Interreg CENTRAL EUROPE

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GreenChemForCE

Activity 3.1. Recovery of precious metals used as homogeneous catalyst

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Introduction

The GreenChemForCE project aims to reduce the negative environmental impact of the chemical industry in Central Europe. It seeks to bring together industrial and academic stakeholders to promote greener chemical production in the region by developing strategies and solutions for more sustainable processes and resource management. These efforts are intended to reduce pollution, minimize environmental damage, and encourage the adoption of circularity principles in chemical manufacturing. Additionally, the project strives to improve public perception of the chemical industry in the region.

The project partners include: Charles University (CU) as the lead partner; the Association of Chemical Industry of the Czech Republic (SCHP CR) and Zentiva from the Czech Republic; the Servier Research Institute of Medicinal Chemistry (SRIMC) and Eötvös Loránd University (ELU) from Hungary; TU Wien (TUW) and Vienna Textile Lab GmbH (VTL) from Austria; and the University of Ljubljana (UL) and the Chamber of Commerce and Industry of Slovenia (CCIS) from Slovenia.

To achieve its goals, the project is organized into the following work packages:

- WP1: Sustainable management of plastics – led by CCIS
- WP2: Carbon dioxide management in industry: emission reduction and utilization – led by SCHP CR
- WP3: Streamlining processes for the production of fine chemicals – led by UL

Within WP3, Charles University has prepared this analysis report to highlight the key challenges and opportunities addressed within this part of the project. The report focuses on strengthening sustainability in the chemical and pharmaceutical sectors, with particular attention to two critical resource streams: precious metals used in catalytic processes and organic solvents widely used in production workflows. Both groups of materials are essential for modern manufacturing, yet they are also linked to high costs, significant environmental impacts, and avoidable losses throughout their life cycle.

The first section focuses on the use of transition metals, particularly the platinum group metals (PGMs) and palladium especially, which remains one of the most widely used catalysts in modern synthetic chemistry. The analysis covers key focus areas such as the lifecycle and recovery of precious metals, their environmental footprint, and the specific context within the GreenChemForCE member countries (Czech Republic, Austria, Hungary, and Slovenia). It also evaluates recovery rates across the EU, provides a SWOT analysis of precious metals as homogeneous catalysts in the GreenChemForCE member countries, and considers the relevant EU legislative framework for metal recovery. This comprehensive review highlights both the scientific and technical importance of these metals and the economic, environmental, and supply-chain challenges associated with their use, underlining the need for alternative strategies and improved management practices.

The second section is dedicated to solvent management, a topic that continues to represent one of the most significant environmental and operational burdens in the chemical industry. It analyzes how solvent consumption, recovery, and disposal contribute to waste generation, and overall process inefficiency, with a particular focus on fine-chemical manufacturing. It provides a brief summary of industrial definition of safe and sustainable commonly used solvents. This part also reviews solvent practices within some of GreenChemForCE member organizations, illustrating current usage patterns.

Together, these two sections provide an integrated view of key sustainability challenges and will serve as a solid foundation for developing future strategies.

1. Precious Metals in industry – focus areas and primary goals

Precious metals are indispensable to modern industry, with their largest application in the automotive sector, followed by the chemical, jewelry, and electronics industries. Their exceptional catalytic, conductive, and corrosion-resistant properties enable cleaner transportation, efficient chemical production, and advanced technological innovation. The chart below highlights their wide-ranging industrial uses.

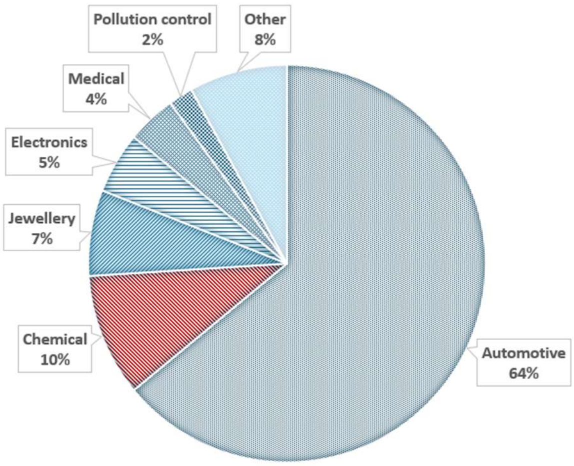

Fig 1: Global end-use distribution of platinum group metals (percent by industry)

(adapted from: Natural Resources Canada - Platinum facts (March 13, 2025))

Platinum group metals (PGMs) such as palladium (Pd), platinum (Pt), rhodium (Rh), ruthenium (Ru), and iridium (Ir) are extensively used as homogeneous catalysts in chemical, pharmaceutical, and fine chemical production across Central Europe, including Germany, the Czech Republic, Austria, Hungary, Poland, and Slovenia. These metals are critical for key reactions such as hydrogenation, carbon-carbon coupling, oxidation, and hydroformylation.

The precious metals industry is increasingly influenced by the global shift toward sustainability and green technologies. Metals such as silver, platinum, and palladium play a pivotal role in renewable energy applications, including solar panels and fuel cells. As adoption of green technologies accelerates and climate action intensifies worldwide, demand for these metals is expected to rise significantly.

In 2024, the European homogeneous precious metal catalyst market—covering platinum, palladium, rhodium, iridium, and ruthenium—was valued at approximately USD 1.3 billion, with palladium leading and platinum also prominent. This market is projected to grow to USD 5.96 billion by 2032, representing a CAGR of around 19% [1].

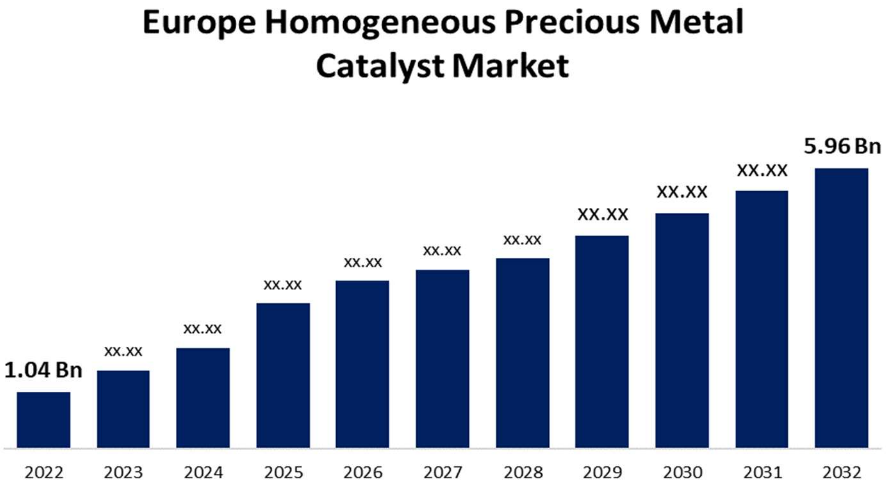

Fig 2: Europe Homogeneous Precious Metal Catalyst Market Size and Forecast

(source: Spherical Insights (Europe Homogeneous Precious Metal Catalyst Market Size forecasts), based on analysis for 2022-2032))

Despite this growth, primary PGM supply in 2024 reached only about 412 tones, falling short of consumption. Supply constraints are further intensified by the highly concentrated geographic distribution of PGM reserves: over 96% are located in just two countries—South Africa and Russia—which together produce more than 80% of the world's supply. As illustrated in the figure 3, Russia and South Africa dominate global palladium production, contributing approximately 40% and 38% of total output, respectively. The remaining production is spread across a few countries—Canada (8%), Zimbabwe (8%), the United States (4%), and other minor producers (2%).

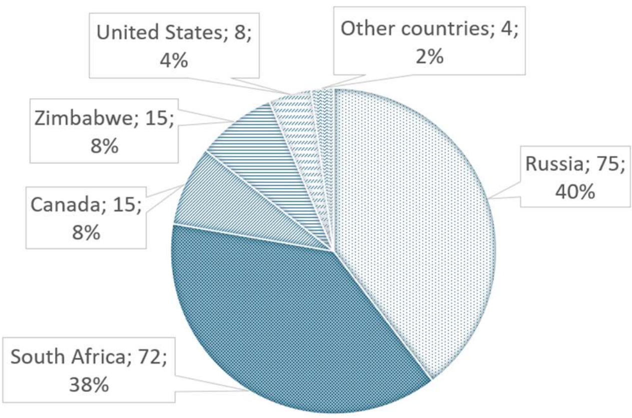

Fig 3: Global Palladium Mine Production by Country in 2024 (in metric tons and percentage)

(adapted from: Statista)

This extreme geographic concentration not only heightens supply vulnerability but also amplifies price volatility, directly shaping market dynamics over the past decade.

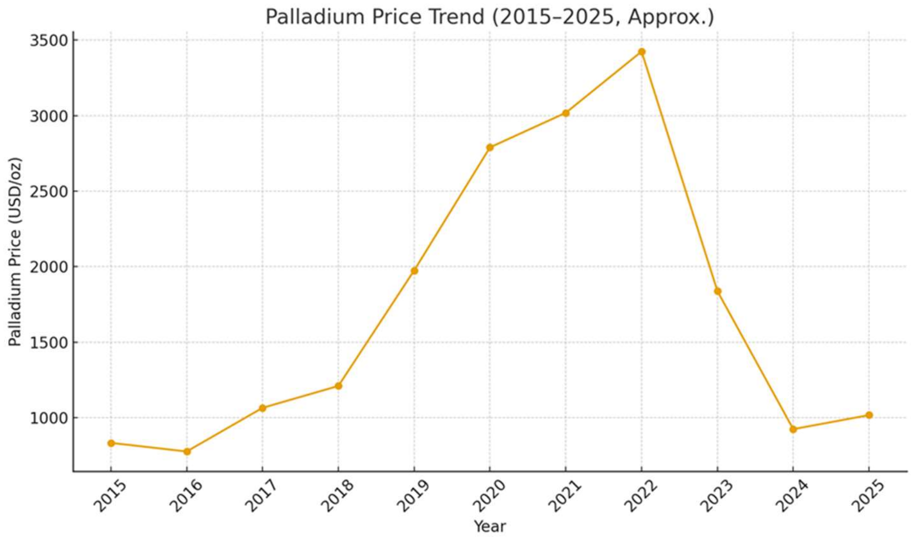

Figure 4: Palladium price trend

The figure 4 illustrates the global palladium price evolution over the past decade, showcasing a complete growth-peak-collapse-recovery cycle. From 2015 to 2018, palladium prices rose steadily from roughly $800/oz to $1,200/oz based on long-term historical price datasets [2], [3], [4]. This period reflects increasing industrial demand—particularly in automotive catalytic converters due to stricter emission standards [5], [6].

A significant acceleration occurred in 2019–2021, when persistent supply shortages and strong consumption drove prices above $3,000/oz, with an unprecedented high around $3,400/oz in early 2022 [2], [5], [6].

After this peak, the market experienced a rapid and prolonged correction. Between 2022 and 2024, palladium prices declined sharply by more than 70%, reaching decade lows near $900/oz, according to LBMA and Macrotrends data [2], [3], [4]. This downward trend was influenced by increased substitution with platinum and reduced supply-risk pressure [7], [8]. In 2025, the market shows partial recovery, stabilizing around $1,000–1,400/oz [2], [6].

Despite the decline, palladium remains a Critical Raw Material for the EU, with highly concentrated primary production and strong supply vulnerabilities [7], [9], [10]. Recovery from secondary sources—such as pharmaceutical catalysts and industrial waste—is therefore strategically important for reducing supply dependence, improving resource circularity, and supporting sustainability objectives outlined in EU critical raw materials policy [7], [9].

Recycling has added more than 150 tonnes annually to the global PGM supply in recent years, with approximately 75% sourced from end-of-life catalytic converters. However, even combined primary mining and recycling efforts struggle to match the pace of rising demand due to technological limitations and supply chain complexities.

For Central Europe, the recovery of precious metals used as homogeneous catalysts is a strategic priority. These metals—especially palladium, platinum, and rhodium—are essential for high-value manufacturing sectors such as pharmaceuticals, fine chemicals, and advanced materials. The region’s strong dependence on imports from geopolitically sensitive areas makes it vulnerable to price volatility and supply disruptions. Implementing efficient recovery technologies would enhance resource independence, reduce production costs, and ensure stable access to critical raw materials. Moreover, recycling directly supports the EU’s Green Deal objectives by reducing the environmental footprint of mining, fostering a circular economy, and minimizing hazardous waste. This approach not only safeguards industrial competitiveness but also reinforces the region's strategic resilience.

The primary objective of this project stage is to analyze current trends in the use of precious metals as homogeneous catalysts in Central Europe, with a particular focus on the Czech Republic, Austria, Slovenia, and Hungary, as well as to investigate the most promising and environmentally friendly methods for their recovery

2. Lifecycle of Precious Metals in Industry

The lifecycle of precious metals spans from extraction and mining (entering the anthroposphere from ore stocks), through refining, manufacturing, and industrial use, to waste generation, recycling, and back into supply chains—with losses along the way as shown in the central loop of the diagram 1.

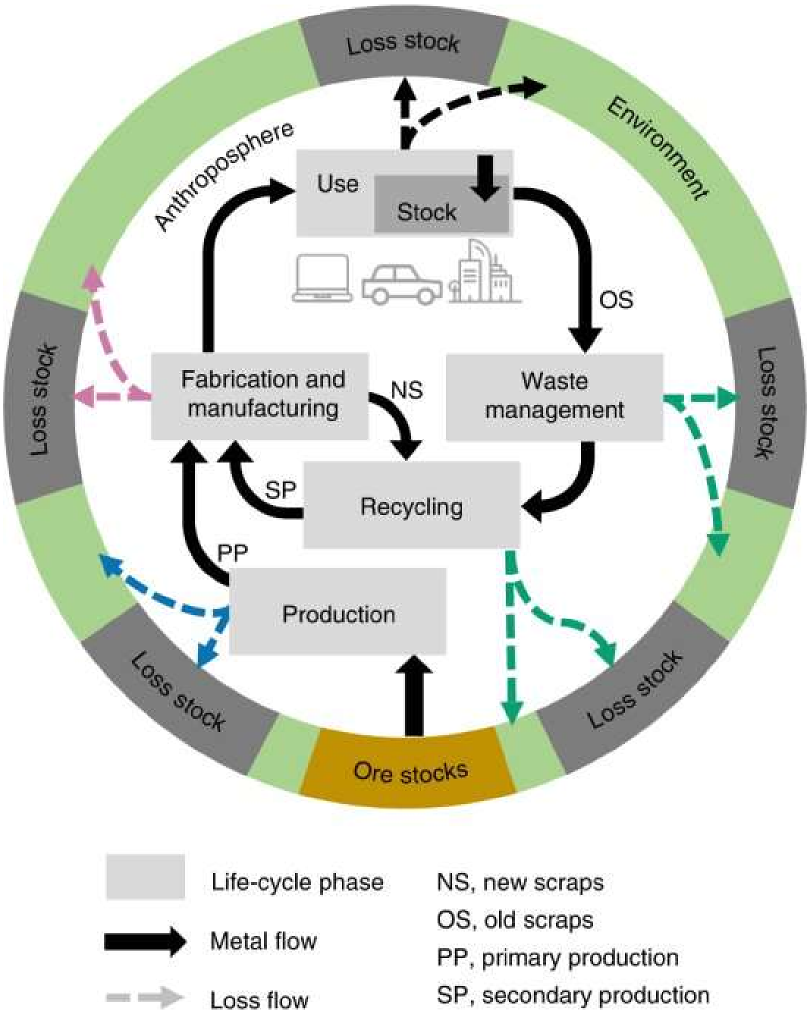

Diagram 1: Global cycle of precious metals.

(Source: Nature Sustainability (2022). DOI: 10.1038/s41893-022-00895-8). Reprinted with permission.

Understanding this circular flow is essential, as it reveals where environmental pressures accumulate within the system. Accordingly, even in recycling pathways—often viewed as the more sustainable option—the environmental footprint per kilogram of precious metals remains remarkably high.

3. Environmental Footprint of Precious Metals

The environmental footprint per kilogram of precious metals is substantial, even when recovered through recycling. Life cycle assessments (LCAs) show that:

- Recycling palladium from scrap typically incurs ~180 kg CO_2-eq/kg, compared with ~60 kg CO_2-eq/kg for platinum, ~40 kg CO_2-eq/kg for gold, and ~11 kg CO_2-eq/kg for silver. The majority of these impacts (80–90%) arise from energy consumption and chemical reagents used in refining processes [11]
- In contrast, the footprint of primary precious metal production is orders of magnitude higher. A recent LCA reports ~18,000–36,000 kg CO_2-eq per kg of platinum and ~28,000 kg CO_2-eq/kg of palladium under baseline 2022 conditions [11]. These figures place primary platinum-group metal (PGM) production among the most carbon-intensive industrial processes worldwide.

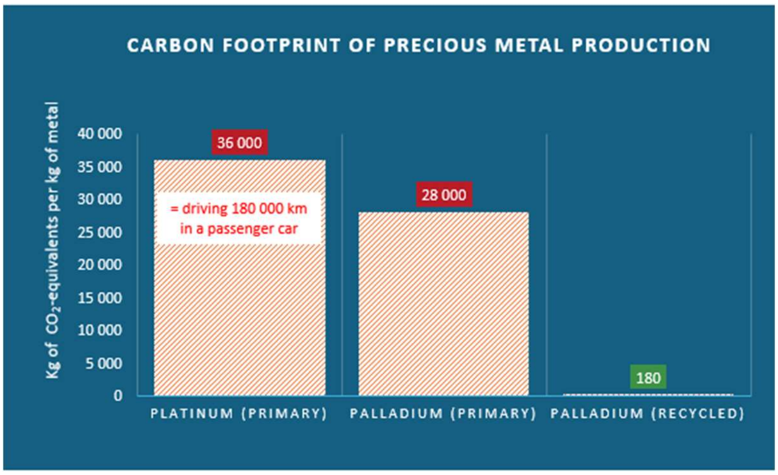

Figure 5: Carbon Footprint of Primary vs. Recycled Precious Metal Production

Sectoral statistics are generally reported as total demand by end use rather than separated into primary and secondary metal. Separation of primary and secondary metal flows for individual end-use sectors is not published by major market analysts (WPIC, Johnson Matthey, USGS, SFA Oxford). The chemical-sector statistics report gross demand, which includes both newly mined ("primary") metal and metal returned via closed-loop recycling from catalyst reprocessing.

Several factors make disaggregation impossible with publicly available data:

- Closed-loop recycling systems — especially in chemical and petrochemical catalysis — reintroduce PGMs directly to refiners without appearing as separate supply streams.
- Refiners pool primary and recycled metal, meaning the chemical industry purchases undifferentiated "metal units" regardless of source.
- No sector-specific recycling datasets exist, because recycling companies treat PGM catalyst returns as proprietary information.

As a result, the most robust method is to compare sectoral demand with global primary production, which provides a defensible estimate of how much newly mined Pt and Pd must enter the chemical sector each year.

For platinum, the chemicals sector accounts for about 8–10% of global Pt demand, corresponding to roughly 22–23 tons of Pt per year [12]. When compared with global mine output of around 178 tons Pt in 2024, this implies that approximately 10–15% of primary platinum production is associated with chemical uses, even though a large share circulates in closed-loop recycling systems [13]. For palladium, industrial chemical demand is estimated at 17–22 tons of Pd per year, i.e. roughly 5–7% of total palladium demand [14], which corresponds to about 10% of global mined palladium (≈206,9 tons in 2025) when compared with primary supply [13].

Metric	Platinum (Pt)	Palladium (Pd)
Global chemical-sector demand	~22–23 tons/year	~17–22 tons/year
Share of total global demand	8–10%	5–7%
Global mine production (primary)	~178 tons/year	~206,9 tons/year
Approx. share of primary supply tied to chemical uses	10–15%	~10%
Recycling contribution	Significant (circular loops in chemical catalysts)	Significant but lower than Pt (shorter catalyst lifetimes)

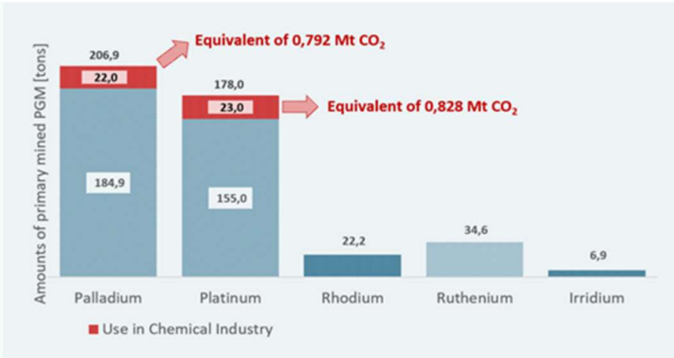

Figure 6: Carbon Emissions Linked to Primary PGM Use in Chemical Applications

(chart representing the higher limits of estimation)

Taken together, the comparison underscores the critical role of recycling and advanced recovery technologies. By reducing reliance on primary extraction and minimizing “loss stocks” across the supply chain, secondary sourcing of PGMs can dramatically cut lifecycle emissions while improving supply security within a circular economy framework.

4. Recovery Rates of Precious Metals in the EU

In the European Union, transition metals such as copper (Cu), nickel (Ni), cobalt (Co), manganese (Mn), and zinc (Zn) are essential to clean-energy technologies, electArical infrastructure, and advanced manufacturing [15]. Precious metals—including gold (Au), silver (Ag), and the platinum-group metals (PGMs: Pt, Pd, Rh, Ru, Ir, Os)—form a highly valuable and strategically important subgroup within the broader family of transition metals. Their unique catalytic and electronic properties make them indispensable in high-tech applications, while their high economic value places them at the core of the EU’s circular-economy priorities. [16]

Despite their high economic importance and well-developed collection chains for certain waste streams, EU recycling indicators reveal significant gaps between technical potential and actual recovery. The European Commission and the Joint Research Centre (JRC) assess recycling performance using the End-of-Life Recycling Rate (EOL-RR)—the share of metal in end-of-life waste that is recovered—and the End-of-Life Recycling Input Rate (EOL-RIR)—the share of EU total supply met by recycled old scrap. These indicators show that precious metals generally outperform most critical raw materials but still fall short of what would be expected given their high value and strong strategic relevance [17].

According to the Raw Materials Scoreboard (EU-28), precious metals such as silver and gold have among the highest EOL-RIR values in the EU (Ag ~23%, Au ~13%), while palladium stands out as one of the very few critical raw materials with measurable recycled contribution to EU supply [18]. However, these values remain far from sufficient, especially considering the high collection rates of some streams like automotive catalysts. A recent EU assessment (H2020 PEACOC) estimates that Europe meets only ~21% of its PGM demand through recycled end-of-life products, despite much higher recovery from autocatalysts (about 50–60%) and extremely low recovery from electronics (5–10%) and fine-chemical/pharmaceutical residues (<5%) [19]. This mismatch highlights how substantial quantities of precious metals are still lost in complex waste matrices—exactly the type of streams targeted by the Interreg project.

Overall circularity also remains low. Eurostat reports that only 11–13% [20] of all materials used in the EU come from recycled sources (Circular Material Use Rate, CMUR), creating a structural limitation for secondary metals, including precious metals. EU policy recognises this gap: under the EU Critical Raw Materials Act (CRMA), the Union has set a goal that 25% of annual consumption of strategic raw materials—a category that includes PGMs—should come from EU recycling by 2030 [21]. This policy emphasis explicitly acknowledges that, while precious metals already perform better than many other critical raw materials, their recycled contribution is still far below strategic needs, and innovative recovery solutions are required to capture metals from low-concentration or unconventional streams [22].

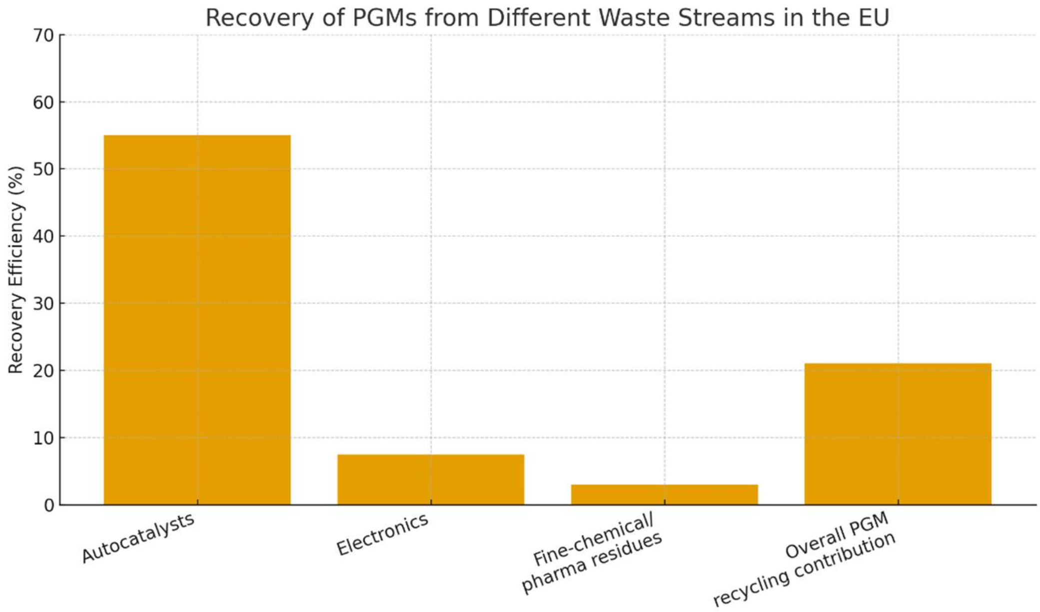

Figure 6: Recovery of PGMs from Different Waste Streams in the EU

Figure 6 illustrates the strong variation in recovery efficiency of platinum-group metals (PGMs) across major waste streams highlighting the strategic need to improve recovery from low-concentration and complex waste streams—such as those targeted in the Interreg project.

For the Interreg project, this European context reinforces the importance of developing new recovery approaches for palladium and related metals. Precious metals have high intrinsic value, well-established market demand, and relatively strong recycling rates from certain sources; however, large fractions remain unrecovered in fine-chemical, pharmaceutical, and electronic waste streams. Improving recovery from these underutilised sources directly aligns with EU strategic objectives, increases supply security, and supports the long-term shift toward a circular, resilient European materials system.

5. Precious Metals in Central Europe

Precious metals, particularly platinum group metals (PGMs) such as platinum, palladium, rhodium, ruthenium, and iridium, are classified by the European Union as critical raw materials due to their strategic industrial importance and limited global availability. Their exceptional catalytic properties make them indispensable in homogeneous catalysis, with significant applications in the pharmaceutical and chemical sectors. For Central European countries—most notably Czechia, Austria, Hungary, and Slovenia—domestic primary production is negligible, resulting in a strong reliance on external suppliers and international trade flows. A detailed understanding of import patterns, consumption trends, and sectoral allocation is therefore essential for assessing supply security, advancing recovery strategies, and aligning with the EU's broader objectives on resource efficiency and circular economy.

Country / Scope	**Gold Compounds [23]**	**Other Precious Metal Compounds [24]**	**Platinum [25]**	**Supported Catalysts [26]**	**Main Suppliers**
Czechia	67.6	-	23.1	425	Germany, UK
Austria	16.4	35.1	-	-	Germany, Switzerland
Hungary	1.27	1.27	-	15.9	Germany, USA, China, Slovenia
Slovenia	0.67	-	-	0.47	Ireland, UK, Czechia
Global Chemical Use (2024)	-	-	Pt ~18 t	Pd ~17 t; Rh ~3 t; Ru ~17.4 t; Ir ~1.2 t	Global industry data (Johnson Matthey, WPIC)

Table 1: Trade in Precious Metal Compounds: Central European Imports and Suppliers (source: World Integrated Trade Solution)

Table 1 summarizes the trade flows and catalytic use of precious metals in Central Europe, with a focus on Czechia, Austria, Hungary, and Slovenia. The data highlight the strong role of Germany, Switzerland, and the UK as key suppliers, and show Czechia's position as both a major importer and exporter of supported catalysts. For context, the table also includes global chemical-sector consumption of platinum group metals (PGMs), illustrating the scale of catalytic demand worldwide and underscoring the importance of sustainable recovery and recycling strategies.

6. SWOT Analysis: Precious Metals as Homogeneous Catalysts.

6.1. Czech Republic

Strengths	Weaknesses
• Established chemical and pharmaceutical industries with strong R&D capacity ([27] • Skilled workforce and academia-industry collaboration [28] • Access to EU markets and funding for innovation in catalysis and green chemistry [29] • Czechia is a regional hub for catalyst trade and distribution [30]	• No domestic primary production of PGMs; full reliance on imports [31] • High cost volatility of Pt, Pd, Rh creates financial risks [32] • Limited domestic recycling/recovery infrastructure compared to Western Europe [33] • Dependence on narrow set of suppliers [34]
Opportunities	**Threats**
• Growing demand in pharmaceutical synthesis [35] • EU circular economy and CRM strategies support local recycling initiatives [36] • Potential for public-private partnerships in recovery and waste valorization [37] • Integration of innovative, sustainable catalytic methods (ligand recycling, nanostructures, bio-hybrids) [38]	• Geopolitical risks and supply chain disruptions (Russia, South Africa) [39] • Competition from cheaper Asian suppliers and global PGM demand in automotive/hydrogen [31] • Stricter environmental regulations may raise compliance costs [40] • Concentration of IP in advanced catalyst technologies limits autonomy [41]

Table 2: SWOT Analysis: Precious Metals as Homogeneous Catalysts in the Czech Republic

This SWOT analysis highlights both the strategic importance and vulnerability of the Czech Republic in relation to precious metals used as homogeneous catalysts. While the country benefits from strong research capacity, established pharmaceutical and chemical sectors, and integration into European trade networks, its full dependence on imports and limited domestic recovery infrastructure create significant exposure to market volatility and supply chain risks. At the same time, EU priorities on critical raw materials, sustainability, and circular economy provide a unique window of opportunity for Czechia to position itself as a regional leader in catalyst recovery and recycling technologies, thereby enhancing industrial resilience and reducing dependence on external suppliers.

6.2. Austria

Strengths	Weaknesses
• Vibrant chemical and pharmaceutical industry with active R&D [42] • Presence of metallurgical companies processing catalyst materials, e.g., Treibacher Industrie AG [43] • Strong integration into EU supply networks; significant imports of supported catalysts (~US$108m, mainly Germany & Poland) [44]	• No domestic mining or primary production of PGMs; full reliance on imports [45] • High volatility of PGM prices (Pt, Pd, Rh) creates economic uncertainty [32] • Recycling capacity exists but is limited compared to Western Europe [33]
Opportunities	**Threats**
• Rising global demand for fine chemicals and APIs using Pd and Pt catalysts [46] • EU circular economy strategy supports recovery and recycling initiatives [45] • Potential for public-private ventures leveraging biotech and metallurgy expertise [47]	• Supply risks from geopolitical tensions (Russia, South Africa) [49] • Competition from lower-cost Asian catalyst producers [41] • Stricter EU environmental regulations may increase compliance costs [40]

Table 3: SWOT Analysis: Precious Metals as Homogeneous Catalysts in Austria

Austria benefits from a well-developed chemical and pharmaceutical sector and the presence of companies like Treibacher Industrie AG, which process and recycle precious-metal-containing materials. Strong integration into European supply chains and R&D centers (e.g., ACIB) support catalyst use and innovation. At the same time, Austria has no domestic PGM sources and is vulnerable to market volatility and geopolitical disruptions. EU funding and circular economy strategies create opportunities to expand recovery capacity and strengthen resilience, while external competition and regulatory pressure may pose risks.

6.3. Hungary

Strengths	Weaknesses
• Strong pharmaceutical industry (e.g., Gedeon Richter, Egis) driving demand for PGM catalysts [41] • Integration with EU markets and suppliers, mainly Germany [45] • Skilled workforce and tradition in chemical R&D [48]	• No domestic PGM mining or primary production [45] • Heavy reliance on imports of catalysts and compounds [44] • Limited recycling/recovery infrastructure [43]
Opportunities	**Threats**
• EU circular economy initiatives create funding potential for catalyst recovery [45] • Scope for public-private partnerships in recycling and sustainable catalysis [47] • Chance to strengthen position as pharmaceutical hub with sustainable catalyst use [46]	• Supply chain disruptions and geopolitical dependence (Russia, South Africa) [39] • Competition from global suppliers with lower costs [31] • Stricter EU environmental regulations [40]

Table 4: SWOT Analysis: Precious Metals as Homogeneous Catalysts in Austria

Hungary's pharmaceutical industry is internationally recognized (notably Gedeon Richter and Egis), driving demand for homogeneous PGM catalysts in drug synthesis. Imports of supported catalysts and precious-metal compounds primarily come from Germany and other EU partners, underlining dependence on external supply. Hungary's weaknesses include absence of primary production and limited domestic recycling infrastructure, but opportunities exist to integrate into EU-funded recovery initiatives and expand public-private partnerships. Geopolitical vulnerabilities, competition from global suppliers, and tightening EU regulations remain the primary threats

6.4. Slovenia

Slovenia hosts a smaller but dynamic pharmaceutical sector (with companies like Krka and Lek) that relies on imports of gold compounds and supported catalysts from European partners. Its strengths lie in EU integration and established pharma capabilities, though small market size and complete import dependence limit autonomy. Opportunities arise from Slovenia's potential to position itself as a specialized niche player in sustainable catalyst applications and to benefit from EU circular economy programs. Key threats include supply chain volatility, regulatory tightening, and global competition from lower-cost producers.

Strengths	Weaknesses
• Dynamic pharmaceutical sector (e.g., Krka, Lek) with catalyst-intensive drug synthesis [49] • EU integration and access to common market [40] • Skilled workforce and tradition in pharma chemistry [41]	• Small market size and limited industrial scale [41] • Complete import dependence for precious metals and catalysts [34 44] • Limited domestic recycling/recovery infrastructure [23 43]
Opportunities	**Threats**
• EU circular economy initiatives create space for niche roles in sustainable catalysis [45] • Potential to build expertise in specialized catalyst applications [48] • Chance to leverage pharma sector for pilot projects in catalyst recovery [47]	• Exposure to supply chain volatility [39] • Global competition from larger and cheaper catalyst producers [31] • Compliance costs rising with stricter EU environmental standards [40]

Table 5: SWOT Analysis: Precious Metals as Homogeneous Catalysts in Slovenia

Overall, the comparative analysis reveals that Central European countries share a structural dependence on imported PGMs and face similar risks of price volatility, supply disruptions, and regulatory pressures. At the same time, their well-developed pharmaceutical and chemical sectors, combined with strong research capacity and EU integration, position the region as a potential leader in sustainable catalyst use and recovery. Coordinated strategies—such as joint research programs, cross-border recycling initiatives, and alignment with EU funding opportunities—could enable Czechia, Austria, Hungary, and Slovenia to transform these shared challenges into a competitive advantage within Europe’s transition to a circular economy.

7. EU Legislative Context for Precious Metal Recovery

The recovery of precious metals in Europe is strongly influenced by the evolving regulatory framework of the European Union. Recent initiatives, such as the Critical Raw Materials Act (2024), the Circular Economy Action Plan, and sector-specific regulations on waste, batteries, and electronic equipment, reflect the EU’s strategic aim to secure access to critical resources while reducing environmental impacts. These measures establish binding targets for recycling, promote eco-design and traceability, and support investment in sustainable recovery technologies. As a result, legislative developments not only provide a regulatory driver but also create significant opportunities for innovation in precious metal recovery within Central Europe.

EU policies such as the Critical Raw Materials Act, the Waste Framework Directive, and sector-specific regulations on batteries and electronic waste (WEEE, RoHS) create the regulatory foundation for enhancing circularity. Together, these measures establish binding recycling targets, strengthen cross-border waste management, and encourage eco-design, making them central drivers for innovation in the recovery of precious metals.

Legislation / Directive	Focus Area	Implications for Precious Metals
Critical Raw Materials Act (2024)	Supply security, recycling targets	Promotes recovery of PGMs, reduces import reliance
Waste Framework Directive (2008/98/EC)	Waste hierarchy, circularity	Prioritizes recycling of metal-rich waste streams
Circular Economy Action Plan (2020)	Resource efficiency, eco-design	Encourages design for recyclability and reuse
Battery Regulation (2023/1542)	Battery lifecycle, recycling targets	Sets binding recovery rates for critical metals
WEEE Directive	E-waste collection & recycling	Ensures recovery of precious metals from electronics
RoHS Directive	Hazardous substance restrictions	Improves recyclability, supports cleaner recovery flows

Table 6: Overview of key EU legislation relevant to precious metal recovery

The European Union has established ambitious targets to enhance the recovery of critical raw materials, including precious and platinum-group metals, under recent legislation such as the Critical Raw Materials Act (2024) and the Battery Regulation (2023/1542). By 2030, at least 25% of CRMs are expected to be sourced from recycling, while recovery targets for lithium, cobalt, and nickel reach 70–95%, reflecting the EU's commitment to building a resilient and sustainable resource supply chain. These policy-driven targets highlight the strategic importance of developing eco-friendly and scalable technologies for precious metal recovery in Central Europe.

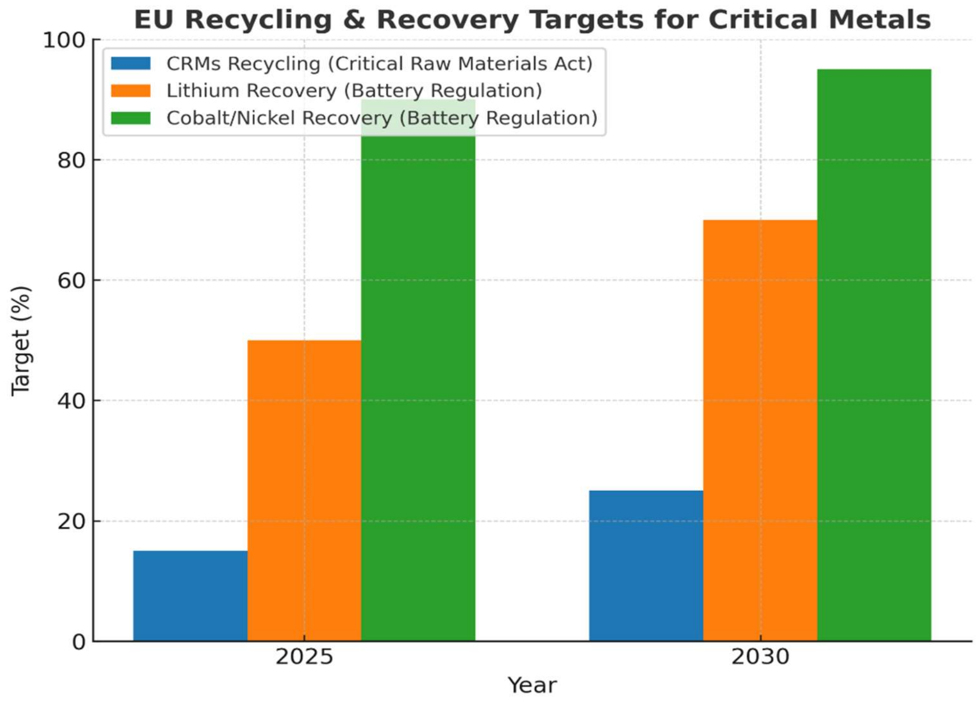

Figure 7: EU recycling and recovery targets for critical metals (2025–2030)

Against this regulatory backdrop, the development and implementation of advanced recovery technologies become not only a scientific challenge but also an industrial necessity. The following section therefore examines the principal methods for precious metal recovery, with a particular emphasis on approaches that combine eco-friendliness with industrial scalability, in line with EU policy objectives.

8. Conclusions

The analysis of precious metal usage and recovery in Central Europe highlights both the strategic importance of these resources and the pressing need for sustainable management practices. Platinum-group metals, in particular, play a vital role as homogeneous catalysts in the chemical and pharmaceutical industries of the Czech Republic, Austria, Hungary, and Slovenia. Yet, the region remains highly dependent on external supply, much of which originates from geopolitically unstable or unreliable countries, resulting in price volatility and supply insecurity. At the same time, primary mining of transition and precious metals carries an extremely high environmental footprint compared with recycling, especially in terms of CO_2 emissions, land use, and energy intensity. For these reasons, increasing the share of metals recovered from secondary sources is both environmentally and economically desirable, reducing dependence on high-risk suppliers while lowering the climate impact of industrial production.

European legislation — from the Critical Raw Materials Act to the Circular Economy Action Plan — creates a favorable regulatory environment that both compels and supports innovation in this field. By aligning scientific research, industrial practice, and policy frameworks, Central Europe can move towards greater resource autonomy, circularity, and environmental sustainability.

In the context of the Interreg project, this report provides a foundation for identifying and piloting recovery methods that not only address regional industrial needs but also contribute to broader EU strategic objectives. Continued collaboration between academia, industry, and policymakers will be essential to transform promising laboratory-scale innovations into robust industrial solutions capable of shaping a resilient and sustainable future for precious metal utilization.

List of References

1. Spherical Insights LLP. (2023). Europe Homogeneous Precious Metal Catalyst Market Size, Share, and COVID-19 Impact Analysis, by Catalyst Type (Gold, Platinum, Iridium, Palladium, Rhodium, Ruthenium, Others), by Industry Verticals (Refineries, Electrochemical, Power Generation, Agrochemicals, Pharmaceutical & Biomedical, Other Verticals), by Country, and Europe Homogeneous Precious Metal Catalyst Market Insights Forecasts to 2032. Retrieved from:

https://www.sphericalinsights.com/reports/europe-homogeneous-precious-metal-catalyst-market

2. Macrotrends LLC. Palladium Prices – Historical Chart Data. Macrotrends, 2025. Historical daily palladium prices in USD/oz (accessed 3 December 2025). Available at:

https://www.macrotrends.net/2542/palladium-prices-historical-chart-data

3. London Metal Exchange. LBMA Palladium – Historical Prices and Volumes. London Metal Exchange, 2025. Daily and monthly palladium price series (accessed 3 December 2025). Available at:

https://www.lme.com/en/metals/precious/lbma-palladium/historical-prices-and-volumes

4. London Bullion Market Association (LBMA). Precious Metal Prices – Gold, Silver, Platinum and Palladium. LBMA, London, 2025 (accessed 3 December 2025). Available at: https://www.lbma.org.uk/prices-and-data/precious-metal-prices

5. World Bank. Commodity Price Data (The Pink Sheet): CMO Historical Data – Monthly and Annual. World Bank, Washington, DC, 2025. Palladium prices reported in USD per troy ounce (accessed 3 December 2025). Available at:

https://thedocs.worldbank.org/en/doc/CMO-Historical-Data-Monthly.xlsx

https://thedocs.worldbank.org/en/doc/CMO-Historical-Data-Annual.xlsx

6. International Monetary Fund (IMF). Primary Commodity Prices – Commodity Data Portal; Table 3: Actual Market Prices for Non-Fuel and Precious Metals. IMF, Washington, DC, 2025 (accessed 3 December 2025). Available at:

https://www.imf.org/en/research/commodity-prices

https://www.imf.org/.../table3.pdf

7. Trading Economics. Palladium – Price, Chart, Historical Data. TradingEconomics.com, 2025 (accessed 3 December 2025). Overview of spot and futures prices for palladium. Available at:

https://tradingeconomics.com/commodity/palladium

8. European Commission. Critical Raw Materials. Single Market and Economy, European Commission, Brussels, 2023-2025 (accessed 3 December 2025). Policy framework and EU list of Critical Raw Materials, including PGMs. Available at:

https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en

9. European Commission. Strategic Raw Materials – Platinum Group Metals (PGMs). Factsheet under the Critical Raw Materials Act. Publications Office of the European Union, Luxembourg, 2025, 1 p. Highlights EU dependence on imported PGMs and the role of recycling (accessed 3 December 2025). Available at:

https://single-market-economy.ec.europa.eu/.../RMSP_PGMs_Factsheet_V2.pdf

10. European Commission Joint Research Centre (JRC). Palladium: Impact Assessment for Supply Security. Raw Materials & the War in Ukraine – Quick Guide, JRC Technical Report JRC133117, European Union, 2023, 8 pp. Discusses global and EU Pd supply, market deficits, and the contribution of recycling. Available at:

https://rmis.jrc.ec.europa.eu/uploads/jrc133117_briefing_palladium_final.pdf

11. Treeze & C.HAFNER. (2022). Life Cycle Assessment of Precious Metal Recycling and Refining Processes. Treeze Ltd. and C.HAFNER GmbH & Co. KG.

12. World Platinum Investment Council (WPIC). (2023). Platinum Essentials – August 2023. World Platinum Investment Council. Retrieved from: https://www.platinuminvestment.com

13. Nornickel. (2025). Quintessentially PGMs: Market Outlook and Supply-Demand Balance 2025. Norilsk Nickel, Moscow.

14. SFA (Oxford). (2023). Palladium Market and Price Outlook 2023. SFA (Oxford) Ltd., United Kingdom.

15. European Commission. (2018). Raw Materials Scoreboard 2018. European Innovation Partnership on Raw Materials (EIP). Publications Office of the European Union. Retrieved from:

https://op.europa.eu/

16. Hagelüken, C., & Goldmann, D. (2022). Recycling and circular economy—towards a closed loop for metals in emerging clean technologies. Mineral Economics, 35, 539-562. Retrieved from:

https://doi.org/10.1007/s13563-022-00319-1

17. Talens Peiró, L., Nuss, P., Mathieux, F., & Blengini, G. A. (2018). Towards recycling indicators based on EU flows and Raw Materials System Analysis data: Supporting the EU-28 raw materials and circular economy policies through RMIS. JRC Technical Report EUR 29435 EN. Luxembourg: Publications Office of the European Union. Retrieved from:

https://doi.org/10.2760/092885

18. European Commission. (2018). Raw Materials Scoreboard 2018. European Innovation Partnership on Raw Materials (EIP). Luxembourg: Publications Office of the European Union. Retrieved from:

https://doi.org/10.2873/398823

19. PEACOC Project. (2022). Platinum Group Metals Recovery Using Selective CO_2-Tailored Processes (PEACOC). Horizon 2020, GA No. 958457. Retrieved from:

https://www.peacoc-h2020.eu/

20. Eurostat. (2020–2024). Circular Material Use Rate (CMUR): EU Indicators on Material Circularity and Secondary Raw Materials. Eurostat Database, European Commission. Retrieved from:

https://ec.europa.eu/eurostat/

21. European Commission. (2023). Critical Raw Materials Act (CRMA). COM(2023) 160 final. Retrieved from:

https://single-market-economy.ec.europa.eu

22. UNEP. (2011). Recycling Rates of Metals: A Status Report. International Resource Panel. Retrieved from:

https://www.resourcepanel.org/reports/recycling-rates-metals

23. UN Comtrade. (2023). International Trade Statistics for HS 2843.30: Precious Metal Catalysts, Imports and Exports (USD millions). United Nations Statistics Division. Retrieved from:

https://comtrade.un.org

24. UN Comtrade. (2023). International Trade Statistics for HS 2843.90: Other Inorganic or Organic Compounds of Precious Metals (USD millions). United Nations Statistics Division. Retrieved from:

https://comtrade.un.org

25. UN Comtrade. (2023). International Trade Statistics for HS 7110.11: Platinum, Unwrought or in Powder Form (USD). United Nations Statistics Division. Retrieved from:

https://comtrade.un.org

26. European Commission. (2020). Study on the EU's List of Critical Raw Materials – Final Report. Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs. Publications Office of the European Union.

https://doi.org/10.2873/11619

27. CzechInvest. (2023). Investment and Business Development in the Czech Republic: Annual Report 2023. CzechInvest – Investment and Business Development Agency, Prague. Retrieved from:

https://www.czechinvest.org

28. Ministerstvo školství, mládeže a tělovýchovy (MŠMT). (2022). Výroční zpráva o stavu a rozvoji vzdělávací soustavy v České republice 2022. Praha: MŠMT. Retrieved from:

https://www.msmt.cz

29. European Commission. (2024). Horizon Europe: The Framework Programme for Research and Innovation 2021–2027 – Programme Overview and Budget Implementation Update 2024. Brussels: Directorate-General for Research and Innovation. Retrieved from:

https://research-and-innovation.ec.europa.eu

30. UN Comtrade. (2023). United Nations International Trade Statistics Database (Comtrade): Global Trade Data by HS Codes, 2023 Edition. United Nations Statistics Division. Retrieved from:

https://comtrade.un.org

31. Johnson Matthey. (2025). PGM Market Report 2025. Johnson Matthey Plc. Retrieved from:

https://matthey.com

32. World Platinum Investment Council (WPIC). (2024). Platinum Quarterly Report 2024. World Platinum Investment Council. Retrieved from:

https://www.platinuminvestment.com

33. European Environment Agency (EEA). (2021). Europe's Circular Economy — Progress and Challenges. EEA Report No. 11/2021. Luxembourg: Publications Office of the European Union.

34. UN Comtrade. (2023). International Trade Statistics for Germany, Switzerland, and the United Kingdom: Bilateral and Global Trade Data by HS Codes (2023 Edition). United Nations Statistics Division. Retrieved from:

https://comtrade.un.org

35. OECD. (2023). Emission Scenario Document on the Use of Catalysts in Industrial and Laboratory Chemical Processes. Series on Emission Scenario Documents, No. 42. Organisation for Economic Co-operation and Development. Retrieved from:

https://www.oecd.org

36. European Commission. (2023). Annex to the Proposal for a Regulation Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials — EU List of Critical Raw Materials 2023. COM (2023) 160 final. Brussels: European Commission.

37. EIT RawMaterials. (2023). Raw Materials Intelligence and Innovation in Europe: Annual Report 2023. EIT RawMaterials GmbH, Berlin. Retrieved from:

https://www.eitrawmaterials.eu

38. Royal Society of Chemistry (RSC). (2022). Catalysis: Innovation and Impact — RSC Catalysis Community Report 2022. Royal Society of Chemistry, London.

39. U.S. Geological Survey (USGS). (2024). Platinum-Group Metals: Mineral Commodity Summaries 2024. U.S. Geological Survey, Reston, VA.

40. European Chemicals Agency (ECHA). (2023). Substances of Very High Concern (SVHC) and Restriction Lists: Regulatory Developments 2023. European Chemicals Agency, Helsinki. Retrieved from:

https://echa.europa.eu

41. Organisation for Economic Co-operation and Development (OECD). (2022). Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences. OECD Publishing, Paris.

42. ACIB – Austrian Centre of Industrial Biotechnology. (2023). Annual Report 2023: Innovation in Industrial Biotechnology and Biocatalysis. ACIB GmbH, Graz, Austria. Retrieved from:

https://acib.at

43. Treibacher Industrie AG. (2025). Sustainable Advanced Materials and Precious Metal Catalysts: Corporate Report 2025. Treibacher Industrie AG, Althofen, Austria. Retrieved from:

https://www.treibacher.com

44. UN Comtrade. (2021). International Trade Statistics for HS 3815.12: Supported Catalysts with Precious Metals (value in USD), 2021 Edition. United Nations Statistics Division. Retrieved from:

https://comtrade.un.org

45. European Commission. (2023). 2023 EU List of Critical Raw Materials. Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs. Brussels: European Commission. Retrieved from:

https://single-market-economy.ec.europa.eu

46. Grand View Research. (2024). Precious Metals Market Size, Share & Trends Analysis Report, 2024–2032. Grand View Research, San Francisco, CA. Retrieved from:

https://www.grandviewresearch.com

47. EIT RawMaterials. (2024). Raw Materials Innovation, Education and Ecosystem Development: Annual Report 2024. EIT RawMaterials GmbH, Berlin. Retrieved from:

https://www.eitrawmaterials.eu

48. Hungarian Academy of Sciences (MTA). (2022). Annual Report 2022: Research, Innovation and Strategic Scientific Activities. Magyar Tudományos Akadémia, Budapest. Retrieved from:

https://mta.hu

49. Krka, d. d., Novo Mesto. (2023). Annual Report 2023. Krka Pharmaceutical Group, Slovenia. Retrieved from:

https://www.krka.biz

9. Solvents in fine chemical and pharmaceuticals preparation

9.1. Background

Chemical industry has been rapidly expanding. In 2017, it was the world's second-largest manufacturing sector, and its production is projected to double between 2017 and 2030 [1]. However, solvent use and solvent-related waste represent one of the industry's most pressing sustainability issues.

Solvents are essential in many chemical operations, including reactions, extractions, purifications, and cleaning. Their industrial-scale production has been estimated at nearly 20 million metric tons annually [2]. Poor solvent selection and inefficient processing contribute significantly to chemical releases, environmental burdens, and health risks [1]. Despite their utility, improving selectivity, safety, and process control [3,4], most commonly used solvents are derived from nonrenewable fossil resources, are often toxic, and contribute substantially to waste generation and environmental harm. Large quantities of solvents are required for the synthesis and purification of fine chemicals and pharmaceuticals; raw materials used for active pharmaceutical ingredient (API) production may be up to 85% solvent by mass [5]. Pharmaceutical sector generates extremely high waste levels, typically reflected in its large E-factors [6,7].

The U.S. Environmental Protection Agency estimates that solvent emissions associated with industrial growth may reach up to 10 million metric tons of CO_2-equivalent annually, accounting for approximately 62% of total chemical-sector emissions in 2017 [8]. These emissions increase global warming potentials (GWP), which measure the energy absorption of various greenhouse gases [9].

9.2. European and U.S. Regulatory framework

In Europe, industrial solvents are regulated under a comprehensive framework that emphasizes both human health and environmental protection. The REACH Regulation (Registration, Evaluation, Authorisation and Restriction of Chemicals, EC 1907/2006) requires manufacturers and importers to register chemical substances, including solvents, and provides for the restriction or authorisation of particularly hazardous substances such as carcinogenic, mutagenic, or reprotoxic (CMR) solvents. Solvents like trichloroethylene (TCE), perchloroethylene (PCE), methylene chloride (DCM), and N,N-dimethylformamide (DMF) [10] are subject to strict use restrictions or bans under REACH due to their toxicity, with specific occupational exposure limits set under Directive 2004/37/EC on the protection of workers from carcinogens or mutagens at work.[11] Additionally, the Solvent Emissions Directive (1999/13/EC, now integrated into the Industrial Emissions Directive 2010/75/EU) controls volatile organic compound (VOC) emissions from industrial processes, further limiting solvent use in paints, coatings, and degreasing operations. Complementary legislation, such as the Classification, Labelling and Packaging (CLP) Regulation, ensures that hazardous solvents are clearly labelled to inform safe handling. Together, these measures create a robust European regulatory environment that restricts the use of hazardous solvents, enforces safe workplace practices, and minimizes environmental impact.

By comparison, in the United States, the regulatory approach is somewhat more fragmented, with multiple agencies and statutes addressing different aspects of solvent use. The Environmental Protection Agency (EPA) regulates solvents under the Toxic Substances Control Act (TSCA), the Clean Air Act (CAA), and hazardous-substance laws such as EPCRA and CERCLA, while occupational exposure limits are enforced by the Occupational Safety and Health Administration (OSHA). Recent U.S. actions have banned or severely restricted solvents such as TCE, PCE, methylene chloride, and carbon tetrachloride, often implementing strict industrial-use controls and phase-out timelines. Unlike the EU's preventive registration and authorization system, U.S. regulation frequently relies on post-market risk evaluation, emissions management, and targeted use restrictions. Despite these structural differences, both regulatory frameworks increasingly align on restricting solvents that pose serious carcinogenic, reprotoxic, or environmental hazards, reflecting a global trend toward safer industrial chemical use.

9.3. Significance and the impact of the solvent use in pharmaceutical industry

In terms of absolute production, the pharmaceutical industry produces far smaller quantities of final products compared to bulk chemical manufacturing or oil re-manufacturing, which means that the total amount of waste generated is lower. However, solvent consumption relative to product mass is much higher in pharmaceuticals, as reflected in the E-factors: oil re-manufacturing has an E-factor of about 0.1, bulk chemicals of approximately 1-5, 5-45 for fine chemicals, and pharmaceuticals 5–25 (Figure 1, chart A). The elevated E-factors in pharmaceuticals result from complex synthesis, purification, and formulation steps requiring high-purity solvents [6,7].

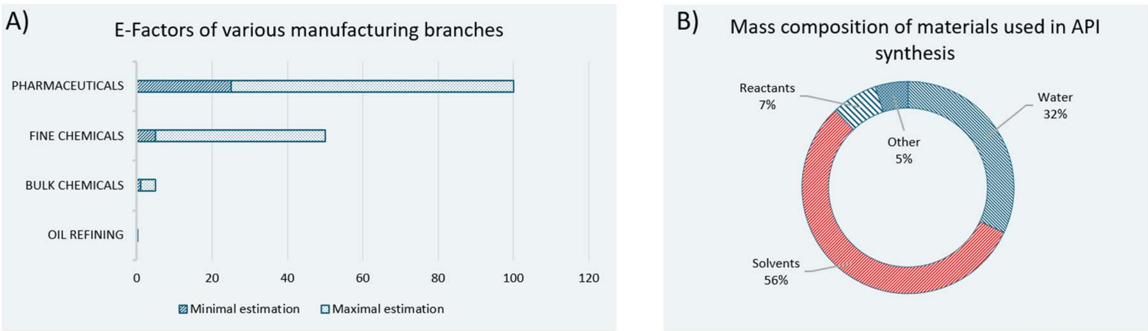

Figure1: E-Factors (A) and Material Breakdown in API Production (B)

Solvents represent 56% of the total mass composition in active pharmaceutical ingredient (API) manufacturing, making them by far the largest material input in the process. Water accounts for an additional 32%, reflecting its extensive use in extraction, purification, and cleaning operations. Reagents contribute roughly 7%, corresponding to the chemicals directly participating in the synthesis of the desired product. The remaining 6% consists of other auxiliary materials, including catalysts, processing aids, and various minor inputs (Figure 1, chart B). [12]

9.4. Sustainability and Safety Evaluation of Common Solvents

To develop our Sustainability and Safety Index, we consolidated and harmonized solvent-assessment methodologies published by GSK, Pfizer, Sanofi Aventis, and the CHEM21 consortium [12–16]. Although these organizations created their solvent-rating systems primarily for internal decision-making within their research and manufacturing operations, their frameworks have become widely referenced because they offer structured and transparent approaches to evaluating solvent safety and sustainability. In these methodologies, solvents are generally grouped into three tiers: a preferred category for solvents considered suitable, more sustainable, and recommended for routine use; a usable-with-caution category for solvents associated with moderate environmental or safety concerns; and a not-recommended category for solvents linked to significant hazards or poor sustainability profiles. While many solvents received consistent classifications across the different sources, some were scored differently depending on the organization, and several were not assessed by all groups. To convert these qualitative tiers into a unified quantitative metric, we assigned numerical values of 1 to preferred, 0.5 to usable-with-caution, and 0 to not-recommended, then calculated the average score for each solvent based on the available assessments. The resulting Sustainability and Safety Index provides an integrated and data-driven representation of solvent performance, capturing the collective insights from these internally developed methodologies.

The Sustainability and Safety Index highlights clear differences in solvent suitability across major chemical classes. Among the highest-scoring group are esters and lower alcohols, reflecting their favorable environmental and safety profiles. Within esters, propyl acetate, isopropyl acetate, tert-butyl acetate, and dimethyl carbonate achieve the maximum score of 1.00, while ethyl acetate scores 0.88, and methyl acetate reaches 0.50. These results indicate that esters, in general, are highly recommended for use in sustainable processes due to their low toxicity, good biodegradability, and broad applicability. Similarly, alcohols such as methanol, ethanol, and isopropanol score 0.88, with n-butanol reaching 1.00. Slightly lower scores for n-propanol and tert-butanol (0.75) show that minor variations in structure influence their environmental and safety impact, yet the class as a whole remains suitable.

Ketones also perform well, with acetone scoring 0.88, methyl isobutyl ketone (MIBK) 0.83, and methyl ethyl ketone (MEK) 0.75. This indicates that ketones, while generally safe and effective, require some consideration for environmental or health aspects. Certain ethers, like 2-methyl-THF (0.63) and THF (0.38), fall into a moderate range, along with diisopropyl ether (0.13) and t-butyl methyl ether (0.38), showing that while some ethers can be acceptable, many present safety or environmental concerns. Acetonitrile and DMSO, representing dipolar aprotic solvents, achieve intermediate scores of 0.50, reflecting moderate suitability. Other solvents in this class prove to be problematic for their safety and environment impacts.

In contrast, several classes display lower overall suitability. Aromatic solvents such as benzene score 0.00 due to well-known carcinogenicity, while toluene and p-xylene score 0.50, indicating limited acceptability. Chlorinated solvents rank as the least suitable, with most—including chloroform, carbon tetrachloride, and 1,2-dichloroethane—scoring 0.00, and dichloromethane slightly higher at 0.13, reflecting their significant toxicity and environmental persistence. Many hydrocarbons also score poorly; hexane, pentane, 2-methylpentane, and petroleum spirit all score 0.00, while cyclohexane, heptane, and isooctane are intermediate at 0.50.

In conclusion, the most suitable solvents for sustainable processes are esters, lower alcohols, and selected ketones. Hydrocarbons, ethers, and dipolar aprotic solvents represent particularly concerning groups, with safety and environmental issues limiting their use. The challenge is especially pronounced for dipolar aprotics, which are important for a variety of chemical transformations, making their replacement in green chemistry a significant but necessary task. The Sustainability and Safety Index provides a quantitative framework to guide solvent selection, balancing functional performance with safety and environmental considerations.

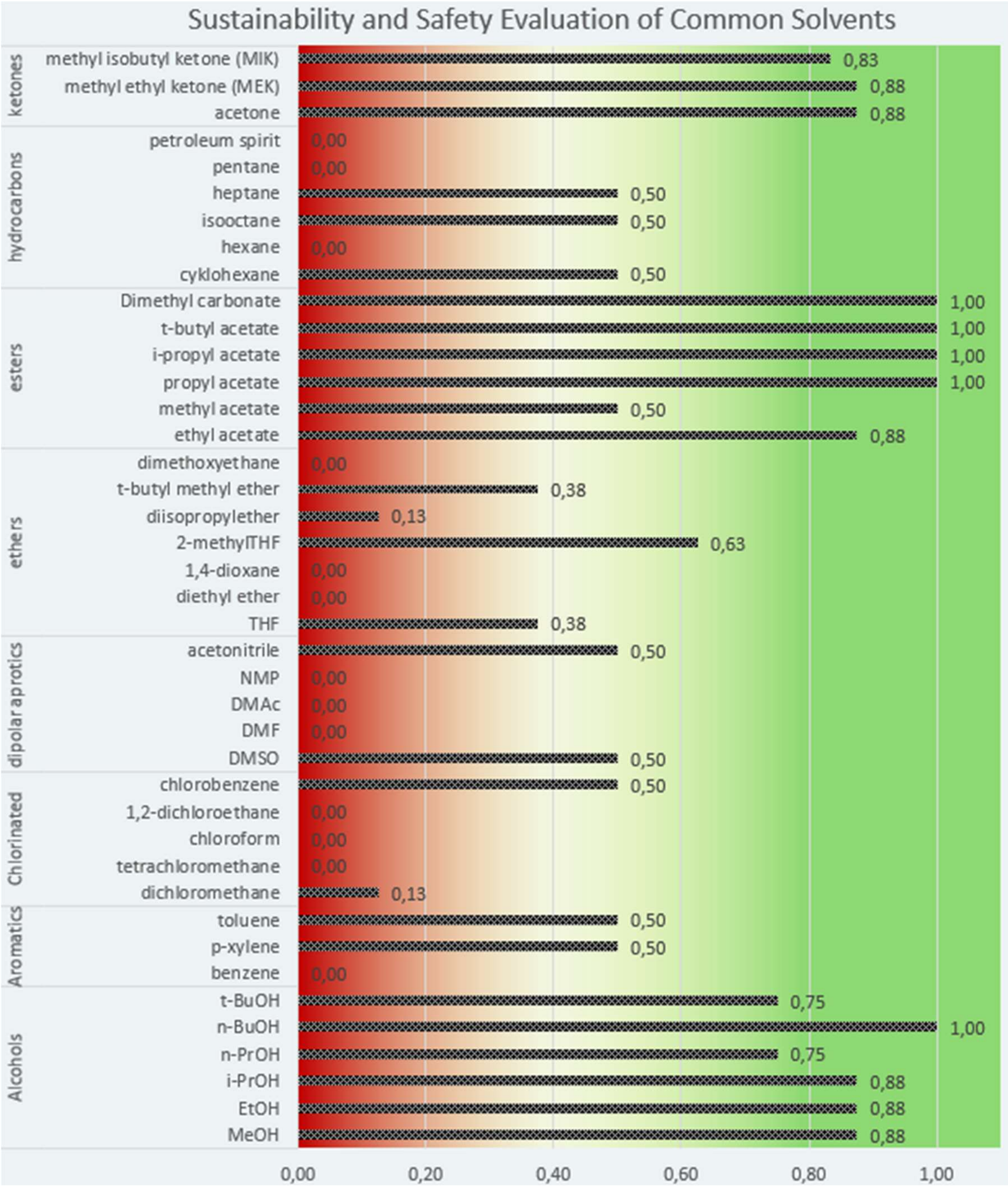

Figure 2: Sustainability and Safety Profiles of Common Organic Solvents

10. Analysis of the solvent use in the GreenChemForCE Consortium.

10.1. Overall solvent consumption

The GreenChemForCE consortium, focused on promoting sustainable chemical manufacturing, has collected solvent consumption data from its four participating companies, Zentiva (development site), EGIS Pharmaceuticals, VTL, and Aquafil SLO. The data provide an overview of absolute solvent usage across these organizations and form a basis for evaluating environmental impact and identifying opportunities for green process improvements, with the absolute amounts of solvents depicted in Chart A and the corresponding relative percentages shown in Chart B.

The analysis reveals that methanol was the most widely used solvent, with an absolute consumption of 1,034,500 kilograms, representing 33.1 percent of the total solvent mass. Isopropanol followed at 558,864 kilograms, corresponding to 17.9 percent of the total, while acetone accounted for 604,150 kilograms, or 19.3 percent. Toluene usage was 404,330 kilograms, representing 12.9 percent of the total, and ethanol contributed 316,974 kilograms, equivalent to 10.1 percent. DMSO was consumed at 48,600 kilograms, corresponding to 1.6 percent of the total, and dichloromethane at 43,380 kilograms, representing 1.4 percent. Ethyl acetate usage totaled 32,490 kilograms, or 1.0 percent, MTBE 33,940 kilograms, or 1.1 percent, and acetonitrile 29,910 kilograms, also 1.0 percent. Tetrahydrofuran (THF) was used at 6,920 kilograms, representing 0.2 percent of total solvent consumption, diethyl ether at 5,796 kilograms, also 0.2 percent, and formaldehyde at 2,140 kilograms, corresponding to 0.07 percent. Other solvents grouped together accounted for 6,554 kilograms, or 0.2 percent of the total. The data indicate that solvent consumption is dominated by methanol, acetone, isopropanol, toluene, and ethanol, which together account for more than 93 percent of the total mass, making these high-volume solvents prime candidates for recovery, recycling, or substitution strategies, while solvents used in smaller quantities, including dichloromethane, DMSO, acetonitrile, and THF, require careful handling due to their chemical properties and potential environmental and safety risks, providing a clear framework for prioritizing green chemistry initiatives within the consortium.

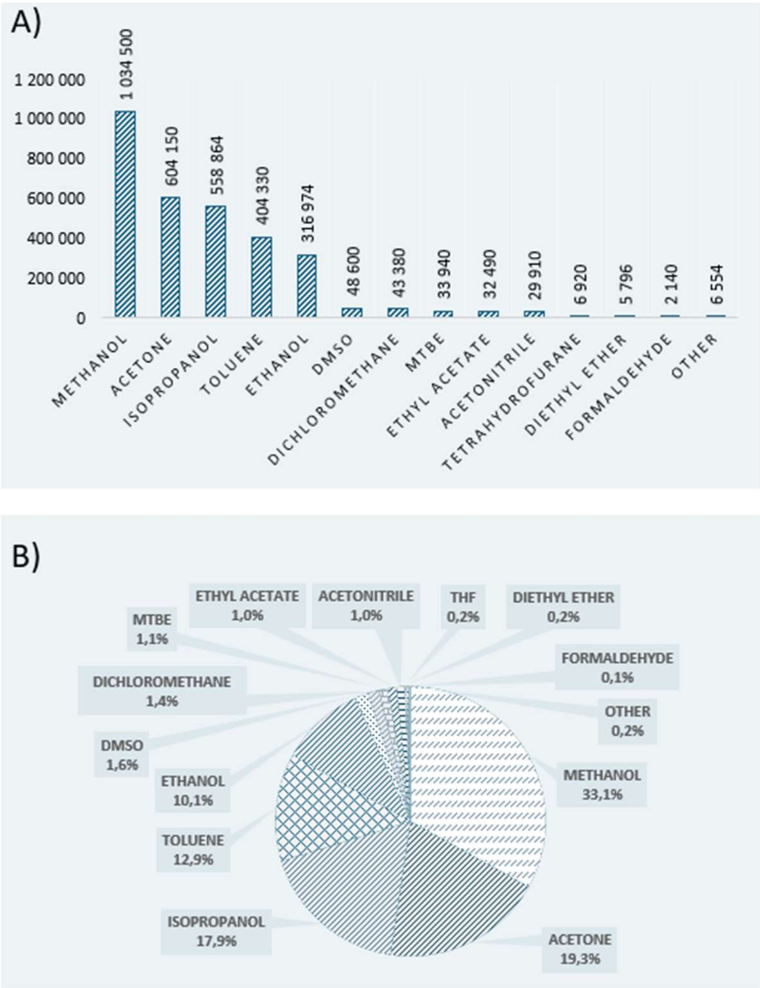

Figure 3: Solvent Use and Sustainability Metrics in Pharmaceutical Production

10.2. Ecological factor and recycling rates

An analysis was conducted to evaluate both the amount of solvent required for the production of one kilogram of product and the corresponding recycling rates. The results indicate a clear relationship between production scale and solvent efficiency: as the amount of product increases, the solvent required per kilogram of product decreases. For instance, producing 105 kg of product requires 52 kg of solvent per kg of product, whereas producing 500 kg reduces solvent consumption to 24 kg per kg of product, and at 952,022 kg of product, solvent use drops to just 3 kg per kg of product (Figure 3, Chart A). The data indicate significant differences in solvent recycling efficiency across production scales. In small-scale production (105 kg), 46 kg out of 52 kg of solvent is successfully recycled, demonstrating a high recycling rate. In contrast, at an intermediate production scale of 500 kg, no solvent recovery is observed. This disparity may reflect operational differences between SMEs and larger, non-SME facilities, where process constraints or economic considerations impact recycling practices.

At the larger production scale, solvent recycling becomes economically feasible, with approximately one-third of the total solvent recovered. This observation suggests that solvent recovery strategies must be evaluated on a case-by-case basis, considering economic viability.

Figure 4: Solvent Consumption and Recycling Performance in Pharmaceutical Production. A) Amounts of solvents per kg of final product related to an overall annual production. B) Total mass percentage of recycled solvents. C) Types and amounts of recycled solvents.

Further we examined the recycling rates of individual solvents. The total recycling amounts show the relatively low recycling rate, highlighting opportunities to improve recovery processes. Out of at least thirteen solvents included in the internal analysis of the GreenChemForCE project, only four are currently subject to recycling. In terms of total solvent mass, this corresponds to only about 27 % being recycled (Figure 4, Chart A). The results show that isopropanol achieves the highest recycling efficiency with 78% recycled, indicating strong potential for reuse. Acetone presents a more balanced outcome, with 47% recycled. Toluene shows limited recycling, with 31% recycled and ethyl acetate demonstrates minimal recyclability, with only 4% recycled compared to 96% not recycled. Overall, the analysis underscores substantial variation in recyclability among the solvents, reflecting differences in chemical properties, usage patterns, and the feasibility of recovery technologies, and emphasizes that solvent recycling remains concentrated on a small subset of substances where economic conditions support its implementation.

11. Conclusions

The analysis of solvent use within the fine chemical and pharmaceutical sectors, together with the data collected from the GreenChemForCE consortium, highlights the central role solvents play in both the environmental footprint and operational performance of chemical manufacturing. Solvents constitute the majority of material inputs in active pharmaceutical ingredient (API) production and are a major contributor to waste streams, underscoring the importance of strategic solvent selection, process optimization, and recycling.

Globally, regulatory frameworks in the EU and U.S. are increasingly aligned in restricting hazardous solvents, particularly those classified as carcinogenic, reprotoxic, or environmentally persistent. The EU's preventive REACH-driven approach contrasts with the more reactive U.S. system, but both converge on prioritizing safer alternatives and reducing volatile organic compound emissions. These regulations reinforce the need for sustainable solvent management across industrial operations.

The Sustainability and Safety Index developed in this study demonstrates clear differences in environmental and safety performance across solvent classes. Esters, lower alcohols, and selected ketones emerge as the most sustainable options, while hydrocarbons, ethers, and especially chlorinated and dipolar aprotic solvents present significant challenges. This highlights that future innovation should target both the replacement of problematic solvents and improved process designs where substitution is difficult.

The GreenChemForCE consortium data show that solvent use is heavily concentrated in a few high-volume solvents—methanol, acetone, isopropanol, toluene, and ethanol—which together account for over 90% of total consumption. Although solvent efficiency improves substantially with production scale, the overall solvent recycling rate remains low, with only about 27% of solvent mass being recovered and only four solvents recycled in practice. These low recycling rates, combined with the continued widespread use of non-renewable fossil-derived solvents, represent not only a significant environmental and economic challenge but also a major opportunity for research and innovation. Advancing solvent-recovery technologies, expanding the use of bio-based or circular solvents, and redesigning processes to improve recyclability can all contribute to more sustainable production systems.

Overall, the findings emphasize that improving solvent sustainability in pharmaceuticals requires a multi-pronged approach: adopting greener solvent alternatives guided by robust assessment tools, enhancing recycling and recovery infrastructure, and harmonizing regulatory compliance with green chemistry principles. The existing gaps—particularly the limited recycling and reliance on non-renewable solvents—highlight clear avenues for future research that can substantially reduce environmental impacts, lower production costs, and accelerate the transition toward sustainable chemical manufacturing.

References

[1] United Nations Environment Programme. Global Chemicals

Outlook II - From Legacies to Innovative Solutions - Synthesis Report

(2019); United Nations Environment Programme, 2019; pp 1-90

[2] J. Clark, T. Farmer, A. Hunt, J. Sherwood, "Opportunities for Bio-Based Solvents Created as Petrochemical and Fuel Products Transition towards Renewable Resources" IJMS 2015, 16, 17101–17159.

[3] E. Buncel, R. A. Stairs, H. Wilson, The role of the solvent in chemical reactions, Oxford Univ. Press, Oxford, 2003.

[4] C. Reichardt, T. Welton, Solvents and solvent effects in organic chemistry, Wiley-VCH, Weinheim, 2011.

[5] R. A. Sheldon, "Green solvents for sustainable organic synthesis: state of the art" Green Chem. 2005, 7, 267.

[6] R. A. Sheldon, "The E Factor: fifteen years on" Green Chem. 2007, 9, 1273.

[7] R. A. Sheldon, "The E factor 25 years on: the rise of green chemistry and sustainability" Green Chem. 2017, 19, 18–43.

[8] O. US EPA, "Global Mitigation of Non-CO2 Greenhouse Gases: Solvents," can be found under https://19january2017snapshot.epa.gov/global-mitigation-non-co2-greenhouse-gases/global-mitigation-non-co2-greenhouse-gases-solvents(accessed 1 December 2025), n.d.

[9] O. US EPA, "Understanding Global Warming Potentials," can be found under https://www.epa.gov/ghgemissions/understanding-global-warming-potentials(accessed 1 December 2025), 2016.

[10], "Regulation - 2021/2030 - EN - EUR-Lex," can be found under https://eur-lex.europa.eu/eli/reg/2021/2030/oj/eng(accessed 1 December 2025), n.d.

[11], "Substances restricted under REACH - ECHA," can be found under https://echa.europa.eu/substances-restricted-under-reach(accessed 1 December 2025), n.d.

[12] R. K. Henderson, C. Jiménez-González, D. J. C. Constable, S. R. Alston, G. G. A. Inglis, G. Fisher, J. Sherwood, S. P. Binks, A. D. Curzons, "Expanding GSK's solvent selection guide – embedding sustainability into solvent selection starting at medicinal chemistry" Green Chem. 2011, 13, 854.

[13] K. Alfonsi, J. Colberg, P. J. Dunn, T. Fevig, S. Jennings, T. A. Johnson, H. P. Kleine, C. Knight, M. A. Nagy, D. A. Perry, M. Stefaniak, “Green chemistry tools to influence a medicinal chemistry and research chemistry based organisation” Green Chem. 2008, 10, 31–36.

[14] D. Prat, A. Wells, J. Hayler, H. Sneddon, C. R. McElroy, S. Abou-Shehada, P. J. Dunn, “CHEM21 selection guide of classical- and less classical-solvents” Green Chem. 2016, 18, 288–296.

[15] D. Prat, O. Pardigon, H.-W. Flemming, S. Letestu, V. Ducandas, P. Isnard, E. Guntrum, T. Senac, S. Ruisseau, P. Cruciani, P. Hosek, “Sanofi’s Solvent Selection Guide: A Step Toward More Sustainable Processes” Org. Process Res. Dev. 2013, 17, 1517–1525.

[16] L. J. Diorazio, D. R. J. Hose, N. K. Adlington, “Toward a More Holistic Framework for Solvent Selection” Org. Process Res. Dev. 2016, 20, 760–773.