

The Importance of Photocatalysis and its Potential Industrial Applications

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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 956324 (PhotoReAct). This white paper reflects only the author's view and the European Commission is not responsible for any use that may be made of the information it contains.

1. Introduction

Chemical manufacturing lies at the heart of modern society, but it remains one of the most energy-intensive and resource-consuming sectors in Europe. The reliance on high-temperature processes and fossil-based energy sources has led to substantial greenhouse-gas emissions and chemical waste. Meeting the European Union's 2030 climate and energy targets therefore requires not only cleaner energy sources but also new ways to perform chemistry itself.

The European Union's 2030 energy and climate targets call for a 40% reduction in greenhouse gas emissions, 27% of energy to be derived from renewable sources, and a 30% improvement in energy efficiency. Meeting these goals demands transformative technologies that can decouple chemical innovation from fossil energy dependence.

Photocatalysis, using light as the driving force for chemical reactions, has emerged as a transformative solution.¹ Instead of heat or harsh reagents, visible light can trigger the formation of reactive species under mild, environmentally benign conditions.² This makes photocatalysis uniquely suited to support the transition toward low-carbon, energy-efficient chemical production.

The PhotoReAct network was established to accelerate this shift. Funded through the Marie Skłodowska-Curie Actions, the project brought together fifteen Early-Stage Researchers (ESRs) and a consortium of academic and industrial partners to explore how visible-light photocatalysis could move from the research bench to industrial reality.

This white paper reflects on the lessons learned during the project and outlines the opportunities and challenges that photocatalysis presents for European industry and sustainability policy.

2. Photocatalysis: From Laboratory Concept to Industrial Enabler

In the early years of the field dating back to 1980s, photocatalysis was often viewed as a curiosity, scientifically elegant but industrially impractical.³ And while progress was made in the past 20 years, practical issues still hampered its widespread adoption. The

PhotoReAct programme contributed to change that perception by addressing both the fundamental and technological barriers.

The 15 ESRs worked across five interlinked themes: catalyst design, method development, technological innovation, industrial implementation, and training. Together, these efforts created a holistic ecosystem for the maturation of photocatalysis.

New generations of visible-light photocatalysts were developed using earth-abundant metals and fully organic materials, replacing expensive iridium and ruthenium complexes. ESRs designed multi-resonant TADF emitters and copper-based complexes that deliver high efficiency and tunable reactivity, paving the way for sustainable large-scale synthesis.^{4,5}

At the same time, the researchers explored how photocatalysis can enable novel synthetic routes: e.g., late-stage functionalisation of pharmaceuticals⁶⁻⁹, asymmetric transformations,¹⁰ and selective C–H activations.^{11,12} Such reactions, once considered impractical under traditional conditions, can now proceed under mild light irradiation, often without toxic reagents.

Crucially, PhotoReAct also built technological platforms to make photocatalysis scalable and reproducible. Automated flow systems,¹³ including the *RoboChem* platform,¹⁴ integrated real-time monitoring and machine learning to optimise reactions autonomously. New reactor designs, including solar-driven and LED-based systems, demonstrated that photocatalysis can operate efficiently using renewable energy sources.

Through industrial secondments at companies such as Janssen Pharmaceuticals (J&J) and Johnson Matthey, ESRs validated these approaches in genuine production environments.¹⁵ Automated flow photochemistry, for example, was implemented across multiple J&J sites,¹⁶ while new photocatalysts became part of routine process development at Johnson Matthey. These collaborations provided a tangible bridge from academic research to industrial application.

3. Industrial Impact and Case Examples

The outcomes of PhotoReAct illustrate the broad potential of photocatalysis to reshape chemical manufacturing.

In the pharmaceutical sector, light-driven reactions now enable faster and cleaner synthesis of complex molecules. Gasparetto *et al.* developed photocatalytic methods for DNA-encoded library synthesis,¹⁷ while Pijper and coworkers from Janssen Pharmaceuticals introduced automated flow coupling protocols that simplified the construction of drug-like scaffolds.¹⁸ Both were successfully applied in ongoing industrial programmes.

For fine chemicals and agrochemicals, photocatalysis offers selective oxidative and reductive transformations that minimize waste. Mariko *et al.* their copper carbene–amide complexes achieved transformations previously limited to noble metals, while Bonciolini *et al.* their solar microreactors produced fine chemicals at gram scale with minimal energy input.

The work has also generated commercial outcomes: new reagents,¹⁹ patented technologies,²⁰ and scalable processes that demonstrate real-world feasibility. In each case, visible-light activation provided not only environmental benefits but also competitive advantages in efficiency, safety, and cost.

4. Photocatalysis and Europe's 2030 Climate Goals

The European Green Deal envisions a climate-neutral continent by 2050 with a 55% reduction in emissions already by 2030.²¹ Photocatalysis directly supports this ambition.

- **Energy efficiency:** Reactions proceed at room temperature under visible or solar light, drastically reducing the energy demand of chemical production.
- **Waste reduction:** Catalytic, atom-economical pathways replace stoichiometric reagents and minimize solvent use.
- **Decarbonisation:** LED-based and solar reactors cut dependence on fossil fuels.

- **Circular economy:** Photocatalysis can valorise CO₂, biomass, and other renewable feedstocks.²²
- **Digitalisation:** Integration with AI-driven²³ automated systems exemplifies Industry 5.0 manufacturing principles, which are smart, sustainable, and human-centric.²⁴

Thus, photocatalysis represents not just a scientific advance but a strategic tool for Europe's green and digital transformation.

5. Remaining Challenges

Despite these successes, several hurdles must be overcome before photocatalysis achieves widespread industrial adoption.

Scaling photochemical processes beyond laboratory volumes remains technically demanding due to limitations in photon flux and reactor geometry.^{25,26} Long-term stability of organic photocatalysts under continuous operation must be further improved, and standardised metrics are needed to compare performance across systems. Finally, broader integration with existing manufacturing infrastructure requires engineering solutions and regulatory clarity.

Addressing these challenges will require coordinated effort across academia, industry, and policymakers.

6. The Road Ahead

To fully realise the promise of photocatalysis, this white paper recommends:

1. **Strategic investment** in pilot-scale photochemical facilities that demonstrate process viability under industrial conditions.
2. **Policy support and incentives** for energy-efficient chemical technologies aligned with the Green Deal.

3. **Standardisation initiatives** to define benchmarks for light-driven processes, including energy input, quantum yield, and life-cycle assessment.
4. **Continuous training** through programmes like MSCA to equip new generations of scientists with interdisciplinary photochemical and engineering expertise.
5. **Public–private partnerships** to accelerate translation from research to market.²⁷

With sustained commitment, photocatalysis can become a cornerstone technology for Europe’s sustainable industrial future.

7. Conclusions

The PhotoReAct project has demonstrated that photocatalysis is no longer a niche academic field but a practical, versatile, and sustainable technology. By uniting molecular design, process engineering, and industrial validation, the network has shown how visible-light chemistry can power the next generation of green manufacturing.

As Europe advances toward its 2030 energy and climate goals, photocatalysis stands ready to illuminate a cleaner path for chemical innovation, transforming light into one of the most powerful tools for sustainable progress.

Acknowledgement

We are grateful to have received generous funding from the European Union H2020 research and innovation program under the Marie S. Curie Grant Agreement (PhotoReAct, No. 956324).

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