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Highlights from the Mech'cheM 2025 conference: New forces in Mechanochemistry, Montpellier, France, June 4-6, 2025

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The International Symposium on Mechanochemistry (Mech'cheM 2025) took place in Montpellier (France) June 4-6, 2025, gathering 145 mechanochemists across the disciplines. Ten years after Mech'cheM 2015, it was an occasion to assess new progress and developments in the field. In this article, we highlight the main features of the plenary lectures and oral communications, illustrating the dynamic current cutting-edge research activities together with significant applications across the field of chemistry.

Introduction

Mechanochemistry has regained a lot of attention in the last years as it is a powerful tool to develop more sustainable chemical processes. In 2019, the IUPAC named "mechanochemistry and reactive extrusion" as one of the ten innovations that will change the world.[1] Defined as the science of inducing reactions through mechanical forces, mechanochemistry has exploded as a field, through its use in organic, inorganic, and organometallic chemistry, materials science and engineering, catalysis, and enzymatic reactions, with applications in the synthesis of active pharmaceutical ingredients, of new electrode or electrolyte materials for batteries, biomass conversion, or plastics degradation. Importantly, the use of mechanochemistry often comes with additional benefits, such as the use of less toxic reagents or the recycling of critical metals (*i.e.*, the batteries or catalysis fields), together with the significant reduction of solvent and reagent use.

The International Symposium on Mechanochemistry (Mech'cheM 2015) held in Montpellier in 2015 gathered prominent speakers and participants from all areas of chemistry, demonstrating the infinite applications of mechanochemistry. Where are we now, ten years later? Mech'cheM 2025: New forces in Mechanochemistry, in Montpellier again, was an occasion to provide an update on the newest developments, from technological advances (reactive extrusion, reactive acoustic mixing, ball-milling…) to a broad range of applications.

This edition of Mech'cheM 2025 was organized by academic chemists from the Institute of Biomolecules Max Mousseron (IBMM: Frédéric Lamaty, Xavier Bantreil, Nicolas Pétry Béatrice Roy) and Institute of Materials Charles Gerhardt (ICGM: Olivia Giani, Laure Monconduit, Julien Pinaud) (Fig. 1).

Mech'cheM 2025 gathered 145 participants from 18 countries, including 74 students and post-docs. The scientific programme involved 8 plenary lectures (Fig. 2), 33 oral communications and 57 poster presentations.

Highlights

Franziska Emmerling

Mech'cheM 2025 started with an opening lecture by Franziska Emmerling, head of the Department Materials Chemistry at the Federal Institute for Material Research and Testing (BAM, Berlin, Germany). As a worldwide expert in materials chemistry, she put into perspective the potential of mechanochemistry for sustainable materials' synthesis. Thanks to cutting-edge technology for monitoring and scaling-up mechanochemical processes, the Emmerling team brought significant advances in the understanding of solid-state transformations. An impressive example is the achievement of time-resolved *in situ* monitoring on a twin-screw extruder, using a synchrotron beamline for energy-dispersive X-ray diffraction.[2] In her talk, Franziska demonstrated the key role of mechanochemistry in the manufacturing of advanced materials such as Metal–Organic Frameworks (MOF) for energy applications. As a perspective, Franziska discussed the integration of emerging technologies like machine learning in the development of continuous flow processes, what could be in the next decade a huge step forward in the context of energy and environmental challenges.

Various topics presented in this lecture were further illustrated in oral communications such as the mechanosynthesis of MOFs, whose discovery and developments as a new molecular architecture were recognized by the Nobel Prize in Chemistry 2025. Mechanochemistry is particularly well adapted for MOFs synthesis, as for example from upcycled terephthalate

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Fig. 1 Organizing committee of Mech'cheM 20225. From left to right: J. Pinaud, L. Monconduit, N. Pétry, B. Roy, F. Lamaty, O. Giani, X. Bantreil.

monomers originating from polyethylene terephthalate *via* a sustainable protocol.[3] Sophisticated architectures can be obtained by milling, allowing the encapsulation of fullerene in MOFs to functionalize them and/or improve their magnetic properties.[4]

Another important aspect which is rapidly developing in mechanochemistry is the *in situ* monitoring of reactions. Interestingly acoustic analysis was investigated and could be integrated in an *operando* analytical platform to investigate the mechanism of mechanochemical reactions.[5]

Jeung Gon Kim

Although the synthesis of polymers by mechanochemistry was still in its infancy while the first edition of Mech'cheM was taking place in 2015, major advances have been made in this area over the past few years, which were well covered during the presentation by Jeung Gon Kim from Jeonbuk National University (South Korea) during Mech'cheM 2025. Both thermoplastic and cross-linked polymers can now be obtained in a ball-mill either by post-polymerization modification or by direct chain-growth or step-growth polymerization methods. Moreover, besides the inherent benefits of mechanochemistry, such as working under greener and safer conditions than solution chemistry, this technique offers the possibility of working with immiscible monomers thus giving access to new polymer architectures not achievable otherwise.[6] Additionally, the intimate mixing of reagents delivered by mechanochemistry allows the modification of polymers that are known to be difficult to solubilize like polysaccharides. However, challenges remain to be solved in this field. In particular, the specific influence of the grinding parameters (frequency, LAG, milling jars, number of balls…) on the outcome of the polymerization are yet to be found. Once unveiled, they should allow for control of the polymerization and the synthesis of polymers with high molecular weight. Although some recent studies have reported such conditions, work is still

Fig. 2 Invited speakers. Back row, from left to right: Véronique Bounor-Legaré, Franziska Emmerling, Virginie Viallet, Jeung Gon Kim. Front row, from left to right: Ina Vollmer, Karine Auclair, Tomislav Friščić, Duncan Browne.

needed for mechanochemistry to compete with solution chemistry, which holds promises for the next years to come.

Virginie Viallet

In the energy field, especially for lithium-ion batteries (LIBs), mechanochemistry is becoming one of the common tools used to prepare many electrode or electrolyte materials. As demonstrated during the lecture of Virginie Viallet from the Laboratoire de Réactivité et Chimie des Solides in Amiens (France), LIBs are the dominant technology and the two main directions of current research in this field are increasing energy density while ensuring safety, and recycling batteries. The development of Inorganic All-Solid-State batteries (ASSBs) is proposed to increase energy density. ASSBs are based on the exploration of conductor electrolytes with high ionic conductivity (10^{-3} S cm^{-1}). Major research efforts have been undertaken to optimize inorganic solid electrolytes (SEs) including sulfides, oxides, polymers and halides for LIBs or more recently for Na-ion batteries. The electrolytes' synthesis can be prepared by solid-state and solvent based reactions, as well as through mechanochemical synthesis by ball-milling.[7] In the case of sulfides and halides, ball-milling is a promising route for upscaling processes since the synthesis without many additives and/or solvent is reproducible, the absence of toxic solvents yielding, in addition, a more sustainable approach. This synthesis technique also enables the stabilization of metastable phases that cannot be achieved at high temperature, and the formation of glassy and glass-ceramic solid electrolytes obtained previously by costly melt-quenching route.[8]

Mechanochemistry is also a preparative method of choice to make a wide variety of inorganic materials as presented during the conference: high-energy ball-milling presents a promising pathway for the sustainable regeneration of sodium borohydride ($NaBH_4$), a potent hydrogen storage medium.[9] In geology and materials science, mechanochemistry is also a powerful tool. Understanding the formation of carbonate[10] minerals is crucial for studying Earth's upper mantle and transition zone, but their synthesis requires high pressures and temperatures. Mechanochemical synthesis provides a viable way for the preparation of minerals, as carbonates, under ambient conditions, offering new insights into their stability and transformations, which have potential applications in geology and material science.[11] Electrocatalysis can also benefit from mechanochemistry in the facile synthesis of nickel sulfides which serve as catalysts in the Hydrogen Evolution Reaction (HER), a key reaction of water splitting. By fine tuning of the ratio of nickel and sulfur, optimal conditions were obtained for this transformation.[10] Carbonates (bi) can be used for applications like both carbon capture and energy storage, and scientists use solid-state NMR to characterize their molecular structure. The ^{17}O nucleus is rarely used due to its low natural abundance and the high cost of isotopic enrichment. Mechanochemistry has been proposed as a sustainable and cost-effective method for ^{17}O-enrichment, thus providing new insights into bicarbonate and carbonate speciation and reactivity.[12] Interestingly, an abundant source of inorganic materials is eggshell waste. After milling, and transformation of calcite into aragonite,[13] it finds application in the preparation of semiconductor nanomaterials, in the degradation of polyvinyl chloride, and heavy metal adsorption. From the equipment point of view, thought-provoking results were obtained with originally designed balls for milling, enhancing mass transfer and promoting more uniform kinetic energy distribution. This results in some cases in different outcomes from the ones obtained with non-corrugated balls.[14] Other important starting materials for many industrial transformations are inorganic fluorochemicals which originate from the naturally occurring mineral fluorspar (>97% CaF_2), relying on an energy-intensive and intrinsically dangerous process involving hydrogen fluoride (HF), a highly toxic and corrosive gas. The same fluorochemicals can be obtained by directly ball-milling fluorspar with the appropriate substrates.[15]

Karine Auclair

Karine Auclair (McGill University, Canada) gave a presentation on mechanoenzymology, an emerging and appealing approach in which mechanical mixing is used to sustain enzymatic reactions in low-solvent or solvent-free mixtures.[16] Unlike in-solution reactions, solvent-free mechanoenzymology avoids solubility issues and can proceed in a minimal volume. Auclair's research group developed a technique, coined RAging, which involves alternating periods of brief, gentle ball-milling and longer intervals of static incubation (aging). This led to an unconventional and more sustainable biocatalytic strategy, particularly well-suited for depolymerizing challenging substrates that are poorly soluble or chemically resistant, such as biomass and plastics.[17] The group has successfully applied this mechanoenzymatic technology to depolymerize biopolymers such as cellulose, hemicellulose, and chitin directly from biomass or paper, but also synthetic polymers such as polyethylene terephthalate (PET), polyethylene naphthalate (PEN) and polylactic acid (PLA) plastics. Enzymes under moist-solid conditions have numerous advantages over using enzymes in traditional in-solution reactions, such as increased selectivity for the desired product, no requirement for chemical or thermal pretreatment of the substrate, and a reduction of solvent waste. This technology opens the door to efficient and environmentally friendly recycling methods, helping to tackle the issue of plastic pollution.

Duncan L. Browne

The talk of Duncan L. Browne (University College London, UK) focused on the concurrent development and discovery of new opportunities for molecular synthesis by small scale mechanochemistry and conversion of these methods to larger-scale processes through continuous mechanochemistry using a twin-screw extruder.[18] Of course, the potential solvent savings afforded by mechanochemistry techniques are particularly appealing at larger scales. However, the translation from the ball-mill to the extruder is not straightforward as the variables and parameters of the tools change. To illustrate this topic, he provided several examples of projects completed by his team, such as the first organic fluorination using extrusion, the nickel catalyzed Suzuki–Miyaura-type coupling of aryl sulfamates and boronic acid derivatives,[19] and the direct amidation of esters.[20]

Furthermore, Duncan L. Browne pointed out the necessity of considering the potential hazards and implementing measures to minimize risk when developing protocols.[21] Indeed, chemical reactions that take place in a ball-mill and in the absence of a bulk reaction solvent present different safety profiles to stirred solution reactions.

Scaling-up mechanochemistry is an important concern to produce the necessary amount of chemicals for widespread applications. One solution for the synthesis of inorganic catalysts and presented by the MechSyn company is to use ball-mills with a higher capacity.[22] A more recent equipment, developed by the WAB company is the bead mill, which integrates both conventional flow chemistry and bead milling technology. Its application in the synthesis of API paracetamol was described.[23]

Many contributions at Mech'cheM 2025 demonstrated the great benefits provided by mechanochemistry to organic synthesis. One-pot mechanochemical multistep reactions have emerged as a powerful, sustainable and revolutionary approach in modern organic synthesis.[24] This was illustrated with the development of an ultra-fast, solvent-free mechanically induced Wittig olefination under ambient conditions, often eliminating the need for tedious ylide pre-formation under strict air and moisture exclusion. Applications were also presented in the field of amino acids and peptides. Acylation of amino acids was performed in a ball-mill, comparing three optimization processes: One Factor at a Time (OFAT), Design of Experiments (DoE) and Bayesian Optimization (BO). BO enables researchers to dramatically reduce the number of experiments as well as to integrate green metrics such as the Process Mass Intensity (PMI).[25] Mechanosynthesis of peptides results in reducing drastically the amount of solvent used. Recent work reported also the possibility of preparing cyclic peptides, molecules of interest for pharmaceutical applications. Their synthesis was facilitated due to a synergy between mechanochemistry and crystal engineering.[26] Another family of biomolecules which can be mechanochemically accessed are nucleosides and nucleotides, with the advantages of solving solubility issues, avoiding anhydrous conditions and the use of toxic solvents and time-saving, including facilitation of purification steps.[27] Mechanochemistry is also an efficient approach for the synthesis of focused libraries of small molecules.[28] The synthesis pathway consisted of 4 steps and included alkylation of various substituted phenols, deprotection of Boc function, and reductive amination followed by sulfonylation of a secondary amine function. The optimized procedures enabled the furnishing of all the designed compounds in high-to-average overall yields and purities, and limiting the use of organic solvents.

Organic mechanosynthetic methods are developing at a rapid pace. Making organosulfur compounds by a 1,4-Michael addition in solvent-free conditions is just as easy by using a very simple base replacing classical organocatalysts.[29] Limonene-derived sulfides with potential anti-proliferative activities on cancer cells can be mechanically synthesized.[30] Ball-milling provides also a modern approach to perform mechanoredox activation utilizing piezoelectric materials such as $BaTiO_3$. This is a practical way to generate radicals that can be involved in organic transformation. This was applied to the preparation of polycyclic structures obtained *via* cascade reactions[31] as well as the synthesis of difluoromethylated heterocycle compounds.[32]

Certainly, the crystallinity of organic molecules can play an important role during a transformation. This is the case of deracemization. This transformation is important in the pharmaceutical industry since more than 50% of marketed drugs are chiral. Deracemization can be performed in a ball-mill, on many substrates, after careful optimization of the milling parameters, resulting in a dramatic decrease in solvent use.[33] Another advantage offered by ball-milling in organic chemistry *versus* solution based chemical reactions is the possibility of obtaining different polymorphs depending on the experimental milling conditions. Under liquid-assisted grinding (LAG) conditions with enough solvent to affect the crystallite surfaces, a "LAG" polymorph is formed. With less or no solvent, one can have access to different polymorphs, and interconversion is possible with further milling. This has important consequences in many areas of chemistry.[34] Organic mechanochemistry can also involve gases as a reactant to be incorporated in a framework.[35] Indeed, ball-milling organic molecules under a CO_2 atmosphere may result in the carboxylation of the starting material, such as alkynes, in the presence of a base and a catalyst.

Véronique Bounor-Legaré

Véronique Bounor-Legaré shared with us the 35 year's of experience in reactive extrusion of polymers developed in the Laboratory of Engineering of Polymeric Materials located in Lyon France. Extrusion is a classical continuous process in which many types of fluids, such as melted polymers, are conveyed and transformed within a barrel/screw system. It is called reactive extrusion when chemical reactions are involved in the process. The significant advantage of extrusion over conventional batch processes for polymer synthesis is to enable the preparation of new materials in a continuous mode of conventionally high-viscosity media and solvent-free conditions. Nevertheless, reactive extrusion in the polymer field combines the difficulties associated with their implementation with the constraints imposed by the control of a chemical reaction under very specific conditions, such as a high-viscosity medium, high temperatures and short extruder residence times. Numerous chemical reactions have been carried out by reactive extrusion, such as grafting and functionalization reactions, polymerization[36] or depolymerization reactions, synthesis of new copolymers, blend compatibilization, and synthesis of vulcanized thermoplastic materials.[37] The experience acquired in this field is very valuable for developing continuous environmentally-friendly processes in other applications such as organic synthesis or biomass upgrading for example.

This was indeed exemplified during Mech'cheM 2025 with the use of a twin-screw extruder as a chemical reactor (i) to perform the continuous synthesis of cellulose mixed esters, notably of cellulose acetate propionate (CAP), an important commercial product,[38] (ii) to valorize of banana tree waste, (iii) to carry out sustainable amidation reactions including active pharmaceutical ingredients such as moclobemide. In this case an optimization approach based on artificial intelligence, more precisely a Bayesian optimization, was proposed with the development of a model based on a surrogate function which suggested new sets of experiments. At each iteration the model integrates the new results, exploring the reaction space and progressing rapidly toward the best experimental conditions, together with a low environmental impact.[39]

Ina Vollmer

Recently, the use of mechanochemistry for degradation/recycling has been reported on thermoplastic polymers such as polyolefins (polyethylene, polypropylene) but also polystyrene and polyethylene terephthalate. It was in this context that Ina Vollmer from the University of Utrecht (Netherlands) presented her cutting-edge work on the direct mechanocatalytic depolymerisation of polyolefins.[40] The conversion of polyolefins suffers from low chain cleavage rates and low stability of radical intermediates. Therefore, insights into the degradation mechanism are crucial to obtain higher yields. Ball-milling polypropylene samples at ambient temperature with unmodified ZrO_2 balls resulted in the steady production of gaseous small hydrocarbons including propene. For example, the Vollmer's group studied the mechanochemical degradation of polypropylene by milling with sand as an additive, which increases depolymerization yields by a factor of 25.[41] The mechanism based on surface radicals dominates over alternative pathways based on locally increased temperature or surface roughening of grinding spheres. In another example, the surface of the milling balls was functionalized to improve the depolymerization process. Sulfated zirconia spheres enabled the reaching of a cumulative yield of 45% within 1 h at room temperature. Mechanism investigations showed the generation of radicals as key intermediates and it is hypothesized that the catalytic sites of the spheres stabilize or interact with them to favor the decomposition into small hydrocarbons.

In this context, the development of kinetic models to optimize and predict the conversion of polypropylene into propene was pursued.[42] To this end, reliable information about the ball movement inside the jar was required. Using a translucent jar, a high-speed camera and colored ZrO_2 spheres, it is possible to track milling balls inside a jar and to record their speed and position. Integrating the velocity values in a previously developed model, computer (DEM) simulations were improved. This demonstrates how a smart video set-up helps in understanding mechanochemical processes.[43]

Direct mechanocatalysis, where the catalyst is present or supported on the surface of a mechanochemical device, *e.g.* balls or jars in ball milling, has known new developments recently. This concept was exemplified with a metallic catalyst directly embedded in the milling ball material, either using raw metallic balls (Cu, Pd) or metallic-coated balls.[44] Throughout collisions inside the ball-mill, energetic contacts between the catalytic surface and the reactants enable a wide range of chemical transformations. Recently, direct mechanocatalysis was extended to other types of catalysts such as small organic molecules, functionalizing zirconia milling balls. A piperazine derivative was covalently attached to the surface and the functionalized ball used in a mechanochemical Knoevenagel reaction, providing the first example of organo-mechanocatalysis, with excellent conversion at very low loading and with very good turn-over numbers and frequencies over many cycles.[45]

Tomislav Friščić

Ending up a symposium with a lecture from Tomislav Friščić is always enlightening, as he summarized the three days of scientific presentations and exchanges with a simple but clear sentence "Mechanochemistry is the new chemistry". He then focused on the latest works of his group, at the University of Birmingham, that aim to understand mechanochemical reactions through integrated monitoring approaches, or theoretical modelling of mechanochemical reactions based on molecular dynamics simulations. As a complementary approach to classical ones for *in situ* monitoring (Raman and powder X-ray diffraction using synchrotron X-rays), low frequency Raman, also known as Terahertz-Raman, was employed to discover the formation of polymorphs and co-crystals that could not be observed in classical Raman spectroscopy.[46] Such analyses can be performed using a vibratory ball-mill and bench-top equipment, making it user-friendly and with high potential for better understanding of mechanochemical reactions. Additionally, molecular dynamics simulations gave a better understanding of the formation of co-crystals, and particularly of the importance of the incident angle for an efficient disruption of the crystal structures of both reagents.[47] Moreover, such simulations may give interesting insights into the role of the liquid additive, which is classically used in ball-milling but whose molecular effect is not clearly understood. Finally, Resonant Acoustic Mixing (RAM) was shown as a promising alternative to ball-mills for the future of mechanochemistry.

RAM was also highlighted in the conference by new developments including the integration of real-time Raman and THz-Raman spectroscopy with thermal imaging to monitor chemical transformations and provide a comprehensive view of reaction dynamics.[48] RAM could be also employed for the deposition of *N*-heterocyclic carbenes on a copper powder surface with the aim of mitigating surface oxidation. NHC–Cu entities were formed, modifying the Cu surface properties but without affecting the particle morphology. The optimized experimental procedure was straightforward and characterization techniques (XPS, LDI-ToF-MS) revealed a significant decrease of surface oxidation, demonstrating the potential for RAM as

Fig. 3 Awards ceremony: from left to right Namita Datta (Royal Society representative), Tomislav Friščić, (Editor-in-Chief, *RSC Mechanochemistry*), Franziska Emmerling (Associate Editor, *RSC Mechanochemistry*), Vivienne Chantrain, Abdul Hafeez, Joseph Marett (Best poster awardees), Thomas Schlatzer (Oral communication awardee), Xavier Bantreil (Vice-president of the *French Chemical Society*-Occitanie Méditerranée).

Fig. 4 Participants at Mech'cheM 2025: New forces in Mechanochemistry.

a mechanochemical technique for surface modification of metal powders.[49]

Awards

The participation of young researchers at Mech'chem 2025 was remarkable (more than half of the participants). The work they presented was of very high quality. Four researchers stood out and received a poster award for three of them (Vivienne Chantrain, Abdul Hafeez, Joseph Marett) and an oral presentation award for the last one (Thomas Schlatzer) (Fig. 3).

Conclusion

These highlights from the plenary lectures and oral communications illustrate the dynamics of the world of mechanochemistry (Fig. 4), which has seen considerable advances over the past 10 years. Lively poster sessions also contributed to sharing and discussing the expansion of new knowledge in the field. From technological advances in synthesis (reactive extrusion, Resonant Acoustic Mixing, functionalized jars and balls) and analysis (combination of methods for *in situ* analysis) to numerous applications in all areas of chemistry, including highly current issues such as depollution, mechanochemistry is here to stay, and maybe just generalize to become "chemistry". Let's meet again in 10 years to check if this proves to be true!

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