

*Title of doctoral research project.***Batch and Flow Strategies for Furfural Valorization via Iron Catalysis***Summary of the project.*

The depletion of fossil resources underscores the need for renewable alternatives, with lignocellulosic biomass emerging as a key alternative. Furfural and 5-(hydroxymethyl)furfural are valuable platform molecules for synthesizing value-added chemicals and biofuels, yet their transformation into furfurylamines, furoic acid, and FDCA relies on noble metals and harsh reaction conditions, limiting both scalability and sustainability. *This project focuses on developing eco-friendly, iron-based catalytic systems to enable the efficient and sustainable conversion of furfurals. By moving from homogeneous to heterogeneous catalysis and continuous-flow processes, we seek to enhance scalability, reduce costs, and promote greener industrial production of furfurylamines and FDCA.*

*State of the art and scientific objectives.***1. Challenges in furfural valorization.**

Despite the depletion of fossil resources, oil, gas, and coal remain central to industrial chemistry due to their low cost, availability, and ease of processing. However, the urgency of climate change calls for a transition to renewable feedstocks, in line with the principles of green chemistry.¹ Among these alternatives, **lignocellulosic biomass**, derived from agricultural waste, stands out as an abundant and sustainable carbon source that does not compete with food crops.² Its valorization enables the production of **platform molecules** such as **furfural (F)** and **5-(hydroxymethyl)furfural (HMF)**, obtained through acid-catalyzed digestion of (hemi)cellulose.³ Recognized by the U.S. Department of Energy as one of the "Top 10" most valuable biomass-derived chemicals, F and HMF serve as key building blocks for the synthesis of **high-value chemicals** and **biofuels**.⁴

A notable example is **furfurylamine** and its derivatives, widely used in resins, pharmaceuticals, and agrochemicals. These compounds are synthesized *via* the **reductive amination** of furfural using homogeneous or heterogeneous catalytic systems, often based on noble transition metals.⁵ Additionally, the **oxidation** products of F and HMF, such as **furoic acid** and **furan dicarboxylic acid (FDCA)**, are attracting increasing interest. Furoic acid is used as a plasticizer and pharmaceutical intermediate, while FDCA is emerging as a sustainable alternative to terephthalic acid in polymer production.⁶ These transformations primarily rely on heterogeneous catalysts combined with strong oxidants, typically high-pressure oxygen or air. Moreover, homogeneous metal-catalyzed oxidation remains challenging due to the rapid degradation of furan-based platforms under alkaline or oxidative conditions at elevated temperatures. To date, only a few well-defined manganese or ruthenium-based complexes with phosphine pincer ligands have demonstrated limited success in this field.

In summary, conventional methods for **reductive amination** and **oxidation** of F or HMF typically require **harsh reaction conditions**, such as high temperatures and, in reductive pathways, elevated pressures of molecular hydrogen. These processes also depend on **noble metal catalysts**, increasing costs and resource constraints.⁷ Such demanding conditions not only raise energy requirements but also limit scalability and environmental sustainability, emphasizing the urgent need for more efficient and greener catalytic approaches.

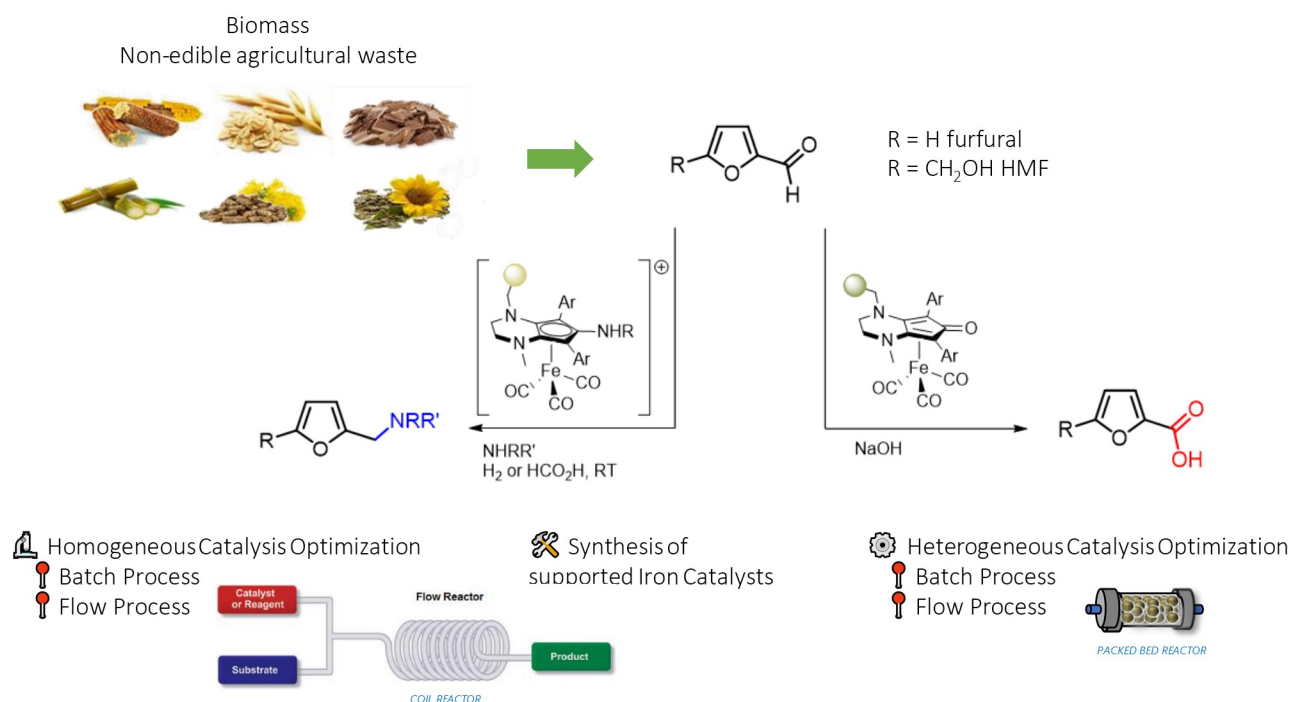
2. Iron-catalyzed transformation.

Green and sustainable chemistry research aims to rethink traditional processes to balance environmental sustainability and economic viability. Key innovation areas include the use of renewable resources and the development of catalytic transformations based on earth-abundant metals.

Within the CASCH@IPCM SU team, we have demonstrated the potential of **well-defined iron-based catalysts** for the reductive amination of aldehydes under mild conditions at ambient temperature.⁸ As an abundant, cost-effective, and eco-friendly alternative to precious metals, iron represents a promising pathway for sustainable catalysis. In particular, some **cationic triaminocyclopentadienyl iron(II) complexes** enable this transformation under low hydrogen pressure or in the presence of formic acid as a hydrogen donor, providing an energy-efficient and economically viable approach to amine synthesis. These non-pincer iron(II) cyclopentadienyl complexes outperform known cyclopentadienone iron carbonyl catalysts in both efficiency at ambient temperature and functional group tolerance. Additionally, related **iron(0) tricarbonyl complexes bearing a diaminocyclopentadienone ligand** have proven effective in reducing CO₂, hydrogenocarbonates, and carbonates to formate in aqueous basic conditions.⁹ These reactivities suggest the applicability of well-defined iron(II) and iron(0) catalysts in the valorization of furfural derivatives, for reductive amination and also for oxidation reactions requiring a basic medium.

To enhance productivity and assess scalability, we will implement **continuous-flow chemistry systems for these transformations**. The high availability and low cost of iron make it particularly well-suited for homogeneous catalysis in flow, enabling precise control over reaction parameters and improving process efficiency.¹⁰

To simplify product isolation and enhance catalyst recyclability, we aim to develop **a heterogeneous version of the iron complexes**. Initially, this will involve simple adsorption onto an inert matrix such as silica. If this approach proves ineffective, we will explore covalent immobilization by modifying the ligand structure to introduce anchoring groups, such as alkynes or aminosilanes. These functionalities will enable linkage via click chemistry or silica surface functionalization, ensuring improved catalyst stability and reusability.¹¹



Proposed Collaboration.

This project marks a new collaboration with Prof. Alessandra Puglisi and Prof. Maurizio Benaglia of the Università degli Studi di Milano, bringing together complementary expertise. The Paris team specializes in organometallic synthesis and homogeneous catalysis, while the Milan team focuses on heterogeneous catalysis and catalyst immobilization. The project also integrates biomass valorization, a key research focus in Paris, and flow chemistry—an emerging approach for both teams—to enhance process efficiency and sustainability.

The research will develop an iron-based catalytic system for the reductive amination and oxidation of furfural and hydroxymethylfurfural. Optimization of reaction conditions will be carried out in Paris under the supervision of Dr. Julie Oble and Dr. Marc Petit, with the expertise of Prof. Jean-Luc Renaud in iron chemistry. Heterogeneous catalysis will be developed in Milan, where catalysts will be immobilized on solid supports and evaluated for activity, stability, and reusability. A continuous-flow system, implemented in both Paris and Milan, will assess the industrial feasibility of the process.

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