COST
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

Brussels, 12 May 2023

COST 057/23

DECISION

Subject: Memorandum of Understanding for the implementation of the COST Action "European metal-organic framework network: combining research and development to promote technological solutions" (EU4MOFs) CA22147

The COST Member Countries will find attached the Memorandum of Understanding for the COST Action European metal-organic framework network: combining research and development to promote technological solutions approved by the Committee of Senior Officials through written procedure on 12 May 2023.

MEMORANDUM OF UNDERSTANDING

For the implementation of a COST Action designated as

COST Action CA22147
EUROPEAN METAL-ORGANIC FRAMEWORK NETWORK: COMBINING RESEARCH AND DEVELOPMENT TO PROMOTE TECHNOLOGICAL SOLUTIONS (EU4MOFs)

The COST Members through the present Memorandum of Understanding (MoU) wish to undertake joint activities of mutual interest and declare their common intention to participate in the COST Action, referred to above and described in the Technical Annex of this MoU.

The Action will be carried out in accordance with the set of COST Implementation Rules approved by the Committee of Senior Officials (CSO), or any document amending or replacing them.

The main aim and objective of the Action is to efficiently transform lab-designed metal-organic framework (MOF) candidates into practical solutions for healthcare, clean water, and sustainable energy. It will achieve this by improving production, creating controllable manufacturing methods, setting publication standards, elucidating structure-activity relationships, and cultivating relationships between industry and academia.. This will be achieved through the specific objectives detailed in the Technical Annex.

The present MoU enters into force on the date of the approval of the COST Action by the CSO.

TECHNICAL ANNEX

OVERVIEW

Summary

The constantly growing world population and current European energetic crisis demand innovative scientific and technological solutions. The crystalline hybrid material class of Metal-Organic Frameworks (MOFs) holds potential to help address societal challenges like health, water and sustainable energy due to their unprecedented high degree of porosity, chemical and structural versatility, and functional tunability. However, the translation of groundbreaking basic research into development of potential MOF-based technologies is still hampered by the lack of precise control over their structure, properties and performance from the molecular-level framework to the nano-, meso- and macro-scale dimension material for each application. This COST Action (EU4MOFs) aims at increasing control and customization over the interplay between (re)activity, selectivity, efficiency and processability of MOF materials to ensure optimal functional properties at these three length scales. EU4MOFs will focus on paving the way towards the development of nano-, meso- and macro-scale high-performing MOF materials for three high-need applications: (cancer) nanomedicine, wastewater treatment and energy storage. To achieve this, manufacturing technologies based on bottom-up synthesis and top-down engineering strategies will be consolidated, and high-throughput computational screening and machine learning methods will be integrated to improve structure-property predictions and the resulting materials performance. By uniting interdisciplinary researches from the fields of (bio)chemistry, materials engineering, physics, nanomedicine, pharmacy, and computational science, together with industrial partners, EU4MOFs will contribute to substantially advance the current frontiers of MOF materials from the laboratory bench towards industrial-scale, in order to ultimately generate societal impact.

Areas of Expertise Relevant for the Action	Keywords
● Chemical sciences: Coordination chemistry ● Materials engineering: Structural properties of materials ● Materials engineering: Solid state materials	● Metal-organic frameworks ● Material Chemistry ● Porous Materials ● Nanotechnology

Specific Objectives

To achieve the main objective described in this MoU, the following specific objectives shall be accomplished:

Research Coordination

● Establishing the most potentially sustainable and cost-efficient methods for the synthesis and functionalization of MOF materials with homogenous size distribution as nanoparticles (10-100 nm), thin-films (μm), and macroscopic materials (mm-cm) into three-dimensional arbitrary geometries.
● Bundling expertise in incorporating MOFs in planar nano- and microfabrication technologies.
● Creating standardized database of material-specific manufacturing processes and parameters for making nano-, micro- to millimeter-scale structures consisting of porous (MOFs) materials.
● Defining minimum information reporting guidelines and standardized characterization methods.
● Best practice guidelines for safe handling, disposal, and sustainable life cycles of MOF materials.
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Capacity Building

● Accessing European researchers to engineer nano-/micro-structured functional porous materials in

different standardized forms suitable for manufacturing high-value products.
● Providing an overview and assessing chemistry trends, characterization, modelling, structuring techniques, and industrial applications of porous materials through at least two perspective articles.
● Assembling a critical mass of European experts in different fields whose work is pertinent to advancing the structuring methods for functional porous materials
● Fostering competitiveness and consolidating a MOF-based society (with impact on other porous materials) also for competitive and academy-to-industry (public-private) co-funding programs in order to promote technology transfer into proof-of-concept and potential commercialization.

TECHNICAL ANNEX

1. S&T EXCELLENCE

1.1. SOUNDNESS OF THE CHALLENGE

1.1.1. DESCRIPTION OF THE STATE OF THE ART

Porous materials have shown a remarkable impact on our society. Already back in ancient Egyptian civilizations, they were utilized for medical purposes, and, currently, materials like charcoal, activated carbons, and zeolites are involved in multiple industrial processes such as (toxic) gas separation, ion exchange and catalytic processes in oil refining, petrochemical, and water treatment industry.[1,2] The exploitation of porosity has attracted enormous research interest (and encompassed many technological advantages) over the years, with porous materials reaching a **market size** bigger than **25 billion USD in 2021**, and with an expected 300% growth in the next 5-10 years.[3] Their specific physicochemical characteristics that result from their porous structure (vast surface area-to-mass and area-to-volume ratio, functional sites, high specific surface area, etc), coupled with the intrinsic properties of the matrix (diverse mechanical characteristics, adsorption, redox, catalytically active sites, etc) endow these materials with high potential for a wide range of applications, including catalysis, separation of complex mixtures, gas and energy storage, drug delivery and chemical/biological sensing.

Therefore, the last decades have witnessed an exponential research growth in more and more efficient and functional (porous) materials that can be translated into **innovative robust, reliable and (ideally) cost-effective high-performing technologies**. Two of the most recently developed classes of ordered porous solids are covalent- and **metal-organic frameworks** (COFs and **MOFs**, respectively). Particularly, MOFs comprise an extensive class of crystalline metal-organic hybrid materials with unprecedented ultra-high porosity (≥ 90% is free volume) and remarkable internal surface areas (≥ 7000 m^2/g), which make them **highly promising materials for gas storage, catalysis, thin-film devices and biomedical applications**.[4] During the last two decades, **more than 100,000 MOF structures** have been synthesized, showcasing high metal-organic chemical versatility, high surface areas (internal and external), and pore tunability.[4] The possibility of tailoring open metal sites and organic linkers has already resulted in functional MOF structures with the **highest adsorption capacity for CO_2**, over other porous materials like zeolites, alumina, silicates and activated carbons.[5] These achievements have promoted the creation of **several start-ups and companies** that aim to translate MOF research into technology, mostly for gas storage applications thus far.[6,7]

To highlight the already high industrial relevance of MOFs, their market size amounted ~280 million USD in 2021 (mostly within gas storage applications), and it is forecasted to rise up to more than 1000 million USD by 2028.[8] Their combined features, together with the possibility of being synthesized at different length scales (**nano-**, **meso-** and **macro-**scale) endow them with the potential to become innovative technologies that help address key societal challenges such as: ***i)* cancer nanomedicine** (***nanoscale***)**,** ***ii)* energy storage** (***mesoscale***), and ***iii)* wastewater treatment** (***macroscale***). The exponentially rising number of cancer deaths (10 million deaths worldwide, about 10% in Europe, in 2021),[9] the current energetic crisis (35% higher electricity prices in EU in 2021 respect to 2020),[10] and the increasing risk of water scarcity (22% of Europe´s surface water bodies and 28% of groundwater are polluted)[11] evidence the urgent need to nurture the development of innovative technological solutions. In this context, the high metal-organic chemical versatility, extremely high-porosity and tailorable surface area place MOF-based technological materials with intrinsic capacity to outperform existing materials in (at least some of) these three high-need applications.

i) **Nanoscale MOFs** (in **cancer nanomedicine)**: MOF nanoparticles have already been explored in different preclinical setups, mostly *via* two main approaches: *a)* as an inert hybrid (inorganic-organic) nanocarrier that can load both hydrophilic and hydrophobic (macro-)molecules into the framework pores; and, *b*), by exploiting the (re)activity and versatility of the constituting building blocks (*i.e.*, metals and organic linkers).[12] These fundamental components can serve as therapeutic entities or imaging agents themselves, and can also enable combination **(immuno-)therapies**[13] and theranostic approaches (*e.g.*, loading drugs into the pores and using metal ions like hafnium as **radiation therapy enhancers**, or iron as magnetic resonance contrast agents).[14] Since the first reports on MOFs for drug delivery (in the 2010s),[15] about 1500 publications (Scopus database) have been reported about MOFs for cancer (combination) therapy and/or diagnosis. Although some MOF-based nanostructures still require research efforts to target stability and biocompatibility issues, at least one **nanoscale MOF** (RIMO-301) **has already entered clinical trials**.[16] Furthermore, MOFs are one of the few (nano)carriers with the potential to encapsulate and transport therapeutic gases, such as nitric oxide or carbon monoxide.[17][18]

ii) **Mesoscopic thin films** (in **energy storage**). The emerging **lithium-sulfur (Li-S) batteries**, which are extremely attractive due to their high theoretical energy density and specific capacity, and the environmental benignancy of sulfur, hold great promise to revolutionize the energy sector. However, the material for their composite cathodes still needs to be optimised so that it can serve as a host for poorly conductive sulfur and chemisorb its discharged products – polysulfides, as well as solid-state electrolyte with high Li^+ conductivity in order to create an optimum interface with electrodes. In the last decade, electroactive metal-organic frameworks (eMOFs) have emerged as a new class of electroactive materials bearing the potential to drastically improve the properties of Li-S batteries because they possess three key properties that are very difficult to achieve simultaneously: high porosity, high electron/ionic conductivity, and a large amount of tuneable chemisorption sites.[19] At present, there are two critical challenges to prepare macroscopic objects (*e.g.*, electrodes) out of eMOFs that are suitable for for Li-S batteries. First, significant loss of the anisotropic conductivity of eMOFs occurs during manufacturing due to misalignment and amorphization of crystals. The second challenge is processability, which is fundamental to bringing MOF materials from lab-bench to industry.

iii) **Macroscale MOF assemblies** (in wastewater treatment): **MOF**-based solutions have also shown promising initial results for the improvement of various well-established **wastewater treatment or desalination methods**, such as reverse and forward osmosis, capacitive deionisation, adsorption desalination, membrane distillation, ultra-, and microfiltration.[20] The most commonly used desalination method to date is the reverse osmosis, where MOF materials such as UiO-66(Zr) and ZIF-8(Zn) as membrane fillers have proven to be beneficial in increasing water flux while maintaining salt retention (lab scale).[20] In addition, their incorporation into membranes could also minimise fouling and allow for easier cleaning, thus extending membrane lifespan.[20,21] Although only a few different well-known MOF structures have been studied for wastewater treatment or desalination so far, the chemical variability and tuneability of MOFs hold promise for high-performing MOF structures in this regard.

However, despite the high potential and industrial promise of MOFs for any of the three abovementioned applications, the number of structures that successfully crossed the **research-to-innovation technology gap** still remains quite low. Advanced experimental and computational techniques like neutron scattering, high-performance computing and cryogenic electron microscopy have been recently developed to increase molecular level insights into and understanding of MOF-based chemistry. Nonetheless, most of the materials still (a) do not have available **scalable production** processes with high **batch-to-batch reproducibility**, (b) exhibit sub-optimal stability for the real-application context (and not only at lab-confined conditions) and, most importantly, (c) do **lack of (property) control** when translated from the crystalline framework (molecular-level) **to the nano-, meso-** and **macro-scale usable material**, especially during upscaling. Hence, and beyond the breakthrough advances in the basic chemistry and materials science of MOFs, as well as beyond the promising performance observed in lab-setup applications, **MOFs' true technological potential is still to be unlocked** (**Figure 1**).

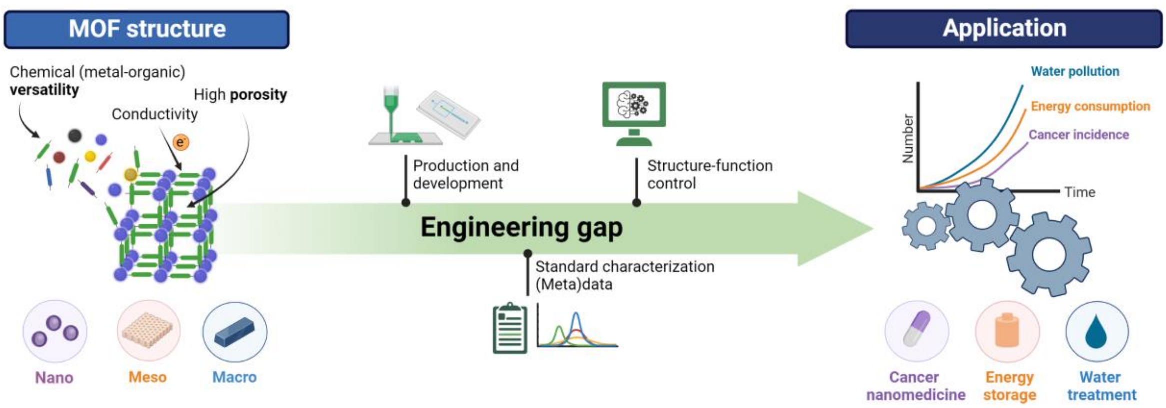


Figure 1: Engineering gap for MOFs from powders towards MOF-based applicable products.

After more than two decades of MOF research, and with currently several companies now taking MOF products to the market, it seems that a **critical developmental stage has now been reached**. Key actions need to be taken to turn MOF research for ‑ but not limited to ‑ cancer nanomedicine, energy storage, and water treatment into an inflection point that promotes technology transfer. To achieve this, the focus has to shift from developing more and more complex MOF structures to start **addressing the crucial technology-translational barriers** from a holistic, multi-disciplinary and **technology/user-driven perspective** by: *i)* implementing and optimizing advanced bottom-up and top-down production, functionalization, processing and manufacturing strategies (*e.g.*, laser writing and 3D printing for meso- and macroscopic MOFs, and microfluidic systems for MOF nanoparticles), which enhance control over the crystalline structure, the dimensions, as well as increase batch-to-batch reproducibility; *ii)* deepening into structural-property understanding and increasing (computationally-assisted) material customization of key functional properties at each length scale; and *iii)* keeping industrial requirements and end-user needs in mind. Individually and together, these actions will assist in **paving the way towards MOFs technological development** and will serve as a starting point towards **future** pre-commercial to market translation that can help to address current societal challenges.

1.1.2. DESCRIPTION OF THE CHALLENGE (MAIN AIM)

As for most cutting-edge research in material science, there are still multiple barriers when transferring new materials from academia into successful technological products with the potential to impact our society. The inability to commercialize is one of the main roadblocks to use new lab-designed materials, oftentimes linked to the high risk related to their production at larger-scales. It is well-established that **industry** aims for *i*) **rapid and simple** (low-cost) synthetic protocols that produce *ii*) **high-purity** and **quality** (MOF) materials in *iii*) **high-yields** and in *iv*) a **sustainable** way with minimal waste production. Therefore, academia-to-industry transition of MOFs faces several structural and properties challenges regardless of (but not fully independent from) the specific application and use:

1. **Simple, sustainable, and scalable protocols.** Most studies encompassing MOFs are performed at the laboratory research-level, at milligram scale with lab-confined conditions, where researchers do not usually aim at optimizing aspects like time, energy use, overall chemical toxicity, and costs. Instead, the primary goal is to maximize purity and crystallinity of the MOF structure to assess their properties and performance. Thus, established synthetic procedures can employ (toxic) organic solvents (*e.g.*, amide based or hydrocarbon solvents like *N,N*-dimethylformamide) and reaction conditions (*e.g.*, high pressure and/or temperature) that pose safety, economic and regulatory limitations and concerns at larger-scales. Additionally, most of the synthetic protocols reported for MOF-based nano-, meso- and macro-sized materials are usually optimized for each specific type of framework, but they are difficult to be standardised and applicable to different MOF structures. Consequently, **developing and optimizing more standard and translatable (green) synthesis protocols in mild conditions**, together with assessment of space-time yield (STY, which defines the quantity of material generated in a reactor per unit of time and volume) at already lab-scale and early research stages can substantially **facilitate future large-scale production**.
2. **Manufacturability and processability of the materials.** Most of the synthetic procedures result in products in powder form, which are difficult to handle and process at industrial levels. Strategies to transform and customize such powders into manufacturable and usable materials are required, such as pelletizing or hybrid-material membrane formation. However, they are still at a very early research stage, not optimized, costly, and can lead to MOF amorphization and loss of functionality. This is key as the optimal performance of MOF materials for each application is strongly linked to the control and customization at each corresponding length scale (*i.e.*, nano, meso, and macro). **Maximizing processability while ensuring optimal performance at each scale requires the implementation of fabrication technologies and manufacturing protocols that effectively combine both bottom-up and top-down strategies.** Many versatile fabrication methods, such as laser writing, 3D printing have been developed in recent years, but they are usually individually optimized and their general application to porous materials is not universally possible. Therefore, further optimization and integration of such processing and manufacturing methodologies for macro- and meso- (*e.g.*, **3D printing**) and nano-sized materials (*e.g.*, **micro, milli-fluidics**) already at an academic research-level (and supported by industry collaborations) are crucial to increase control over the properties and **batch-to-batch reproducibility**; key aspects towards efficient MOF-manufacturing.
3. **Standardized characterization.** One of the main issues in the multidisciplinary field of MOFs and their broad range of applications is the high number of reports with varied characterizations that hinder analysing trends and establishing structure-properties-performance connections to truly generate progress. Although this material class is relatively new, MOFs rapidly caught attention and they are explored in multiple labs worldwide (over 5000 laboratories working on MOF research).[22] In spite of the advances already achieved, the information and **characterization data** reported **is usually scattered and not yet standardized**, which highly **limits reproducibility and increases risks for potential technology development**. To maximize control over MOFs production and to

increase knowledge about structure-property relationships towards optimal performance, **standard characterization protocols** have to be defined. Standardizing information will contribute to increase robustness, reproducibility, and usefulness of published research. In addition to general guidelines for MOF structures, it is crucial to define **specific guidelines** and **minimum reporting information** for each length scale and their potential related applications.

4. **Control, optimization, and predictability of MOF properties** (*e.g.*, reactivity, stability, efficiency, toxicity) are strongly linked to structural design. This aspect is partly a consequence of the convergence of the three abovementioned challenges. The high number of structures reported, and the lack of standard databases that facilitate trend analyses at each specific length scale (nano, meso and macro), production-level (mg, g, kg, and tones), and application (cancer nanomedicine, energy storage and water treatment) **hamper MOF structure-property predictability.** Consequently, also the optimal design and development of high-performing MOF structures with technological value. While this issue affects the (MOF-based) materials field in general, it is obvious that it is dependent on certain key design parameters specific for each application (*i.e.*, highly related to the inherent limitations of each dimension scale: nano, meso, and macro). Within **EU4MOFs** we aim thus to strengthen such relationships and to thereby enhance control and prediction over properties like *i)* long-term (storage) stability, reproducibility, efficacy and toxicity of MOF nanoparticle formulations for nanomedicine, *ii)* anisotropic alignment, conductivity, efficiency, and material stability for energy storage, and *iii)* reusability, robustness, and low-cost of macroscopic materials for treatment of water. Also, (very importantly) how these properties could potentially be affected during large-scale production of MOF nano-, meso- and macroscopic materials.

To optimize structure-performance by modulating MOF properties, we need to first identify the key functional- and technology-promoting properties, specific for each of the three applications in which **EU4MOFs** will focus, and, secondly, to enhance the translatability of such properties from the molecular-level framework into the (large-production) of the nano-, meso- and macroscale MOF material. This will include, among others, the utilisation of **(computational-assisted) high-throughput screening methods and machine learning tools**. Overall, all the aforementioned challenges are independent but interconnected, and lead to **production obstacles** (*i.e.*, the material faces engineering issues to control its crystalline structure and functionality at different production levels and dimensions required for each specific application), and to **economic and commercialization limitations** by complicating future technological development, overall increasing the product risk and lowering the interest of stakeholders, investors, and companies.

1.2. PROGRESS BEYOND THE STATE-OF-THE-ART

1.2.1. APPROACH TO THE CHALLENGE AND PROGRESS BEYOND THE STATE OF THE ART

Each of the objectives and tasks (more detailed in section 1.2.2 and section 4) go beyond the current state-of-the-art in the MOF field. By combining innovative techniques/strategies with standardization and systematic optimization of synthetic procedures and performance, we expect to address the key challenges in translating MOFs into technological products. It is suggested that, despite the high value of fundamental research on reticular chemistry and MOF structures, there has been an overfocus on specific lab-confined applications, under non-standardized, restricted, and hardly controllable conditions. This fundamental research is more driven by the attractiveness of the material class and, unfortunately, the high-scientific pressure for publishing, rather than by realistic scenarios and by utilizing MOFs at conditions with **enhanced translational and technological value**. All of this comes with the risk of pushing MOFs expectations into the “trough of disillusionment” phase of the typical Gartner´s hype cycle for emerging technologies (**Figure 2, orange trajectory**), and therefore far from the plateau of productivity. To unlock the full technological potential of MOFs, and therefore, to pave the way towards successfully bridging research knowledge and innovation acquired over the last 20 years into technology commercialization, we need to embrace a more concerted and holistic vision that (1) not only approaches MOFs from a (fundamental) chemistry and pure material perspective, but from a more **integrated engineering, developmental an applied point-of-view**, where the industrial requirements also motivate the design and customization of the material. Several scientists in the field have agreed that, despite the promises and expectations of MOF materials – which have shown breakthrough performances at a lab-scale level, the field needs to more and more focus on standardizing and improving synthetic methods and engineering strategies to enhance control over MOF properties and to maximize performance across different dimensions, including when producing them at larger-scales.

By doing that, **EU4MOFs** expects to minimize the risk of disillusionment of MOF field and to promote (technological) productivity (**Figure 2**, **green trajectory**) in (cancer) nanomedicine, energy storage, and wastewater treatment applications, among others. The key is to ensure that the promising performance of the material in lab-settings can be translated (in the most optimized and manufacturable manner possible) into potential industrialization to, eventually, reach society and generate real-world impact. Thanks to the conjoint and interdisciplinary action of scientists from multidisciplinary areas ranging from synthetic and engineering materials science to nanomedicine, biochemistry, and computational fields, **EU4MOFs** can and will uniquely contribute to the path towards technological progress beyond the state-of-the-art based on:

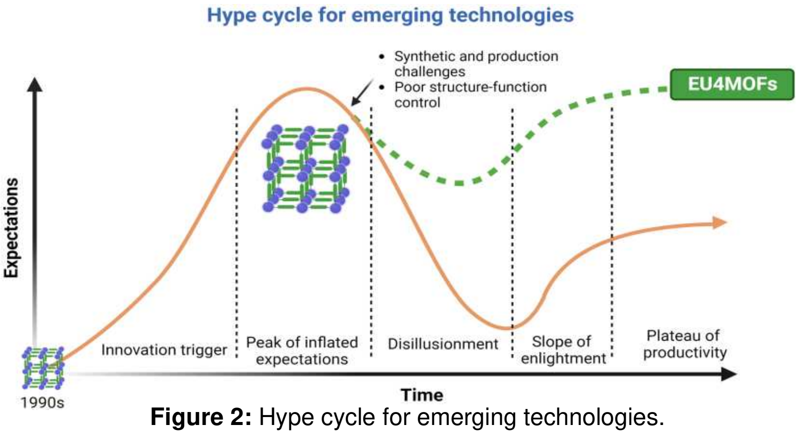


Figure 2: Hype cycle for emerging technologies.

1. Instead of developing more and more MOF structures, we rather aim to (a) **establish** and **optimize robust, simple, more sustainable,** and **scalable preparation methods** for (currently reported) MOF structures, with the idea of fostering **technological value**. Thus, this Action will bring together expertise from different groups to focus on *i*) establishing suitable room temperature, environmentally friendly solvents (*e.g.*, water) and low-cost methods for a series of different MOFs for each dimension scale, and *ii*) implementing continuous manufacturing procedures to ensure the production of high-quality crystalline MOF materials, rather than difficult-to-handle powders, typical from the lab-scale. Patterning of porous materials over a wide range of scales requires a combination of bottom-up and top-down methodologies. There are several promising proof-of-concept studies of this in the literature.[23][24] These provide important insights on the unique opportunities and the challenges of creating well-defined micron-sized structures. It is anticipated that the consolidation of methods like 3D printing for macroscale MOFs, casting for thin films in MOF electrodes and microfluidics for MOF nanoparticles at a lab-scale and academic-research level, and with **feedback from industrial partners**, will increase control over structures and properties, and will facilitate translation towards technological development. Additionally, the systematic evaluation carried out to implement the different synthetic and manufacturing methods will enable **EU4MOFs** to generate **characterization databases** of the reported information that will help promote the **standardization** within the MOFs field to maximize reproducibility across different types of structures and trend analysis. Considering that standard information also requires the commitment and engagement of many scientists in the field, we are convinced that this COST Action (composed of more than 40 scientific groups and 5 companies related to the MOF field or the intended key applications) represents a unique opportunity to start optimizing scientific efforts, ultimately resulting in a benefit for MOF research and society.
2. Building upon previous point, the Action will also interlink forces to expand MOF production beyond mg-scale, and to truly focus on assessing technology-readiness-level (TRL) at each specific length-scale. **MOF large-scale production** is intended to be explored for macroscopic, thin-films, and nanoscale MOF materials, including rationalization on how properties change from the molecular-designed framework to the nano-, meso- or macroscale production of materials. To do that, EU4MOFs will establish close collaboration between **key opinion leaders in the field (research and industrial partners)** to minimize risks already at early-stages and to optimize production and manufacturing protocols towards potential future industrialization of MOFs. We want to ensure that our methods do not only preserve the properties of the lab-scale produced crystalline frameworks (point 1), but are also truly scalable in a sustainable and economically feasible manner. It is envisioned that by also optimizing post-synthetic modifications we can shape materials towards optimal performance and processability at larger-scales, and towards potential future prototype technology. In parallel, the **industrial landscape** and **market** for MOFs in (cancer) nanomedicine, energy storage, and treatment of wastewater will be analysed to *i*) assess potential market niche, end-user requirements, competitors, and commercialization opportunities; *ii*) explore potential IPR strategies for developed products, protocols, or post-synthetic strategies, and to *iii*) **build more networks between academia and industry**.

3. EU4MOFs wants to consolidate (**computational-assisted**) **high-throughput screening** for MOFs in (cancer) nanomedicine, energy storage, and wastewater treatment by also integrating **machine (and deep) learning tools** that maximize structure-performance relationships. By adequately employing artificial intelligence, optimized physical and functional properties (*e.g.*, size, shape, porosity, charge, surface coating, stability, conductivity, toxicity) could be predicted and customized at all length scales. Recent works on using machine learning tools in MOFs for gas storage and separation are very promising and have enabled the prediction of relevant properties such as gas loading capacity and delivery.[25,26] While machine learning (and artificial intelligence in general) has been already explored for certain applications,[27] the results in areas like (cancer) nanomedicine or wastewater still remain sub-optimal due to insufficient data arising from the **lack of standard databases for MOF materials**. The progress in computational methods and technologies have led to algorithms and predictive models with high accuracy (*i.e.*, even beyond 90-95%). However, the remaining 5-10% margin of error (partly due to insufficient data) can result in millions of unacceptably wrong decisions for *e.g.*, health-related applications. Thus, taking advantage of the **involvement of multiple groups** in the Action, EU4MOFs aims to generate and establish guidelines for high-fidelity, robust, and comparable (meta)data to systematically train current computational systems and enable more accurate structure-property-function predictions. This task goes beyond the state-of-the-art because will be focused on *i*) structuring data and establishing MOF structure-performance trend analysis; *ii*) assessing validity of predictions for certain MOF properties within the three main applications, and *iii*) evaluating potential technological value by predicting factors like space-time yield (STY). Such data can only be achieved by establishing **characterization standards** (one of the main goals, as mentioned in previous point 1). It is expected that this ambitious objective will generate high-quality and valuable information not only for the MOF community, but can also serve as a role model for other scientific fields: by providing knowledge on how to integrate artificial intelligence and machine learning tools in materials science.

1.2.2. OBJECTIVES

1.2.2.1. Research Coordination Objectives

- Establishing the most potentially sustainable and cost-efficient methods for the synthesis and functionalization of MOF materials with homogenous size distribution as nanoparticles (10-200 nm), thin-films (µm), and macroscopic materials (mm-cm) into three-dimensional arbitrary geometries.
- Bundling expertise in incorporating MOFs in planar nano- and micro-fabrication technologies.
- Creating standardized database of material-specific manufacturing processes and parameters for making nano-, micro- to macro-scale structures consisting of porous (MOFs) materials.
- Defining minimum information reporting guidelines and standardized characterization methods.
- Best practice guidelines for safe handling, disposal, and sustainable life cycles of MOF materials.
- Testing and evaluating new and optimized (upscaled) functional materials in view of predetermined properties regarding the three specific applications by leveraging the broad expertise of the network.

1.2.2.2. Capacity-building Objectives

- Accessing European researchers to engineer nano-/micro-structured functional porous materials in different standardized forms suitable for manufacturing high-value products.
- Providing an overview and assessing chemistry trends, characterization, modelling, structuring techniques, and industrial applications of porous materials through at least two perspective articles.
- Assembling a critical mass of European experts in different fields whose work is pertinent to advance the structuring methods for functional porous materials.
- Fostering competitiveness and consolidating a MOF-based society (with impact on other similar porous materials) also for competitive and academy-to-industry (public-private) co-funding programs in order to promote technology transfer into proof-of-concept and potential commercialization.

2. NETWORKING EXCELLENCE

2.1. ADDED VALUE OF NETWORKING IN S&T EXCELLENCE

2.1.1. ADDED VALUE IN RELATION TO EXISTING EFFORTS AT EUROPEAN AND/OR INTERNATIONAL LEVEL

The relevance of porous materials in our society is undeniable, and the EU supports this research area (*e.g.*, *NMP-03-2015:* Manufacturing and control of nano-porous materials and *POROUS4APP*: Innovative Carbonaceous Porous Materials). However, generating scientific and technological development and innovation impact, and ultimately, societal benefit, requires bringing together multiple (inter)national expertise and backgrounds at different academic and industrial level. All the scientific and technological breakthroughs in history have resulted from multi-, inter- and trans-disciplinary collaborations that, from multiple angles and fields, accelerate innovation impact. By establishing, for the first time, a European-based network on the already highly promising material class of MOFs, this Action aims to strengthen the (European) capacity to face high-need societal challenges by primarily focusing on energy storage, wastewater treatment and cancer therapy.

To the proposers´ knowledge, no other parallel EU project is focusing on the objectives proposed in this Action. Thus, the **European-based network** EU4MOFs Action will, for the first time, unite (European) **cross-border expertise** in chemical sciences, material engineering, physics, electrical and information engineering, computational science, nanotechnology, nanomedicine and biological sciences in order to, together with industrial collaboration and international partners, increase research value and foster innovation technology of MOFs in several key application areas (**Figure 3**). This Action will engage in **interdisciplinary research and further collaborations** with complementary projects, mostly: *i)* Action CA15107: Multi-Functional Nano-Carbon Composite Materials Network (MultiComp), designed to bring together theorists, experimentalists and industrialists in the field of nano-carbon materials technology; *ii)* Action CA15119: Overcoming Barriers to Nanofluids Market Uptake (NANOUPTAKE), addressing the precise synthesis of nanomaterials; *iii)* Action MP1406: Multiscale in modelling and validation for solar photovoltaics (MultiscaleSolar), dealing with novel multiscale modelling and characterization approaches to optimize solar photovoltaics; *iv)* Action CA21121: European Network for the Mechanics of Matter at the Nano-Scale (MecaNano); *v)* Action CA21101: Confined molecular systems: from a new generation of materials to the stars (COSY); and, *vi)* Action CA17140: Cancer nanomedicine - from the bench to the bedside (NANO2CLINIC).

2.2. ADDED VALUE OF NETWORKING IN IMPACT

2.2.1. SECURING THE CRITICAL MASS, EXPERTISE AND GEOGRAPHICAL BALANCE WITHIN THE COST MEMBERS AND BEYOND

A network of **41 experts from 20 COST full member countries** and from **2 international** partnered countries are involved in this Action. This consortium was constructed first by defining what kind of expertise is needed to accomplish the objectives, and then by deciding who in Europe can offer the best expertise on the selected topics. In this Action, leading multi- and interdisciplinary expertise is brought together, ranging from chemical sciences, materials engineering, physics, computational science, nanotechnology, (nano)medicine, and biology (**Figure 3**). The high attractiveness and technology relevance of this Action have already caught attention of several international partners from USA and Canada as well as **5 companies** (**SMEs**) that are already involved in the consortium to provide their industrial experience. More than 50 additional partners have also expressed their interest to join **EU4MOFs**. Thus, the consortium has (and attracts) the necessary critical mass.

Additional partners that already showed interest and/or will be interested in joining over the course of the Action will be discussed during the Kick-off and annual meetings, and approved by the managing committees (MC). In this regard, efforts to include members with relevant expertise from other countries that are so far not represented and towards ensuring appropriate gender balance will be given priority. The MC will continually monitor early career support, gender balance, and geographic attributes of this COST network. So far **EU4MOFs** is extremely successful in attracting many of the top European female researchers in the MOF field: almost half **(46.5%)** of the proposers of EU4MOFs are **females** leading to full gender parity in all its committees. In addition, the members are distributed all over Europe, including **50% of ITC members** and **44% of early-career investigators**. The MC will ensure that

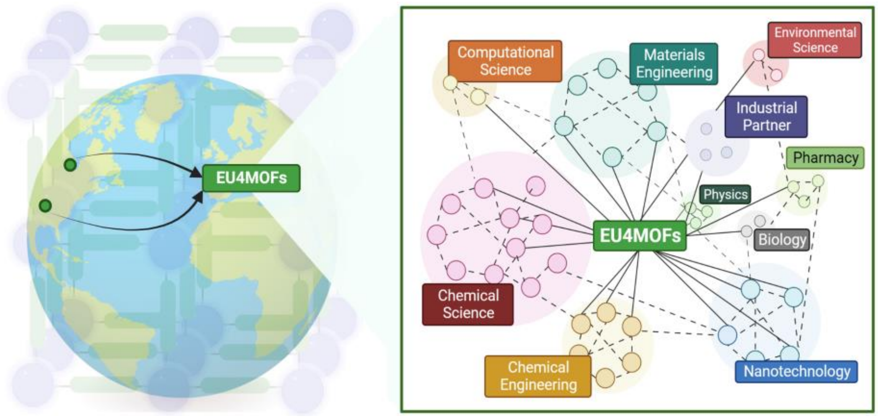


Figure 3: Overview of the **EU4MOFs** network with expertise from various fields.

geographic, gender and early-career investigators balance are achieved at both the recruitment and decision-making levels. In this regard, the MC aims to designate 2 coordinators in each of the different working groups (see section 4. Imple-mentation), and to create an external advisory board that provides external expertise, including tackling potential risks. They will meet regularly (bimonthly) to maximize progress within the Action course. Altogether, **EU4MOFs** will open the door towards consolidating MOF research and innovation in Europe for the future establishment of **European MOF-focused research societies** (with different focus groups targeting cancer, energy storage and wastewater treatment challenges), which will endow the necessary competitiveness for future **co-programmed and co-funded research** and innovation European partnerships, including **public-private** cooperation, for not only boosting technology-readiness-level (TLR) of MOF-based materials, but also of other similar porous materials.

2.3. INVOLVEMENT OF STAKEHOLDERS

The broad and interdisciplinary mix of research interests (porous and MOF materials, nanomedicine, machine learning, materials engineering, microfluidics, wastewater treatment, batteries for energy storage) and interactions pursued by **EU4MOFs** promises to generate not only a network for new and fundamental scientific insights and achievements, but mainly to pave the way towards bringing ground-breaking basic research and development into useable technology with higher economic potential: in the field of cancer nanomedicine, the treatment of water and energy-related applications. The **three main stakeholders** for this COST Action are **academia**, **industry,** and the **public**.

Academia is already heavily involved in **EU4MOFs** with 20 COST and 2 international partner countries and many others have stated their strong interest in the future participation. To attract new academic stakeholders, the **EU4MOFs** Action website (planned as *www.eumofs.com*) will be an important tool, supplemented by networking at scientific meetings (the Action will organize annual meetings which, in addition to discussing critical next steps of the Action, will be open to other academic and industrial partners interested in the research carried out) and direct contact *via* mail. Additionally, this Action aims for transparency and reproducibility, by disseminating the milestones and deliverables (see section 4) regularly via newsletters, website, twitter, and other social network updates, including scientific videos and via some publications in OPEN access. Never has such an interdisciplinary MOF network been assembled at a European level. Ultimately, this will improve the chances for high-quality data and successful applications for future funding programmes.

EU4MOFs wishes to create strong and successful collaborations with established **European research-intensive industries**, as well as with **small and medium-sized enterprises** (SMEs) that in many cases have been spawned from fundamental research pursued in academic laboratories. Although the field of MOFs is relatively recent (*i.e.*, since the late 1990s, and even later for biomedical applications: 2010s), the **commercial relevance and potential applicability of MOF materials** as innovative technology **are already palpable in our society** with **more than 30 companies and spin-off focusing on MOF materials** for, mostly, catalytic, gas storage and water harvesting applications**. The interest in the Action, with five SMEs** joining the consortium already at this stage, is very high**.** To further explore the market and identify potential competitors and further stakeholders and investors, **EU4MOFs** will organize interactive multi-stakeholder workshops at the end of each year (with special interest for industry sector) and will actively contact additional relevant SMEs (and even larger companies) to invite them to join the Action. **Industrial stakeholders from the following field** will be prioritised as targets: industrial MOF synthesis (BASF, MOF Technologies, ProfMOF), nanomedicine/pharmaceutics (Ardena, AstraZeneca), batteries (Northvolt, Electrovaya (Litarion), ELEO Technologies B.V., 3dbattery, Battrion AG) and water treatment (SunToWater Technologies LLC, Genesis Water Technologie Inc., AqSep, Enki Water Treatment Technologies Ltd., ACWA Services Ltd., KWR Water Research Institute). Furthermore, **EU4MOFs** intends to strongly support **entrepreneurial activities** by young scientists by offering access to know-how and to the facilities of the participating institutions. Additionally, the creation of such network will foster the preparation of **transnational funding acquisition in European programmes**, especially for calls focused on innovation and technology transfer, including co-funded or co-partnered with industrial partners.

The acceptance of the importance of MOF materials research and the resulting technologies **by the public** will highly depend on suitable information polices. The **EU4MOFs** homepage (planned as *www.eumofs.com*) will inform all interested people worldwide about the topics MOF synthesis, MOF functionalization, MOF characterization, MOF structuring at the nano-, meso- and macro-scale and the resulting MOF-based technological solutions for nanomedicine, batteries, and water treatment.

EU4MOFs will establish and develop systematically a press network (newsletter) and other social media announcements (*e.g.*, Twitter, LinkedIn, Instagram) with their members and with the support of the press offices of their universities and institutes. All those outreach **activities will be organized and guided by the MC** and together with the two coordinators from each working group (see Section 4).

3. IMPACT

3.1. IMPACT TO SCIENCE, SOCIETY AND COMPETITIVENESS, AND POTENTIAL FOR INNOVATION/BREAK-THROUGHS

3.1.1. SCIENTIFIC, TECHNOLOGICAL, AND/OR SOCIOECONOMIC IMPACTS (INCLUDING POTENTIAL INNOVATIONS AND/OR BREAKTHROUGHS)

Since the late 1990s, the MOF field has expanded exponentially with more than 100,000 MOF structures reported.[4] Nevertheless, despite their promise, MOF-based products have still not proven to be beneficial in actual real-world applications for the areas of cancer treatment, wastewater treatment and energy storage. To address this, the Action will have an *impact* at multiple levels:

SCIENTIFIC AND TECHNOLOGICAL. By coordinating and bringing together leading and emerging groups that, one or another are focused on MOF materials, this Action will enable:
- Fostering the formation of a new interdisciplinary network and mobilising the European scientific expertise in MOF material research to translate the basic science into technologies at the interface of chemistry, materials and environmental science, nanotechnology, physics, and engineering.
- Uniting experts in micro/nanofabrication technology of inter-/multidisciplinary research fields.
- Optimizing research efforts and minimizing the number of failed experiments by bringing together multiple MOF-focused research laboratories in Europe.
- Generating standard databases and implementing guidelines and consensus to obtain high-quality MOF data that foster technology innovation. Increase the amount of suitable, available data for machine learning (successful and failed experiments), thus, improving the quality of predictions.
- Developing models after data analysis and artificial intelligence that help establish decision-making trees and optimizing MOF in the future: minimizing expenses of experimental work by optimizing tests/structures, also predicting the best structure to test for each application.
- Consolidating synthetic strategies at potentially larger scales, paving the way towards more sustainable preparation to solve the interdisciplinary challenge of structuring and functionalizing MOF materials at different scales (from nm all the way to cm scale).
- Consolidating MOF and porous-based research societies worldwide, to attract international interest, not only from the academy but also from industry, including towards further funding acquisition in co-partnering public-private fundings, which are key to promote technological development.

INDUSTRY. Pharmaceutical, energy, and water industries need the development of novel materials and high-performing technologies with minimal production risk. The high risk ascribed to optimally develop (at larger-scale) such complex materials raises the bar for attracting private investors and industrial partners, which is known to be key for proof of concept and, eventually, commercial product transition. There are already more than 30 companies worldwide exploring MOF-based materials for several applications, and, for instance, within cancer treatment, at least one MOF structure has already entered clinical trials (despite being a relatively recent field of research). Within this Action, thus, MOF materials will increase their technology-readiness-level (TRL) in at least three key applications, by providing more optimized performances and by implementing more robust, reproducible, and scalable methods for MOF preparation. This will help the industry to lower the risk associated to MOF-materials development. The fact that within the Action consortium there are already 5 SMEs will be highly valuable to establish scaling-up procedures, and they will support introduce MOF materials into (cancer) nanomedicine, energy, and wastewater industrial pipelines.

SOCIO-ECONOMIC. Increasing the TRL of MOFs in *i)* nanomedicine, *ii)* energy, and *iii)* wastewater applications will assist in paving the way towards urgently needed innovative (MOF) products. The size of pharmaceutical, renewable energy, and water treatment worldwide markets in 2021 amounted to more than 1.25 trillion USD (>150 billion USD for oncology, with a 7.5% predicted growth by 2030), 880 billion USD (predicted 8.5% growth by 2030) and 280 billion USD (7.1% growth by 2029), respectively. Additionally, *i)* in 2021, about 20 million new cancer cases and more than 10 million cancer-related deaths worldwide were estimated, and an increase to more than 17 million cancer deaths per year is expected in the next 5-10 years.[28] In the EU, the economic consequences of the disease already exceed 100 billion € each year, thus, the targeted design and development of innovative cancer nanomedicines and therapies is of pressing need. *ii*) Since 1800, the global energy consumption has increased dramatically from 5600 TWh to more than 160 000 TWh in 2021, and the year-to-year consumption still grows around 1-2%.[29] Although the commercialisation of lithium ion batteries enabled the use of various portable electronics in daily life, the development of next-generation batteries that are made of less critical resources, and that last not only for months-to-years but for decades, needs to be accelerated.[30][31] *iii)* As more than 733 million people live in countries with high and critical levels of water stress, and for at least 3 billion people the quality of their drinking water is unknown due to lacking monitoring, ensuring access to clean water is of utmost importance.[32] To tackle this urgent challenge, the EU for instance topped-up Horizon 2020 with additional 200 million €.[33] Beyond the clear economic impact, **EU4MOFs** will also increase societal awareness on importance and potential of MOF materials, and catalyse employment opportunities by training leaders in the synthesis, functionalization, structuring and characterization of MOF materials.

EUROPE. Fostering innovative technologies within a European-based consortium will definitely make Europe benefit from societal, healthcare, economical and competitiveness, bringing European research to the fore-front of innovative porous (nano)materials, and improving Europe´s competitive position as compared to other countries and continents.

<u>*Potential innovations and breakthroughs*</u>: The performance and scalability of MOF materials will be drastically enhanced by enabling their precise structuring across length scales and field of applications:

- MOFs for utilization as **cancer nanomedicines** have to fulfil complex tasks in the human body. Ideal nanomedicines feature high loading with a therapeutic cargo, exhibit controllable bio-interactions and pharmacokinetics, provide site-specific activity, and avoid undesired adverse reactions. On the other hand, industrial and **clinical translation requires feasible, scalable, reproducible**, and cost-effective production. Furthermore, the quality control of nanomedicines, which requires alternative techniques than conventional pharmaceutical analytics, represents a critical challenge for compliance with the regulatory requirements. **EU4MOFs** will establish criteria for the design of MOF cancer nanomedicines addressing the key parameters of safety, reproducible and scalable production, material characterization, formulation, and long-term storage stability.
- Tailored chemistry to **organize electroactive MOF** (eMOFs) **nanoparticles** into periodically ordered macroscopic structures (*e.g.,* electrodes) will be developed, in such a way that their electroactive anisotropic property is preserved. This breakthrough development will pave the way for solving a major issue of the 21st century: the development of safer, next-generation lithium-sulfur (Li-S) quasi-solid-state batteries with higher capacities and energy densities. Introducing **eMOFs superlattices into Li-S batteries** will significantly boost their performance given that eMOFs are the only material class that combine high porosity, conductivity, and chemisorption. These features are required for addressing the key challenges of Li-S batteries, namely the creation of *i)* a porous conductive composite cathode that serves as a host for poorly conductive sulfur atoms and chemisorbs extraneous discharge products, and *ii)* a solid-state electrolyte with high Li^+ conductivity and electrode compatibility.
- MOF-based solutions offer several advantages for water treatment, where different 'purification issues', such as filtration of pharmaceuticals, heavy metal ions or excessive ion concentration, may be involved to ensure that the resulting water is potable: *i)* due to the enormous **chemical versatility** of MOFs, the production of different MOF-based composites for different specific purification tasks is easily feasible; and *ii)* when combined, such innovative MOF-based solutions for water treatment processes could handle **different purification tasks simultaneously**; *iii)* their **high porosity allows for higher water flow** than filters and membranes commonly used for water treatment processes; *iv)* in terms of energy consumption, MOF-based composites significantly outperform currently used techniques as they can solve various 'purification issues' based on adsorption; and *v)* MOF-based composites can be regenerated and recovered multiple times.

3.2. MEASURES TO MAXIMISE IMPACT

3.2.1. KNOWLEDGE CREATION, TRANSFER OF KNOWLEDGE AND CAREER DEVELOPMENT

The COST Action will create a well-established and intensive communication and collaboration among the Action Participants. This spirit of fruitful discussion and cooperation, which will be intensified by the COST Action Activities, will provide an interdisciplinary research environment that will be particularly well suited to trigger novel and unorthodox ideas.

The **EU4MOFs** project has a clear organizational structure including partners with complementary and interdisciplinary expertise and has defined specific milestones and deliverables for each work package (see point 4: Implementation). Since efficient knowledge exchange and networking require common and complementary interests and voluntary engagement, the **EU4MOFs** project will provide an encouraging and supportive atmosphere that enhances creative interdisciplinary interactions and refrains from directing research top-down. This will be the guiding principle for the management of the **EU4MOFs** COST Action.

Knowledge creation will be pursued through internships of master, and exchange of doctoral and postdoctoral students. Also, several working-group focused and annual COST meetings will be organized, in which ideas, challenges, and experimental data will be presented and discussed. It will contribute to the development of scientific and professional competencies that can be applied throughout participant´s careers, including soft skills like networking, communication skills, data presentation and discussion. In addition, both postdoctoral researchers and young group leaders will be able to use this network as a stepping stone for their scientific/industrial **careers**, supported by the experience of many leading scientists, professors, and industrial partners from different countries. It is also important to improve language skills among young scientists, both by incorporating the words and cultures of scientific English, but also in the communication of developments of specific fields. The Action plans to organize trainings (summer) schools for young researchers, which will allow them to do in-depth analysis, develop a deep understanding of synthesis, functionalization, structuring, modelling and characterization of MOF materials at different scales for nanomedicine, battery, and wastewater applications. The project will be a platform for infrastructure exchange and joint publications. This will help young researchers in obtaining academic titles and undergo internships under the supervision of experienced professors participating in the project.

The transfer of knowledge to the three main stakeholders for this COST Action (academia, industry, and the public) will be organized and guided by the MC and with the consensus of the different coordinators of each working group (see Section 4). To do so, they will meet regularly (bimonthly), the outcomes will be presented to all Action members at leading conferences, and dissemination will be done in high-leading publications, including OPEN access. In addition, the engagement of the academic, industrial, and public communities will be at the centre of all discussions. The stakeholders will be actively involved in all COST Actions (*e.g.*, in WG meetings, training school, conferences). For that purpose, stakeholder-target workshops will also be organized within those meetings, in which interactive discussions will be engaged towards increasing the impact of the Action. **Special emphasis will be placed on EU4MOFs long-term perspective**, the creation of industrially applicable technologies for use by the general population to solve global and community problems. Furthermore, the Action is sincerely excited about the prospect of engaging a diverse group of innovators, unique both in their ideas and in their individual experiences. Clearly, it will take many people, patiently and compassionately working together and supporting each other, to seed new ideas and nurture them into fruition. EU4MOFs is committed to gathering and sustaining a group in which each member is valued.

3.2.2. PLAN FOR DISSEMINATION AND/OR EXPLOITATION AND DIALOGUE WITH THE GENERAL PUBLIC OR POLICY

EU4MOFs will stimulate synergies and constitute one of the leading European nodes for combining research and development for technological solutions. With a rapidly evolving and growing community, the COST Action will ensure rapid dissemination of research and technologies for the benefit of European researchers and enterprises as well as the public. The dissemination strategy of **EU4MOFs** aims to:

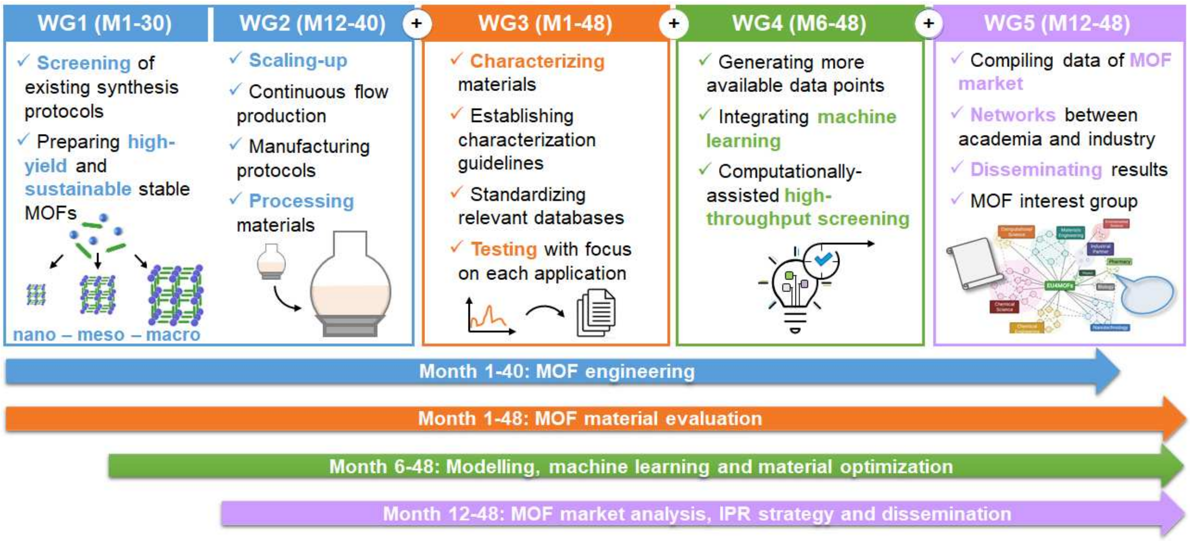
- Preparing a corporate design to represent the COST Action, a strategy and plan of dissemination activities, as well as maintaining a project website and social networking tools (especially LinkedIn webpage and an Instagram and Twitter account by creating a MOF Interest Group, to engage young public too, which comprise the next-generation of science and industry).
- Organizing (bi)monthly online talks with key opinion leaders in the field of MOFs and training schools. For each working group, there will be at least one training school session focused on different topics (see section 4). At least, five are planned, such as: in porous materials synthesis and characterization, machine learning integrated into materials research, nanomedicine *in vitro* and *in vivo* evaluation, IPR strategies and market assessment for novel technologies (regulatory), materials reproducibility and high-quality standard data generation.
- Preparing publications, press releases and brochures/flyers, including OPEN access publications to promote the diffusion of knowledge to the scientific community and beyond.
- Participating in (inter)national/European conferences.

4. IMPLEMENTATION

4.1. COHERENCE AND EFFECTIVENESS OF THE WORK PLAN

4.1.1. DESCRIPTION OF WORKING GROUPS, TASKS AND ACTIVITIES

EU4MOFs will focus on integrating European (and international) expertise to **concertedly** address *i)* the engineering, *ii)* the evaluation, *iii)* the prediction and optimization, and *iv)* the market assessment of MOFs. This will be done in **five working groups**, namely WG1: Greener synthesis and functionalisation,



WG2: Manufacturing and processing, WG3: Characterisation and performance assessment, WG4: Modelling and Computational, and WG5: Market, IPR and dissemination (**Figure 4**).

Figure 4: Overview of the timeline and tasks of the five working groups (WGs) of EU4MOFs.

Working group 1: MOF synthetic protocols and optimization (WG1; Months 1-30)

Objective: To establish and optimize MOF (lab-scale) synthetic strategies and protocols that enable high-yield and more sustainable preparation of stable MOFs with higher translational at all length scales.
Tasks: Several synthetic methods of MOF materials will be optimized to eventually select those with higher sustainable and technological potential, such as template-directed synthesis, self-assembly, and selective growth methods. WG1 will be divided into three sub-groups (nano-, meso-, and macro) that, in parallel but highly coordinated manner, will work on the following goals:

- Screening of existing protocols and identification of those that could potentially meet 'sustainable' requirements, which will be defined in collaboration of academic and industrial network members.
- Assessing and establishing synthetic processes to produce MOFs in a more sustainable and with technological potential by: *i)* developing and implementing (green) production methods with use of (organic) minimal solvent. This will increase industrial interest and attract potential investors from MOF (and other porous materials) companies; *ii)* developing faster production methods (already some MOFs can be produced in 15 s with microwave, but this knowledge has to be transferred to other structures); and *iii)* focusing on the strategies that give rise to higher yields and more stable structures.
- Consolidating computational tools and modelling approaches to predict and optimize structures *via*.

Working group 2: MOF processing, manufacturing, and upscaling (WG2; Months 12-40)

Objective: To implement and consolidate methods for customizing, processing, and manufacturing MOF structures into usable MOF materials that preserve the crystalline framework properties, with batch-to-batch reproducibility under potential scaling-up conditions, while ensuring high-performance.
Tasks: Uniting efforts from academia and industry, with background in materials engineering, physics, and technological development, and focus on establishing methods for processing and towards upscaling MOF materials at each length scale, in order to preserve the properties observed in the molecular crystalline framework at bench-scale. This will be divided into three main tasks based on the different length scales (applications) covered, and they will work closely with WG1 in an attempt to go beyond mg-scale production, into (hundred) g- or even kg-scale production.

- Optimizing and upscaling MOF syntheses *via* continuous-flow-manufacturing (*e.g.*, proof-of-concept of integration of microfluidics for MOF nanoparticles or 3D printing for MOF macroscale materials).
- Investigating suitable MOF material processing and formulations for long-term storage, *e.g.*, by adding cryoprotectants and lyoprotectants for cold-chain supply and lyophilization of MOF nanomedicines.

Working group 3: MOF characterization and performance evaluation (WG3; Months 1-48)

Objective: To carry out full characterization of the developed MOF materials, including key tests to evaluate the performance in each of the three applications. The goal is to assess the batch-to-batch reproducibility of the produced nano-, meso- and macroscale MOF materials and the quality of the produced materials regarding their (physicochemical) properties and application performance.
Tasks: WG3 will oversee the evaluation of the (upscalable) MOFs prepared *via* the greener synthetic approaches and different processing/manufacturing strategies. This will be mostly constituted by experimental scientists, but highly supported by computational scientists from WG4 to predict and optimize the screening of these materials. The sub-aims of WG3 will be the following:

- Characterizing the lab-scale and potentially upscaled materials (from WG1 and WG2) regarding their physicochemical properties (*e.g.*, size, charge, porosity, drug retention and stability).
- Evaluate performance using established high-throughput screening methods. Three sub-groups will evaluate selected key properties and parameters that result in crucial feedback to iteratively improve synthetic and processing/manufacturing protocols of MOFs. *i)* For cancer nanomedicine: serum and blood stability, *in vitro* toxicity assessment, *in vivo* evaluation (including a) pharmacokinetic properties: half-life circulation and biodistribution; and b) tolerability and (therapeutic) performance in several xenograft mouse models). *ii)* Battery for energy storage: cell voltage, energy density, cycle stability, rate of charge/discharge, optimal temperature of operation, Coulombic discharge, overall efficiency, rigorous safety tests (*e.g.*, operation at high temperature and pressure, battery rupture, and short circuits); *iii)* Wastewater treatment: porosity, robustness of the material upon pressure swings, water flux, separation efficacy, lifetime, and recyclability of the materials.

Working group 4: MOF computational tools and machine learning (WG4; Months 6-48)

Objective: To establish a MOF-focused database for the existing structures and their properties, and to foster the integration of machine learning tools to assist in high-throughput experiments and for improved MOF design and properties prediction. The different sub-aims are:

- Establishing a standardized database for MOF materials and their functional properties (performance) in the three main applications beforementioned as the basis for machine learning. The key to foster integrated computationally-assisted high-throughput screening and highly accurate machine learning tool-based predictive algorithms to optimize MOF structure design relies on the generation of accurate (meta)data and the collection of MOF-based database. Standardized data (from WG3) on physical characteristics, such as porosity, volume, structure, but also performance (*e.g.*, toxicity, conductivity, porosity, and chemical stability) under different conditions will be collected. Additionally, establishing consensus and guidelines for the generation of high-quality (meta)data will be a priority.
- Assessing the predictive quality of machine learning tools and algorithms by integrating existing and novel MOF data. To do that, the working group will *i*) systematically analyze and collect already published (and potentially available unpublished due to unsuccessful outcomes) MOF data for the three applications, and *ii*) integrate novel data from WG1-3 to train models and strengthen the quality of the algorithms and the accuracy of the prediction.

Working group 5: Dissemination, industrial networking, and MOF market assessment (WG5; Months 12-48)

Objective: To analyze and compile a comprehensive data package about the technological and market potential of MOFs for cancer nanomedicine, energy storage, and wastewater treatment, including strengths and weaknesses that will help attract future investors, including industrial partners.

- Disseminating results to the public and the scientific community. WG5 will disseminate the results of the Action *via* (internet) social media (*e.g.,* LinkedIn, Twitter and Instagram). EUMOFs website will be updated regularly. Through the website, scientists and members of the public will have access to a database of all members of the COST Action, videos of the conferences, calendar of all Action Committee and WG Meetings, and Training Schools. Results will be published in high-quality and renowned scientific journals (including OPEN access) and conferences, where support by the COST framework will be prominently acknowledged.

- Building networks between established Research Institutes, Centers of Excellence, large companies (*e.g.,* BASF, Siemens, AstraZeneca, and Wacker Chemie) and especially newly developed start-ups.
- Performing a comprehensive and extensive MOF market competitive analysis to identify and select potential competitors and partner opportunities. Feedback from industrial partner members within EU4MOFs, and potential stakeholders/investors will be crucial. This will be divided into three main sub-actions: *i)* top-down landscape analysis to map the current state of energy, waste water and nanomedicine industry, including potential competitors; *ii)* bottom-up market analysis to identify the target customer (end-user) and payers; and *iii)* analysis of industry partners and investors by eventually approaching several companies for partnership (interviews with interested licensees like) to determine the real interest in MOF-based technological products and for future co-funded programs.
- Intellectual Property Management and Entrepreneurship. The Participants that generate Intellectual Property (IP) in the form of patents, software, and proprietary protocols and methods will also manage the IP through their established institutional means (Technology Licensing Offices, IP Departments, *etc.*). WG5 will review regularly the IP generated through the Action and related IP generated by other stakeholders, in collaboration with Patent and Trademark agencies that will support the attorney process. The WG members will collect and make available the IP in a central location. Moreover, the WG will promote exploitation by start-ups by generating networking opportunities for young researchers and Early Career Investigators. Special sessions at Training School and academia-industry networking events at Action meetings will foster entrepreneurial actions among participants.

4.1.2. DESCRIPTION OF DELIVERABLES AND TIMEFRAME

The **milestones** and **deliverables** mostly represent the different tasks of the working groups, including those related to strengthening the network towards future conjoint (European) actions. Each WG will include its own (online) kick-off WG meeting (month 1) to plan and already minimize risks at early-stage, one annual (in-person/hybrid) meeting with all WG (months 13, 25, 37) and a final (in-person) closure meeting (within a conference context) (month 48), as milestones. Each will include the corresponding WG reports as deliverables, which will help address challenges, evaluate the progress of the Action and, eventually, determine future steps to consolidate the established network and towards proof-of-concept technology. Additionally, there will be a mid-term report (**deliverable**, month 25), coordinated by the MC and the two coordinators from each WG, which will serve to evaluate the progress during the first two years, address challenges and plan the actions for the following two years. At the end of the project, the MC of the Action will collect and assemble the deliverables of each WG into a final document to the show technical and commercial potential of MOFs as innovation technology to pharmaceutical, energy, and water industry, including potential materials investors. The MC will also use the outcomes of the project, including the market and competitors' analysis (see WG5 deliverables) to develop a business plan that can be presented to relevant stakeholders, industrial partners, and investors.

WG1 – Milestones (M) and Deliverables (D)
M1.1: Establishing lab-scale synthetic protocols for nano-, meso- and macroscopic MOF materials with scalable and sustainable potential (**Month 12**)
M1.2: Functionalization methods that could be applied to tailor and improve performance for MOFs for each specific application established. (**Month 30**)
D1.1: Publication of a perspective article that includes an overview lab-synthesis and functionalization strategies with sustainable and technology potential and mostly focusing on each length scale and application. (**Month 15**)
D1.2: Report focused on suitable computational methods for optimized design of MOFs. (**Month 24**)
D1.3: Public availability of MOF synthesis and optimized methods via website of the Action. (**Month 30**)
WG2 – Milestones (M) and Deliverables (D)
M2.1: Defined industrial requirements for MOF upscaling with an industry-focused meeting. (**Month 25**)
M2.2: Most suitable large-scale synthetic protocols for MOF nanoparticles, thin-films and macroscopic materials established. (**Month 40**)
D2.1: Training School on industrial exploitation (processing and manufacturing techniques), GMP production and regulatory requirements for commercializing MOF and porous materials. (**Month 30**)
D2.2: Technical report with consensus protocols established for MOF industrial production at each length scale. (**Month 40**)
WG3 – Milestones (M) and Deliverables (D)
M3.1: Established minimum reporting (characterization) information for MOFs at each length scale (nano, meso, macro) and for each application. (**Month 30**)
M3.2: Characterization of MOFs physicochemical properties, including stability established. (**Month 36**)
M3.3: Evaluation of experimental performance (*e.g.*, toxicity, therapeutic, conductivity, robustness, water treatment efficacy) of lab-scale and upscaled synthesized MOFs from WG1 and WG2. (**Month 48**)

D3.1.: Training school/Workshop focused on experimental techniques for (porous) materials performance assessment. (**Month 20**)
D3.2: Scientific and technical diagrams with the best practices for MOF and porous materials characterization, to generate high-quality (meta)data, including a standardized database. (**Month 36**)
D3.3: Report with the (comparative) characterization of the produced MOFs in WG1 and WG2. (**Month 40**)
D3.4: Perspective paper with consensus guidelines for minimum reporting information of (MOF) and other porous materials at each length scale and for the three -and other- applications, together with key opinion international leaders. (**Month 48**)
WG4 – Milestones (M) and Deliverables (D)
M4.1: Computational methods for optimized design and structural screening of MOFs established. (**Month 24**).
M4.2: Validated machine learning models and algorithms for MOF structure-property (*e.g.*, toxicity, stability, conductivity, absorptivity) prediction. (**Month 48**)
D4.1: Training school/workshop on focused on high-throughput screening, modelling, and artificial intelligence (machine learning) tools for materials science. (**Month 12**)
D4.2: Perspective on machine learning integrated to functional porous (nano)materials (**Month 36**).
D4.3: Expandable online database connecting measured material properties with synthesis methods and modelling data. (**Month 48**)
WG5 – Milestones (M) and Deliverables (D)
M5.1: Comprehensive online presence: Participant database (year 1), activity reports, and event calendar. (**Month 13**)
M5.2: Bottom-up and top-down market analyses completed, including potential future investors. (**Month 40**)
D5.1: Training School including sessions on IP, Entrepreneurship, and industrial liaison. (**Month 30**)
D5.2: Report compiling academic and industrial stakeholders resulting from market analysis and networking activities. (**Month 24 + 48**).
D5.3: Summary report of actions and guidelines achieved by EU4MOFs. (**Month 48**)

4.1.3. RISK ANALYSIS AND CONTINGENCY PLANS

Since the Action aims at promoting technology readiness-level of MOFs from multiple angles in parallel, even if certain (parts of the) tasks turn out to be unsuccessful, the progress achieved in each WG already individually will serve as stepping stones to foster development of MOFs and will also serve as models for other (porous) materials at different dimension scales. Possible **risks** include:

Description of the risk	Mitigation strategy
Delay in achieving Milestones due to time underestimation.	Tasks will be partially completed if necessary. Unresolved challenges can be used as a basis for more in-depth future research advices.
Insufficient budget, account of limited resources, uncertainties in the network structure, uncertainties about consequences, complex statistical distributions.	MC will review all tasks and their feasibility at the bimonthly coordinating and annual (Action) meetings, and adjust (*e.g.*, shifting in-person to online meetings). Networking tasks focusing on publishing perspectives, market evaluation, technological requirements reports, and potential conjoint future funding programs assessment will be prioritized over experimental work to leverage **EU4MOFs** academia-to-industry network opportunity.
Lack of (high-quality) MOF data and/or failed experiments.	Unsuccessful outcomes will be also compiled and published. Every result will contribute to assess technological potential of MOFs, even failed ones.
Low interest from companies or investors in MOFs for any of the three specific applications.	This is an inherent risk due to the high-ambitious aims of the network. The MC will reinforce patent position on the most-promising application and expand other markets where MOFs can add value.
Conflict between members of the Action.	Create an external crisis committee (independent from the MC), including with the support of external advisory board as mediators.

4.1.4 GANTT DIAGRAM