systems.

Nevertheless, recycling is not universally the most sustainable option. The environmental benefits depend on factors such as solvent composition, contamination level, recovery efficiency, energy demand, transportation requirements, and the environmental burden associated with production of the virgin solvent being replaced. Consequently, decisions regarding solvent management should be guided by life-cycle assessment (LCA) and supported by techno-economic analysis (TEA) to ensure that the selected approach delivers genuine environmental benefits.[11]



Where solvent recycling is identified as the preferred option, a further decision must be made between on-site and off-site recovery. On-site recycling can minimize transportation requirements, enable direct reuse within the production process, and simplify solvent-management logistics. In contrast, centralized off-site recycling facilities may benefit from economies of scale, specialized purification technologies, and the ability to process larger and more diverse solvent streams. Neither approach can be considered universally superior. The optimal solution depends on transportation distances, available infrastructure, recovery efficiencies, solvent purity requirements, energy consumption, and economic considerations. Therefore, the choice between on-site and off-site solvent recovery should likewise be evaluated using LCA and TEA methodologies, ensuring that solvent circularity is achieved in a manner that maximizes environmental and economic performance.

7.2.3. Solvent-Free and Solvent-Minimized Technologies

Strategic objective: Reduction of solvent intensity through implementation of alternative process technologies minimizing or eliminating solvent consumption.

Key enabling technologies:

- mechanochemistry and ball-milling technologies,
- continuous-flow and microflow chemistry,
- process intensification,
- telescoped and one-pot reactions,
- and integrated reaction-separation systems.

Mechanochemical approaches, particularly ball milling, represent one of the most promising solvent-minimized synthetic technologies because they frequently enable reactions to proceed under solvent-free or near solvent-free conditions while simultaneously reducing waste generation and improving material efficiency.[13-17]

Similarly, continuous-flow technologies may reduce solvent consumption through improved heat and mass transfer, intensified processing, reduced reactor volumes, and simplified work-up procedures.[18-20]

The Strategy further recognizes that solvent minimization should not focus solely on reaction conditions themselves, but also on downstream purification and isolation steps, which frequently represent major contributors to solvent consumption within pharmaceutical manufacturing.

7.2.4. Alternative and Renewable Solvent Systems

Strategic objective: gradual replacement of environmentally problematic solvents with safer, renewable, and more sustainable alternative solvent systems.[21,22]

Key enabling technologies:

- bio-based solvents,
- renewable dipolar aprotic solvents,
- aqueous micellar systems,
- deep eutectic solvents (DES),
- supercritical fluids,
- ionic liquids,
- and water-based alternative reaction media.

Particular attention is currently directed towards renewable bio-based solvents capable of replacing conventional fossil-derived dipolar aprotic solvents. One important example is Cyrene (dihydrolevoglucosenone), a cellulose-derived solvent increasingly investigated as a sustainable alternative to solvents such as DMF and NMP due to its favorable toxicity and biodegradability profile.[23]

Another promising technological direction involves aqueous micellar systems, where reactions proceed within surfactant-based micellar environments dispersed in water. Such systems may substantially reduce consumption of conventional organic solvents while maintaining high catalytic and synthetic efficiency, consequently leading to elimination of the organic waste.[24-27]

Additional promising alternative solvent systems include deep eutectic solvents (DES), ionic liquids, and supercritical fluids, which are increasingly investigated as lower-volatility and potentially recyclable alternatives to conventional organic solvents.[28-31]

At the same time, the Strategy recognizes that alternative solvents should not automatically be considered sustainable solely because they are bio-based or possess improved hazard profiles. Comprehensive lifecycle validation remains essential, particularly with respect to:

- solvent production pathways,
- energy demand,
- recyclability,
- scalability,
- and industrial compatibility,
- industrial manufacturing sectors.

7.2.5. Strategic recommendations

Successful transition towards more sustainable solvent management requires a gradual and evidence-based approach combining technological innovation, environmental assessment, and industrial feasibility. The Strategy therefore recommends the following priorities:

- **Prioritize solvent circularity and recovery** whenever lifecycle assessment (LCA) and techno-economic analysis (TEA) demonstrate clear environmental and economic benefits over disposal routes.
- **Promote solvent intensity reduction** through adoption of process-intensification technologies, including mechanochemistry, continuous-flow processing, telescoped reactions, and integrated reaction–separation systems.
- **Support the gradual substitution of environmentally problematic solvents** with safer and more sustainable alternatives, particularly renewable bio-based solvents, aqueous micellar systems, and other low-impact reaction media where technically feasible.
- **Encourage lifecycle-oriented solvent selection**, integrating environmental, safety, economic, and technical performance criteria into process development and scale-up activities.
- **Strengthen research, demonstration, and industrial validation activities** focused on emerging solvent technologies, including deep eutectic solvents, renewable dipolar aprotic solvents, and advanced solvent-recycling technologies.

The Strategy further recognizes that no universal solvent solution exists for all manufacturing sectors and processes. Consequently, solvent-management decisions should be based on a case-by-case evaluation balancing process performance, product quality requirements, environmental impacts, resource efficiency, and economic viability. Long-term implementation should be supported through collaboration between academia, industry, and policymakers, enabling the development and deployment of solvent technologies that contribute to both industrial competitiveness and environmental sustainability.

7.3. Transition Metal and Catalytic Technologies

7.3.1. Strategic transformation objective

Reduction of environmental burden and dependence on critical raw materials through implementation of circular catalyst-management approaches, improved catalyst recovery, reduction of catalyst losses, and development of highly efficient catalytic systems with lower material intensity.

The Strategy recognizes catalysis as one of the key enabling technologies of modern pharmaceutical and fine chemical manufacturing. At the same time, transition and precious metals used in catalysis – particularly palladium, platinum, rhodium, ruthenium, and iridium – represent economically and strategically critical materials associated with high environmental footprint and supply-chain vulnerability.

For this reason, sustainable catalytic technologies should focus on:

- catalyst recovery and recyclability,[32]
- reduction of catalyst consumption,
- extension of catalyst lifetime,
- process intensification by development of efficient catalysts

These approaches simultaneously contribute to improved material circularity, lower environmental burden, and reduced generation of metal-containing waste streams.

Implementation of novel catalytic technologies should further be validated using lifecycle-oriented assessment (LCA) methodologies to ensure that technological improvements provide genuine sustainability benefits across the entire process lifecycle. Particular attention should be paid to:

- catalyst preparation,
- energy demand,
- catalyst recovery efficiency,
- recyclability,
- process intensification benefits,
- and overall material efficiency.

7.3.2. Heterogeneous and Supported Catalytic Systems

Strategic objective

Development of catalytic systems enabling improved catalyst recyclability, simplified catalyst separation, and reduction of catalyst losses during manufacturing processes.

Key enabling technologies

- heterogeneous catalysis,
- immobilized and supported catalysts,

Heterogeneous catalysis represents one of the major technological directions for improving catalyst circularity because solid-supported catalysts generally allow easier separation and recycling compared with homogeneous catalytic systems. Recent developments include polymer-supported catalysts, silica-supported systems, porous catalytic materials, carbon-supported catalysts, and structured catalytic reactors suitable for intensified processing.[33-35]

7.3.3. Recovery and Recycling of Homogeneous Catalysts

Strategic objective

Reduction of transition metal losses through implementation of efficient recovery and recycling technologies for homogeneous catalytic systems.

Homogeneous catalysis remains indispensable for many pharmaceutical and fine chemical transformations due to its exceptional activity and selectivity. However, recovery and reuse of homogeneous catalysts remains technologically challenging because catalysts are dissolved within the reaction medium and difficult to separate from products and waste.

Key enabling technologies

- catalyst scavenging technologies,[36]
- membrane-based catalyst recovery,[37]
- organic solvent nanofiltration (OSN),[38]

- adsorption and extraction technologies,[39]
- precipitation and crystallization approaches,

7.3.4. Process Intensification and Low Catalyst-Loading Technologies

Strategic objective

Reduction of transition metal consumption through development of highly efficient catalytic processes requiring lower catalyst loadings while maintaining industrial performance and process robustness.

Key enabling technologies

- highly active catalytic systems,
- continuous-flow catalytic processing,
- microreactor technologies,

Reduction of catalyst loading represents one of the most direct approaches for improving material efficiency and reducing environmental burden associated with critical transition metals. Process intensification technologies may significantly improve catalyst efficiency through enhanced heat and mass transfer, optimized mixing, controlled reaction environments, and improved catalyst utilization.[40]

Flow chemistry and microreactor technologies represent important enabling tools for sustainable catalytic manufacturing. By performing reactions in continuously flowing streams within small-volume reactors, these technologies provide superior heat and mass transfer, enhanced mixing efficiency, improved process safety, and precise control over reaction conditions. Such advantages often result in higher catalytic activity and selectivity, reduced solvent consumption, lower energy requirements, and simplified scale-up through process intensification and numbering-up approaches. Flow reactors are particularly attractive for catalytic transformations involving hazardous reagents, highly exothermic reactions, multiphase systems, and continuous production of fine chemicals and pharmaceuticals. Consequently, flow chemistry and microreactor technologies are increasingly recognized as key components of greener and more resource-efficient chemical manufacturing.[41-44]

7.3.5. Strategic recommendations

The transition towards more sustainable catalyst management requires a combination of technological innovation, improved resource efficiency, and implementation of circular approaches throughout the catalyst lifecycle. The Strategy therefore recommends the following priorities:

- **Promote catalyst circularity** through wider implementation of catalyst recovery, recycling, and regeneration technologies, particularly for catalytic systems based on critical and precious metals.
- **Support the development and industrial adoption of heterogeneous and supported catalysts** where these systems provide improved recyclability, simplified separation, and reduced catalyst losses without compromising process performance.
- **Encourage deployment of advanced catalyst-recovery technologies**, including membrane-based separations, catalyst scavenging systems, adsorption technologies, and integrated catalyst-recycling approaches.
- **Prioritize reduction of catalyst loading and extension of catalyst lifetime** through development of highly active catalytic systems, improved catalyst stability, and optimization of reaction conditions.
- **Advance process-intensification technologies**, including continuous-flow processing and microreactor systems, to improve catalyst utilization, reduce resource consumption, and enhance manufacturing efficiency.

The Strategy further recognizes that catalyst-management solutions should be selected on a case-by-case basis, considering catalyst value, process requirements, recovery efficiency, environmental impacts, and economic feasibility. Long-term implementation should be supported by collaboration between academia, industry, and technology providers to accelerate the development of catalytic systems that simultaneously improve sustainability, resource security, and industrial competitiveness.

7.4. Renewable Feedstock and Renewable Carbon Technologies

Strategic transformation objective

Reduction of dependence on fossil-derived feedstocks through gradual integration of renewable and circular carbon sources into fine chemical and pharmaceutical manufacturing. The Strategy recognizes renewable and circular carbon as an important pathway towards lower lifecycle emissions, improved resource efficiency, and enhanced long-term sustainability of chemical production. At the same time, implementation of alternative carbon sources should be supported by lifecycle-oriented assessment methodologies to ensure genuine environmental benefits and avoid burden shifting across the value chain.

7.4.1. Enabling technologies

Key enabling technologies

- Utilization of biomass-derived chemicals,
- Waste-derived and circular carbon feedstocks

Biomass-derived platform chemicals represent one of the most promising technological pathways for introducing renewable carbon into chemical manufacturing. Important examples include furfural,[45,46] 5-hydroxymethylfurfural (5-HMF),[47-49] levulinic acid,[50,51] oxalic acid,[52-56] and Cyrene.[57] Particular strategic interest is directed towards renewable feedstocks capable of integration into existing industrial workflows without requiring extensive redesign of manufacturing infrastructure. Implementation should nevertheless consider feedstock availability, land-use impacts, agricultural intensity, scalability, and overall lifecycle sustainability.

Waste-derived carbon resources represent an emerging opportunity for reducing dependence on virgin fossil feedstocks in fine chemical and pharmaceutical manufacturing. Particularly promising directions include the conversion of plastic waste into building blocks[58], utilization of CO_2-derived intermediates[59]. These approaches support circular economy principles by simultaneously reducing waste generation and creating new value streams while maintaining compatibility with existing chemical manufacturing infrastructure. Biocatalysis and biotechnological approaches

7.4.2. Strategic recommendations

- Support development and industrial validation of renewable-carbon feedstocks and biomass-derived platform chemicals.
- Promote utilization of waste-derived and circular carbon resources as alternatives to virgin fossil feedstocks.
- Strengthen integration between carbon-management, biotechnology, and fine chemical manufacturing strategies.
- Encourage lifecycle-based evaluation of renewable and circular carbon technologies.
- Support collaboration between academia, industry, biotechnology providers, and waste-processing sectors to accelerate implementation of sustainable carbon sources.

7.5. Biocatalysis and biotechnological approaches

Strategic transformation objective

Development and implementation of biocatalytic and biotechnological manufacturing approaches enabling greener, more resource-efficient, and sustainable production of fine chemicals and pharmaceutical intermediates. The Strategy recognizes biocatalysis as one of the key enabling technologies of sustainable chemistry due to its ability to perform highly selective transformations under mild reaction conditions, frequently in aqueous media and without the need for hazardous reagents or extreme process conditions. Compared with conventional synthetic methodologies, biocatalytic processes can reduce energy consumption, minimize waste generation, decrease solvent demand, and improve overall material efficiency through superior chemo-, regio-, and stereoselectivity. In many cases, biocatalysis also enables shorter synthetic routes, reduces the need for protecting-group manipulations, and facilitates the use of renewable feedstocks and fermentation-derived intermediates. Consequently, biocatalysis represents an important technological pathway towards lower environmental impact, reduced process complexity, and more sustainable fine chemical and pharmaceutical manufacturing.[60-62]

8. Strategic Activities of GreenChemForCE

The GreenChemForCE (GCF) project serves as a practical implementation platform for the strategic framework described in this document and contributes directly to the **Regional Collaboration Pillar (Chapter 5), Educational Pillar (Chapter 6), and Technological Pillar (Chapter 7)**. Through cooperation between academic institutions, industrial partners, and sectoral organizations across Central Europe, the project supports the development and implementation of sustainable solutions for fine chemical and pharmaceutical manufacturing.

Within the **Regional Collaboration Pillar (Chapter 5)**, GCF strengthens cross-border cooperation, knowledge transfer, dissemination of best practices, and validation of sustainable technologies under industrially relevant conditions. The consortium facilitates collaboration between academia, industry, and public organizations, supporting the regional transition towards more sustainable chemical production.

Within the **Educational Pillar (Chapter 6)**, the project supports the development of Green Chemistry education through curriculum development, student involvement in sustainability-oriented research, creation of thesis opportunities, and establishment of dedicated Green Chemistry research activities at participating institutions.

The **Technological Pillar (Chapter 7)** focuses on the development and validation of technologies enabling greener chemical manufacturing. Key activities include **recovery and recycling of homogeneous catalysts, process intensification through low catalyst-loadings and continuous-flow technologies, implementation of renewable feedstocks and renewable-carbon-based building blocks, use of alternative and renewable solvents, development of solvent-free and solvent-minimized methodologies such as mechanochemistry, and application of biocatalytic transformations for selective and sustainable synthesis.** Together, these activities contribute to reduced waste generation, improved resource efficiency, lower dependence on fossil resources, and increased circularity within the chemical industry.

Overall, GreenChemForCE demonstrates how coordinated regional collaboration, educational development, and technological innovation can jointly support the transition towards a more sustainable and competitive chemical sector in Central Europe.

9. Conclusions

The Strategy identifies three principal technological priorities: sustainable solvent management, catalyst circularity and transition metal recovery, and the integration of renewable feedstocks and renewable carbon sources. These technological directions are supported by four interconnected strategic pillars: regulatory framework and governance, regional collaboration, education, and technological innovation.

The Strategy recognizes that sustainable transformation cannot be achieved through isolated technological improvements alone. Long-term progress requires coordinated action involving academia, industry, policymakers, and sectoral organizations. Regional cooperation will facilitate knowledge transfer, technology validation, and the development of circular value chains, while educational activities will ensure the availability of skilled professionals capable of implementing Green Chemistry principles in future industrial practice.

The technological activities promoted within GreenChemForCE, including catalyst recovery, process intensification, alternative solvent systems, mechanochemistry, flow chemistry, biocatalysis, and renewable feedstock utilization, demonstrate practical pathways towards reducing waste generation, lowering resource consumption, improving circularity, and decreasing dependence on fossil resources and critical raw materials.

Ultimately, the Strategy aims to contribute to the development of a resilient, competitive, and environmentally responsible chemical industry in Central Europe, aligned with the objectives of the European Green Deal, the Circular Economy Action Plan, and broader sustainability goals. By combining technological innovation, education, and regional cooperation, GreenChemForCE provides a foundation for the long-term implementation of Green Chemistry principles across the region.

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