



# **BIOLOGISATION AND BIO-INSPIRATION IN MATERIALS SCIENCE AND PROCESS CHEMISTRY**

White paper summarizing and evaluating the workshop “Biologisation and Bio-Inspiration in Materials Science and Process Chemistry” held on December 5, 2024

# Biologisation and Bio-Inspiration in Materials Science and Process Chemistry

## Executive Summary

This paper is the outcome of the workshop “Biologisation and Bio-Inspiration in Materials Science and Process Chemistry” from December 2024 with experts from the research fields Catalysis and Process Chemistry, Polymers and Functional Materials, and Inorganic Functional Materials. The workshop’s purpose was to explore how principles from biology can drive innovation in chemical processes and material design. These principles aim at connecting natural strategies, such as self-assembly, adaptability, and energy efficiency, with advanced technologies to create sustainable solutions by the means of bio-inspired approaches for catalysis, polymer development, and process optimisation, leveraging concepts like biomimetic structures and metabolic pathways – thematically centred on the three topics

1. Bio-Intelligence – exploring how biological systems inspire smart, adaptive materials and processes;
2. Bio-Interfaces – focusing on the design of interfaces that mimic or interact with biological systems;
3. Bio-Transition – discussing pathways for transitioning to sustainable, bio-integrated technologies.

## Thematic research funding proposals

Thorough databased analysis of intensive discussions leads to funding proposals as follows:

### Meta Area I: Bio-Inspired and Bio-mimetic Next Generation Polymers and Polymer Synthesis

- ▶ Promote **interdisciplinary projects combining biotechnology, materials science, and process engineering**.
- ▶ Support **scalable biotechnological synthesis routes** for advanced polymers.
- ▶ Drive the **development of bio-inspired separation and recycling technologies** with measurable energy and carbon savings.
- ▶ Encourage **digital integration** (AI, modelling) for design and **optimisation of biologically inspired processes**.
- ▶ Require **demonstration of industrial relevance**, including pilot-scale validation and lifecycle impact assessment.



## Meta Area II: Bio-Inspired and Bio-mimetic Approaches in Catalysis, Inorganic and Hybrid Materials

- ▶ **Support interdisciplinary consortia** combining materials science, catalysis, biotechnology, and computational design.
- ▶ **Prioritize adaptive and multifunctional systems** with real-time responsiveness.
- ▶ **Encourage hierarchical and templated architectures** for improved selectivity and energy efficiency.
- ▶ **Integrate digital tools (AI, modelling) for predictive design** of bio-inspired structures.
- ▶ Require **proof-of-concept demonstrations at relevant scales** and quantifiable sustainability metrics (energy savings, recyclability, CO<sub>2</sub>-reduction).

## Meta Area III: Data, Simulation, and AI as enablers for Bio-Inspiration

- ▶ **Interdisciplinary projects** combining computational science, materials chemistry, and biotechnology.
- ▶ **Development of digital twins for bio-inspired processes and materials.**
- ▶ **AI platforms** for predictive design and optimisation of **adaptive materials and catalytic systems.**
- ▶ Creation of **open data ecosystems** for bio-inspiration research.
- ▶ Demonstration of industrial relevance through **virtual prototyping and scale-up simulations in addition to “real world transfer”.**

## Conclusions on funding mechanisms and structures

- ▶ **Close involvement of companies in designing research programmes** on key technologies, so industry stakeholders can help shape the programmes and measures both structurally and in terms of content.
  - ▶▶ Programme design should be **supported by an accompanying board structure** that enables equal-footing collaboration between academia and industry
- ▶ **Fast-track/prototyping projects** should allow rapid validation of new research concepts against current technological trends, e.g. run through idea challenges, giving partners high flexibility to test R&D ideas toward scaling – as a precursor to larger projects
- ▶ **Enable follow-on funding to higher TRLs and scale-up as “successor projects”:**
  - ▶▶ Extend programmes and funding instruments to subsequent TRL levels to improve continuity from research to applied R&D
  - ▶▶ To reduce the internationally critical time-to-market, **programmes should fund all stages of the innovation chain (TRL levels) without gaps**, requiring sufficient budget flexibility to adapt as needs evolve.



# Biologisation and Bio-Inspiration in Materials Science and Process Chemistry

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## 1. Purpose and Overview of the Workshop

The workshop “Biologisation and Bio-Inspiration in Materials Science and Process Chemistry”, held on 5 December 2024, brought together 50 participants from three research groups, Catalysis and Process Chemistry, Polymers and Functional Materials, and Inorganic Functional Materials, to explore the potential of biology-inspired innovation in materials science and chemistry. The purpose of the workshop “Biologisation and Bio-Inspiration in Materials Science and Process Chemistry” was to explore how principles from biology can drive innovation in chemical processes and material design. It aims to connect natural strategies, such as self-assembly, adaptability, and energy efficiency, with advanced technologies to create sustainable solutions. Participants discussed bio-inspired approaches for catalysis, polymer development, and process optimisation, leveraging concepts like biomimetic structures and metabolic pathways. The workshop fostered interdisciplinary collaboration between chemists, material scientists, and engineers to accelerate the transition toward greener, smarter, and more efficient industrial processes inspired by nature’s ingenuity.

Structured around a World café format, the workshop featured 9 interactive sessions across three thematic World cafés:

1. Bio-Intelligence – exploring how biological systems inspire smart, adaptive materials and processes;
2. Bio-Interfaces – focusing on the design of interfaces that mimic or interact with biological systems;
3. Bio-Transition – discussing pathways for transitioning to sustainable, bio-integrated technologies.

Through discussions and collaborative ideation, the participants generated over 200 ideas, ranging from conceptual frameworks to concrete research directions. The format fostered cross-disciplinary exchange, creativity, and a shared vision for biologically inspired impulses for materials science. Each World café featured ideas within three distinct groups: Group 1: Catalysis and Process Chemistry, Group 2: Inorganic Functional Materials, and Group 3: Polymers and Functional Materials. The World cafés were complemented by a list of needs and currently unserved Technology Options.

All workshop ideas were systematically digitalised into a structured database to ensure transparency and comparability. Each idea was evaluated against predefined principles of biologisation, focusing on aspects such as resource efficiency, circularity, and integration of biological processes. These principles served as the foundation for ranking, which was conducted using a statistical, evidence-based approach. Quantitative metrics and qualitative assessments were combined to create a robust scoring model, ensuring objectivity and reproducibility.

In parallel, every idea was mapped to relevant Technology Fields, enabling a clear linkage between biologisation concepts and technological innovation areas. This association facilitated cross-sectoral insights and highlighted synergies between emerging technologies and sustainability-driven approaches.

The evaluation results were aggregated and analysed to identify patterns and priority areas. From this evidence base, nine Focus Fields for action were formulated, representing the most promising domains for impact and development. These fields encompassed topics such as bio-based materials, biotechnological processes, and digital-bio integration.

Building on these nine fields, three overarching Meta Areas were derived to provide strategic direction. Each Meta Area was complemented by concrete funding recommendations, designed to accelerate implementation and foster innovation ecosystems. These recommendations addressed both short-term pilot initiatives and long-term structural investments, ensuring alignment with policy objectives, technology gaps, and market needs.

This structured process, from idea digitalisation to evidence-based prioritisation, created a clear roadmap for biologisation-driven innovation, bridging conceptual thinking with actionable strategies.

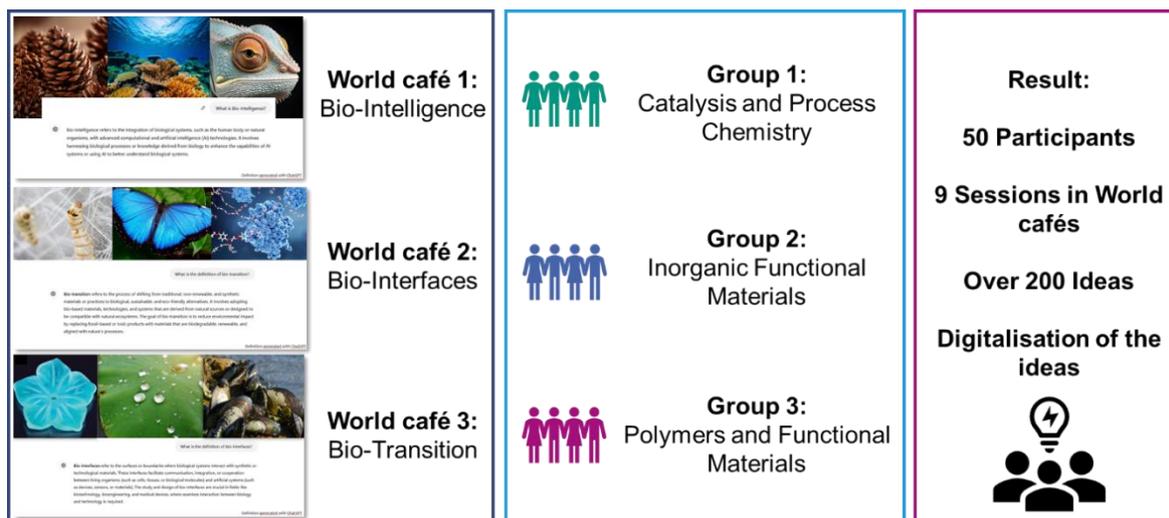


Figure 1: Overview of the World café structure, showing the division into thematic areas (Bio-Intelligence, Bio-Interfaces, Bio-Transition) and their discussion groups (Catalysis, Inorganic, Polymer), from group formation to idea collection.

## 2. Outcome of the Workshop: Summary of Recommendations

Via the workshop “Biologisation and Bio-Inspiration in Materials Science and Process Chemistry”, nine strategic Focus Fields (explained in detail in chapter 2.4) were identified as key drivers for future innovation. These areas represent high-potential opportunities where



biological principles and bio-inspired approaches can transform material design and chemical processes. They span topics such as bio-based feedstocks, biomimetic catalysts, adaptive and self-healing materials, bio-inspired manufacturing, and digital tools for biologically informed design. Each Focus Field addresses critical challenges in sustainability, resource efficiency, and advanced functionality. To accelerate progress, these domains are prioritized to facilitate their uptake in upcoming funding initiatives, fostering interdisciplinary research and industrial implementation.

The Focus Fields have been consolidated into three strategic Meta Areas that provide a clear, technology-driven framework for funding bodies. These Meta Areas enable targeted investment in bio-inspired materials and catalysis, circular process technologies, and digital enablers such as AI and simulation. This structure ensures funding calls can drive interdisciplinary innovation with measurable impact on sustainability and industrial competitiveness:

## **2.1 Meta Area I: Bio-Inspired and Bio-mimetic Next Generation Polymers and Polymer Synthesis**

This Meta Area summarizes the following Focus Fields:

- ▶ Focus Field 3: Biotechnological Methods as a Solution Enabler in Polymer Synthesis
- ▶ Focus Field 4: Bio-Inspired Separation Technologies as a Solution Enabler for Sustainable Process Engineering
- ▶ Focus Field 5: Bio-Inspired Recycling Technologies for Polymer, Inorganic, and Hybrid Materials

The three Focus Fields share a common vision: leveraging biological principles and biotechnological methods to enable sustainable material lifecycles and efficient process engineering. This Meta Area integrates:

- ▶ Biotechnological synthesis for creating functional polymers with minimal environmental impact.
- ▶ Bio-inspired separation technologies for energy-efficient purification and resource recovery.
- ▶ Bio-inspired recycling strategies for polymers, inorganic, and hybrid materials to close material loops.

Together, they form a holistic approach to circularity and resource efficiency, guided by nature's strategies for adaptability, selectivity, and low-energy transformations.

### **Proposed Funding Call Emphasis for Meta Area I:**

Future funding initiatives should:

- ▶ Promote interdisciplinary projects combining biotechnology, materials science, and process engineering.



- ▶ Support scalable biotechnological synthesis routes for advanced polymers.
- ▶ Drive the development of bio-inspired separation and recycling technologies with measurable energy and carbon savings.
- ▶ Encourage digital integration (AI, modelling) for design and optimisation of biologically inspired processes.
- ▶ Require demonstration of industrial relevance, including pilot-scale validation and lifecycle impact assessment.

## **2.2 Meta Area II: Bio-Inspired and Bio-mimetic Approaches in Catalysis, Inorganic and Hybrid Materials**

This Meta Area summarizes the following Focus Fields:

- ▶ Focus Field 1: Adaptive and Interactive Materials Inspired by Biology
- ▶ Focus Field 2: Process Integration of Biological and Inorganic Catalysis Technologies
- ▶ Focus Field 6: Biomimetic Approaches in Catalysis and Materials Synthesis
- ▶ Focus Field 7: Approaches Involving Biotemplating in Catalysis and Materials Synthesis
- ▶ Focus Field 8: Approaches Involving Bio-Inspired Hierarchical Structures in Catalysis and Materials Synthesis

All five Focus Fields converge on a common vision: leveraging biological principles to design adaptive materials and catalytic systems with hierarchical architecture and integrated functionality. This meta field combines:

- ▶ Adaptive and Interactive materials that respond to stimuli like living systems.
- ▶ Integration of biological and inorganic catalysis for hybrid reaction networks.
- ▶ Biomimetic approaches to replicate nature's efficiency in synthesis and transformation.
- ▶ Biotemplating strategies to create precise nanostructures and active sites.
- ▶ Hierarchical Structures inspired by biological organisation for optimized performance.
- ▶ Together, these approaches enable next-generation catalytic and material platforms that are dynamic, efficient, and sustainable.

### **Proposed Funding Call Emphasis for Meta Area II:**

Future funding initiatives should:

- ▶ Support interdisciplinary consortia combining materials science, catalysis, biotechnology, and computational design.
- ▶ Prioritize adaptive and multifunctional systems with real-time responsiveness.



- ▶ Encourage hierarchical and templated architectures for improved selectivity and energy efficiency.
- ▶ Integrate digital tools (AI, modelling) for predictive design of bio-inspired structures.
- ▶ Require proof-of-concept demonstrations at relevant scales and quantifiable sustainability metrics (energy savings, recyclability, CO<sub>2</sub> reduction).

## 2.3 Meta Area III: Data, Simulation, and AI as Enablers for Bio-Inspiration

This Meta Area summarizes the following Focus Fields:

- ▶ Focus Field 9: Data, Simulation, and AI as Enablers for Bio-Inspiration

This field provides the digital backbone for accelerating innovation in biologically inspired materials and processes. By integrating data-driven modelling, multiscale simulations, and AI-based optimisation, it enables predictive design and rapid iteration, reducing experimental trial-and-error. These tools allow researchers to:

- ▶ Decode complex biological principles and translate them into material and process design.
  - ▶ Simulate adaptive behaviours, hierarchical structures, and catalytic mechanisms before physical implementation.
  - ▶ Optimize synthesis routes and recycling strategies for efficiency and sustainability.
- Support for other Focus Fields
- ▶ For Interactive and Adaptive Systems and Hierarchical Structures: AI-driven design identifies optimal architectures and stimuli-responsive functionalities. For Bio-Inspired Catalysis & Biotemplating: Simulation predicts active site performance and reaction pathways, guiding rational catalyst design.
  - ▶ For Circular Materials & Processes: Data analytics enables lifecycle modelling and process integration for bio-inspired recycling and separation.

### Proposed Funding Call Emphasis for Meta Area III:

Future funding initiatives should:

- ▶ Interdisciplinary projects combining computational science, materials chemistry, and biotechnology.
- ▶ Development of digital twins for bio-inspired processes and materials.
- ▶ AI platforms for predictive design and optimisation of adaptive materials and catalytic systems.
- ▶ Creation of open data ecosystems for bio-inspiration research.



- Demonstration of industrial relevance through virtual prototyping and scale-up simulations.

## 2.4 From Top-Rated Ideas to Focus Fields

In the following, the Focus Fields that were extracted from the workshop based on the ranked ideas are described in detail. The Focus Fields are discussed in the following order:

- Focus Field 1: Adaptive and Interactive Materials Inspired by Biology
- Focus Field 2: Process Integration of Biological and Inorganic Catalysis Technologies
- Focus Field 3: Biotechnological Methods as a Solution Enabler in Polymer Synthesis
- Focus Field 4: Bio-Inspired Separation Technologies as a Solution Enabler for Sustainable Process Engineering
- Focus Field 5: Bio-Inspired Recycling Technologies for Polymer, Inorganic, and Hybrid Materials
- Focus Field 6: Biomimetic Approaches in Catalysis and Materials Synthesis
- Focus Field 7: Approaches Involving Biotemplating in Catalysis and Materials Synthesis
- Focus Field 8: Approaches Involving Bio-Inspired Hierarchical Structures in Catalysis and Materials Synthesis
- Focus Field 9: Data, Simulation, and AI as Enablers for Bio-Inspiration

### Focus Field 1: Adaptive and Interactive Materials Inspired by Biology

Adaptive and interactive materials have the potential to revolutionize technology in catalysis, polymers, and inorganic and hybrid materials by enabling systems that respond dynamically to their environment. This will lead to smarter, more efficient, and multifunctional applications across application sectors. However, their development often faces hurdles, such as complex integration, stability under real-world production conditions, and high production costs. A research programme should therefore address these challenges holistically by combining materials science with systems engineering, for materials application and production, fostering interdisciplinary collaboration, and including early-stage considerations for scalability, manufacturability, and lifecycle sustainability.

**Perspective Focus Field 1:** Developments in adaptive and interactive materials will redefine technological capabilities by introducing systems that actively respond to environmental stimuli such as temperature, pressure, or chemical changes. This dynamic behaviour enables unprecedented efficiency in catalysis, where reaction conditions can self-optimize, and in polymers, which can alter properties for durability or flexibility on demand. Inorganic and hybrid materials will gain multifunctionality, integrating sensing, actuation, and self-healing features. These advancements will push boundaries by merging material intelligence with system-level adaptability, reducing energy consumption, enhancing performance, and



enabling scalable, sustainable solutions across sectors like energy, healthcare, and manufacturing, transforming passive components into active, smart technologies.

## **Focus Field 2: Process Integration of Biological and Inorganic Catalysis Technologies**

Biotechnology and heterogeneous/homogeneous catalysis can be united in a single process technology approach by integrating biological and chemical catalytic steps into hybrid systems that leverage the selectivity of micro-organisms and enzymes with the robustness and scalability of inorganic homogeneous and heterogeneous catalysts. This synergy enables more efficient, sustainable, and flexible production pathways for complex molecules. A research programme should address development hurdles, such as the compatibility of reaction conditions, catalyst stability, and process integration by fostering interdisciplinary collaboration, developing modular reactor concepts, and including early-stage techno-economic and lifecycle assessments.

**Perspective Focus Field 2:** Developments in hybrid catalytic systems combining biotechnology with heterogeneous and homogeneous catalysis will dramatically expand the possibilities for chemical production. By integrating the selectivity of enzymes and microorganisms with the robustness and scalability of inorganic catalysts, these systems enable highly efficient, sustainable, and flexible synthesis of complex molecules. This synergy reduces energy consumption, minimizes waste, and opens pathways for producing advanced pharmaceuticals, specialty chemicals, and bio-based materials under milder conditions. Overcoming compatibility and integration challenges will lead to modular, adaptive processes that merge biological precision with industrial throughput, pushing current technological limits toward greener, smarter, and economically viable chemical manufacturing.

## **Focus Field 3: Biotechnological Methods as a Solution Enabler in Polymer Synthesis**

Biotechnology enables the synthesis of advanced and sustainable polymers by harnessing engineered microorganisms or enzymes to convert renewable feedstocks into monomers or directly into polymeric materials under mild, energy-efficient conditions. This approach enables precise control over polymer structure and functionality, opening pathways to tailor-made materials with enhanced biodegradability, recyclability, or performance. However, technological hurdles remain, such as optimizing metabolic pathways for high-yield production, ensuring polymer consistency at scale, and integrating biotechnological steps with downstream processing. A research programme should therefore focus on developing robust microbial strains, scalable bioprocesses, and continuous production systems, while also addressing purification, formulation, and compatibility with existing manufacturing infrastructure. Advanced analytics, digital process control, and lifecycle assessments should



be embedded from the start to guide development toward economically and environmentally viable solutions.

**Perspective Focus Field 3:** Advances in biotechnological polymer synthesis will push technological boundaries by enabling precision-designed, sustainable materials that outperform conventional plastics. Engineered microorganisms and enzymes can convert renewable feedstocks into monomers or polymers under mild, energy-efficient conditions, reducing reliance on fossil resources. This approach allows unprecedented control over polymer architecture, enabling tailor-made properties such as enhanced biodegradability, recyclability, and high-performance functionality. Integrating bioprocesses with continuous production systems and digital process control will transform manufacturing into a flexible, low-carbon, and circular model. These innovations will not only revolutionize packaging, textiles, and medical materials but also establish biotechnology as a cornerstone of next-generation material science.

#### **Focus Field 4: Bio-Inspired Separation Technologies as a Solution Enabler for Sustainable Process Engineering**

A research programme focused on bio-inspired separation processes should aim to replicate the high selectivity and low energy demands of natural systems, such as membrane transport, protein-ligand binding, or phase separation, while ensuring industrial scalability and robustness. These processes offer significant potential for improving energy efficiency and sustainability by reducing the need for heat-driven separations like distillation, which are major energy consumers in chemical production. To overcome development hurdles, the programme should prioritize the design of durable, tuneable materials (e.g., synthetic membranes or responsive gels), explore mild operating conditions, and develop integrated process concepts that minimize waste and solvent use. Embedding digital process control, real-time monitoring, and lifecycle analysis will be essential to guide optimisation and ensure environmental and economic viability.

**Perspective Focus Field 4:** Developments in bio-inspired separation processes will push technological boundaries by replacing energy-intensive methods like distillation with highly selective, low-energy alternatives modelled on natural systems. Synthetic membranes, responsive gels, and advanced materials mimicking biological transport mechanisms will enable separations under mild conditions, drastically reducing energy consumption and environmental impact. These innovations will allow integrated, continuous processes that minimize waste and solvent use while improving efficiency in sectors such as chemical production, water treatment, and pharmaceuticals. Coupled with digital monitoring and lifecycle analysis, bio-inspired separations will transform industrial operations into smarter, more sustainable systems, setting new standards for resource efficiency and process design.



## **Focus Field 5: Bio-Inspired Recycling Technologies for Polymer, Inorganic, and Hybrid Materials**

A research programme focused on bio-inspired recycling technologies for polymers, inorganic, and hybrid materials should prioritize the development of technically robust, selective, and energy-efficient processes that mimic natural degradation and transformation mechanisms. This includes engineering enzymes or bio-mimetic catalysts capable of depolymerizing complex materials under mild conditions, designing adaptive interfaces for selective separation of mixed waste streams, and integrating these into continuous or modular process platforms. To overcome development hurdles, the programme should advance autonomous high-throughput screening of biocatalysts, develop scalable bioreactor and separation technologies, and ensure compatibility with existing recycling infrastructure. Additionally, it should incorporate digital process control, real-time analytics, and predictive modelling to optimize reaction conditions and material flows. Programme directions should evolve toward platform technologies that are flexible across material classes, supported by techno-economic and lifecycle assessments to guide sustainable industrial implementation.

**Perspective Focus Field 5:** Developments in bio-inspired recycling technologies will push the boundaries of today's technology by enabling selective, energy-efficient recovery of polymers, inorganic, and hybrid materials through processes that mimic natural degradation pathways. Engineered enzymes and bio-mimetic catalysts will allow depolymerisation under mild conditions, reducing energy use and chemical waste compared to conventional recycling. Adaptive interfaces and modular platforms will enable precise separation of mixed waste streams, creating flexible solutions across material classes. Enabled by digital control, real-time analytics, and predictive modelling, these innovations will transform recycling into a smart, integrated system that advances circularity and sustainability.

## **Focus Field 6: Biomimetic Approaches in Catalysis and Materials Synthesis**

A research programme addressing development hurdles in biomimetic approaches to catalysis and materials synthesis should focus on translating the structural precision, functional complexity, and energy efficiency of natural systems into scalable synthetic strategies. Technically, this involves designing catalysts that mimic enzyme active sites or natural reaction networks, developing hierarchical material architectures inspired by biological templates, and integrating self-assembly or adaptive behaviour into synthesis pathways. To overcome challenges such as limited stability under industrial conditions, low throughput, or complex precursor requirements, the programme should invest in advanced characterisation techniques, computational modelling for mechanism elucidation, and modular reactor technologies. Programme directions should evolve toward platform technologies that enable tuneable functionality, compatibility with green chemistry principles, and integration into continuous or hybrid manufacturing processes.



**Perspective Focus Field 6:** Developments in biomimetic catalysis and materials synthesis will push technological boundaries by translating nature's precision and efficiency into scalable industrial solutions. Catalysts inspired by enzyme active sites and reaction networks will enable highly selective, energy-efficient transformations under mild conditions, reducing reliance on harsh chemicals and high temperatures. Hierarchical material architectures and self-assembly strategies will deliver advanced functionalities such as adaptability and tunability, surpassing conventional synthetic approaches. Coupled with computational modelling and modular reactor technologies, these innovations will integrate seamlessly into continuous, green manufacturing processes. This convergence of biology-inspired design and industrial scalability will redefine.

## **Focus Field 7: Approaches Involving Biotemplating in Catalysis and Materials Synthesis**

Biotemplating is a powerful biomimetic strategy in catalysis and materials synthesis that uses natural structures, such as proteins, viruses, diatoms, or plant tissues, as templates to guide the formation of inorganic or hybrid materials with precise architectures and functionalities. These biological templates offer hierarchical organisation, nanoscale precision, and high surface area, which are difficult to achieve through conventional synthetic methods. A research programme should address development hurdles by focusing on the controlled replication of biological features, the stability of templates under processing conditions, and the scalability of templating techniques. Technological directions should include the development of robust biotemplate immobilisation methods, integration with sol-gel or vapor-phase deposition processes, and the design of template removal or transformation strategies that preserve structural fidelity. Additionally, coupling bio-templating with advanced characterisation and modelling tools will be essential to understand structure–function relationships and optimise performance for applications in catalysis, energy storage, and sensing.

**Perspective Focus Field 7:** Developments in biotemplating will push the boundaries of today's technology by enabling the creation of materials with structural precision and functional complexity inspired by nature. Using biological templates such as proteins, viruses, or plant tissues allows for hierarchical architectures and nanoscale control that conventional synthesis cannot achieve. These features have the potential to dramatically enhance performance in catalysis, energy storage, and sensing by maximizing surface area and optimizing active sites. Coupling bio-templating with scalable processes like sol-gel or vapor-phase deposition will bridge laboratory innovation and industrial application. This approach merges biological sophistication with synthetic versatility, delivering sustainable, high-performance materials for next-generation technologies.



## **Focus Field 8: Approaches Involving Bio-Inspired Hierarchical Structures in Catalysis and Materials Synthesis**

A research programme aiming to overcome development hurdles in bio-inspired approaches for creating new catalysts and advanced inorganic or hybrid materials through hierarchical structures should focus on replicating the multi-scale organisation and functional integration found in nature. Technically, this involves designing synthesis pathways that enable precise control over structure from the nano- to the macro-scale, using techniques such as self-assembly, layer-by-layer deposition, or templating with biological scaffolds. Challenges such as structural stability under operational conditions, reproducibility, and integration into existing process chains must be addressed through advanced materials characterisation, in situ monitoring, and scalable fabrication methods. The programme should evolve toward modular, adaptive synthesis platforms that allow for tuneable material properties, while embedding digital design tools, machine learning for structure–function prediction, and sustainability assessments to guide development toward industrial relevance and environmental compatibility.

**Perspective Focus Field 8:** Developments in bio-inspired hierarchical material synthesis will push the boundaries of today's technology by enabling multi-scale structural control and functional integration that mimics natural systems. These approaches allow precise organisation from nano- to macro-scale, creating materials with superior strength, adaptability, and catalytic efficiency. Techniques such as self-assembly, layer-by-layer deposition, and biological templating will deliver architectures that would be unattainable through conventional methods. Coupled with digital design tools, machine learning for structure–function prediction, and modular synthesis platforms, these innovations will enable tuneable properties and seamless integration into continuous manufacturing. This convergence of biology-inspired design and advanced engineering will redefine performance standards across energy, catalysis, and high-tech materials.

## **Focus Field 9: Data, Simulation, and AI as Enablers for Bio-Inspiration**

A research programme aiming to advance bio-inspired materials and processes should deeply integrate digitalisation, FAIR data principles, AI, and simulation to overcome technical bottlenecks and accelerate innovation. On the technical side, high-throughput experimentation platforms should be coupled with automated data acquisition systems that generate structured, machine-readable datasets adhering to FAIR standards. These datasets can feed into AI/ML models for predictive materials design, enabling inverse design workflows where desired properties guide the synthesis of new materials. Multiscale simulations, from quantum chemistry to continuum modelling, should be used to understand complex bio-inspired mechanisms such as hierarchical self-assembly, adaptive behaviour, or catalytic



site dynamics. Digital twins of experimental setups can support real-time optimisation and scale-up, while knowledge graphs and ontologies can help unify heterogeneous data sources across disciplines. The programme should also invest in open, interoperable data infrastructures and collaborative platforms to ensure reproducibility, accelerate discovery cycles, and support cross-domain innovation in sustainable, bio-inspired technologies. Existing standards, tools, and workflows from initiatives such as Projekt “MaterialDigital” and “Nationale Forschungsdaten Infrastruktur” should be leveraged to support this effort.

**Perspective Focus Field 9:** Developments in digitally integrated bio-inspired materials and processes will push the boundaries of today’s technology by transforming how innovation occurs. By embedding FAIR data principles, AI-driven predictive design, and multiscale simulations into research workflows, materials development will shift from trial-and-error to data-centric, automated discovery. High-throughput experimentation combined with digital twins will enable real-time optimisation and rapid scale-up, while inverse design powered by machine learning will allow properties to dictate synthesis strategies. This convergence of biology-inspired concepts with advanced digitalisation will accelerate discovery cycles, enhance reproducibility, and unlock complex functionalities—creating smarter, sustainable technologies that redefine performance and innovation speed across industries.

### 3. Detailed Results of the Workshop

The following section describes workshop structure, layout of World cafés, and stimulus that was given to the World café participants. It continues with the collection of individual ideas, followed by categorisation, ranking, and trend identification based on statistical analysis.

#### 3.1 Detailed Summary Layout World cafés

##### 3.1.1 World café 1: Bio-Intelligence

The purpose of the Bio-Intelligence World café was to explore how biological principles, processes, and systems can be integrated into material and technology design to develop solutions that are adaptive, efficient, and sustainable. Participants discussed how nature’s inherent capabilities, such as self-repair, environmental sensing, and adaptability, can inspire synthetic systems with similar functionalities.

The session was stimulated with a narrative on the topic of responsive materials, which are capable to react on external stimuli, such as light, temperature, magnetic fields, or electricity. As a natural example, pinecones were introduced, showcasing their ability to open and close in response to humidity. This was complemented by a synthetic counterpart: 4D-printed hygromorphs that change shape in response to moisture.<sup>[1]</sup> The presentation then moved to adaptable materials, which are designed to be modified, either manually or automatically, to suit specific applications or environmental conditions. Chameleon skin served



as the biological reference due to its dynamic colour-changing ability. On the synthetic side, polymer-based micro-phonic multifunctional metamaterials were presented, offering tuneable optical and mechanical properties.<sup>[2]</sup> Finally, the session was motivated by the example of self-healing materials, which can autonomously repair damage without the need for external diagnosis or intervention. Coral reefs were highlighted as a natural model for regenerative systems. This concept was mirrored in synthetic materials by self-healing concrete enhanced with nano-silica, which is capable of repairing cracks independently.<sup>[3]</sup>

### **3.1.2 World café 2: Bio-Interfaces**

The Bio-Interfaces World café focused on the surfaces or interfaces in which biologically inspired systems interact with synthetic compounds and/or materials. Understanding the interactions at these interfaces enables the fabrication of biologically inspired hybrid materials for various applications, e.g., energy efficiency, catalysis, artificial sensors, and bio-composites. Participants were stimulated by examples of the design and scientific basis of bio-interfaces, which are both crucial for the creation of novel bio-inspired materials to address future challenges in sustainable chemical processes.

The stimulus of the World café started with an example of photosynthesis in nature and its counterpart, an artificial leaf for energy-efficient chemical reactions.<sup>[4]</sup> Furthermore, it addressed the fabrication of hybrid materials with multiple functionalities, such as Covalent Organic Frameworks (COFs), heteroatom-doped carbon, and enzymes for CO<sub>2</sub> conversion. The attention of the participants was then shifted to the design of highly stable catalysts under reaction conditions, being resistant to poisoning, inspired by the lotus effect with water droplets.<sup>[5]</sup> In addition, photo-responsive materials based on interface modifications were presented as an example for sensing applications. From a different perspective, the example of mussels adhering to sea rocks inspired the discussion on fabricating bio-inspired adhesive materials from renewable resources, e.g., the catalytic fractionation of lignin to phenolic monomers.<sup>[6]</sup>

The session highlighted several key principles as tools for the participants: (1) energy optimisation at interfaces, (2) integrated processes with optimal atom and energy economy, and (3) utilisation of renewable resources for smart materials, which together will support the transition to biologically inspired materials and processes.

### **3.1.3 World café 3: Bio-Transition**

The Bio-Transition World café introduced the shift from conventional, fossil-based, and synthetic materials toward biological, sustainable, and eco-compatible alternatives as a trigger. This impulse was used to induce the reduction of the environmental impact by embracing materials and technologies that are derived from natural resources or designed to integrate seamlessly with natural ecosystems as a driving principle. Central to this approach is the use of bio-based materials, bio-compatible systems, and natural analogues that support circularity and sustainability throughout their life cycle.



The impulse focused on bio-based materials, which are wholly or partially derived from biological sources such as plants, animals, enzymes, and microorganisms, for example. Silk, assembled from natural amino acids, served as a biological example of a high-performance, renewable material. In contrast, a synthetic example was presented in the form of Nylon-6,6, produced from biomass-derived adipic acid and hexamethylenediamine, demonstrating how traditional polymers can be reimagined using renewable feedstocks.<sup>[7]</sup> The conversation then turned to bio-compatibility, a key requirement for materials that interact with biological systems. A bio-compatible material should be compatible with the organisms it contacts. Chitin, which is enzymatically synthesized from trehalose and glycogen and naturally degraded by enzymes, was highlighted as a model compound of biological origin with high biocompatibility. This was complemented by an impulse on synthetic polymers used in tissue engineering, which are designed to support biological functions without causing damage or rejection.<sup>[8]</sup> Finally, the session explored natural analogues, compounds that mimic the structure of natural molecules but differ in specific components such as functional groups or substructures. Proteins, synthesized enzymatically from amino acids and degraded back into polypeptides and amino acids, illustrated the natural paradigm. As a synthetic counterpart, polyamide acids were discussed, which are used in applications such as controlled drug release and offer structural similarities to natural proteins while enabling tailored functionality.<sup>[9]</sup>

Throughout the session, the three key characteristic tools were given to the participants, which are characteristic of any bio-transition: the use of bio-based materials, biocompatibility across the entire life cycle, and the synthesis and recycling of natural analogues. The enabling principle identified included the development of bio-based monomers and building blocks, the use of biosynthetic pathways, and the integration of bio-degradation mechanisms.

## **4. Detailed Description of the Workshop Evaluation**

### **Workflow including Data Analysis**

The evaluation of 217 ideas followed a systematic, multi-step approach to ensure clarity, relevance, and strategic alignment. The simplified workflow is shown in Figure 2.

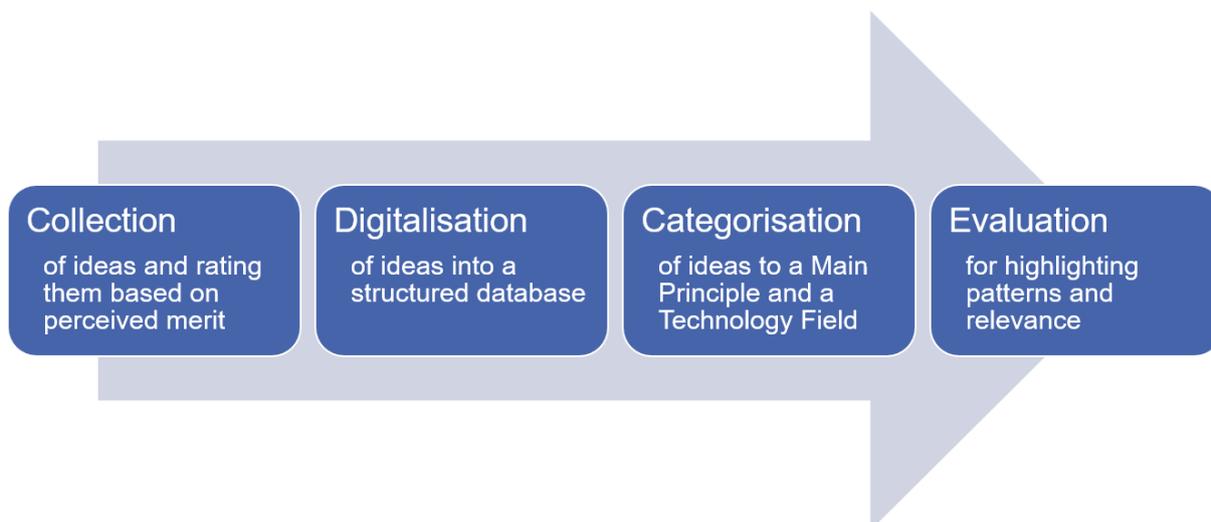


Figure 2: Structured workflow from World café session to Evaluation.

### a) Digitalisation of ideas

All ideas were:

- ▶ Collected from analogue formats (flipcharts, sticky notes)
- ▶ Transcribed into a digital database for structured analysis
- ▶ Tagged with metadata (e.g., session, group, World café theme) for traceability.

From the 217 collected analogue ideas, 199 ideas could be processed further, due to identification or clarification challenges. The 18 ideas either had missing evaluation scores, missing metadata or both. Therefore, they were excluded from further processing.

### b) Classification

Each idea was categorized based on the following criteria:

#### ▶ **Technology Fields:**

- ▶▶ **Functional Polymers:** Functional polymers refer to a class of synthetically available or natural polymers that have been designed, synthesized, chemically modified, and/or functionalized to possess specific properties, functions, or interactions. These polymer modifications can be achieved through various synthetic pathways involving defined monomer units or chemical reactions, such as grafting, cross-linking, or copolymerisation, which introduce specific functional groups or moieties into the polymer backbone to impart desired properties. This purposeful architecture transforms polymers from passive materials into active enablers of innovation across



applications ranging from smart coatings and biomedical devices to energy storage and catalysis.

- » **Polymer Synthesis:** Polymer synthesis refers to the process of creating polymers, which are long-chain molecules composed of repeating units called monomers. Polymer synthesis involves the chemical transformation of monomers into polymers through various methods, including polymerisation, copolymerisation, grafting, and cross-linking. Far beyond mere assembly, polymer synthesis is a cornerstone of modern materials science, driving innovation in sustainability, energy, and technology.
  
- » **Recycling:** Recycling is the strategic process of transforming discarded materials into valuable resources, turning waste into new products or raw materials. Far beyond disposal, recycling is a cornerstone of sustainable technology, conserving finite natural resources, reducing environmental burdens, and minimizing landfill impact. By closing material loops, recycling enables circular economies, lowers carbon footprints, and drives innovation in resource efficiency. It is not just a waste-management practice - it is a critical enabler of global sustainability and industrial resilience.
  
- » **Catalysis:** Catalysis is the process in which a substance, called a catalyst, provides an alternative reaction pathway with a lower activation energy, thereby increasing the reaction rate without altering the overall thermodynamic equilibrium (standard Gibbs energy change) and without being consumed in the reaction cycle. Catalysts operate by stabilizing transition states or intermediates, enabling selective bond activation and energy-efficient transformations. This technology field focuses on the rational design and optimisation of catalytic systems, including heterogeneous, homogeneous, and biocatalysts, to enhance activity, selectivity, and stability. Advanced strategies involve tailoring surface structures, electronic properties, and active sites through nanostructuring, alloying, and functionalisation, often supported by computational modelling and AI-driven screening.
  
- » **Biomimetic Catalysis:** Biomimetic catalysis is a Technology Field that involves the design and development of catalysts that mimic the behaviour of biological systems like enzymes. These catalysts are inspired by the structure and function of enzymes, which are highly efficient and selective catalysts that play a crucial role in various biological processes. Biomimetic catalysis combines the principles of chemistry, biology, and materials science to create artificial catalysts that can perform specific chemical reactions with high efficiency and selectivity. These catalysts are designed to



mimic the active sites of enzymes, which are responsible for catalysing specific chemical reactions.

**Advanced Materials:** Advanced Materials are a Technology Field that involves the discovery, development, and characterisation of new materials with specific properties tailored to certain applications. According to the Organisation for Economic Co-operation and Development Advanced Materials are defined as materials that are rationally designed to have new or enhanced properties, and/or targeted or enhanced structural features, leading to specific or improved functional performance.<sup>[10]</sup> Advanced Materials have typically been focused on achieving excellent superior properties in high-tech applications are the key lever to the performance characteristics. mechanical, electrical, or optical properties for the profound understanding of advanced materials on an atomistic level, and superior design through advanced synthesis and processing capabilities make these materials the ideal solution for applications that range from construction, electronics, devices, sensing, energy storage and conversion, and healthcare, and touch our daily lives as consumers in various forms. Advanced Materials is a multidisciplinary field that combines expertise from chemistry, physics, materials science, and engineering to create such materials with tailored performance, efficiency, and sustainability.

» **Separation Technology:** Separation Technology is a Technology Field that involves the process of separating a mixture of substances into its individual components. Separation is a critical step in many industrial processes, including chemical synthesis, pharmaceutical production, and food processing. Separation processes often account for a significant portion of the total energy consumption in the production of materials and chemicals. Consequently, this technological Field places strong emphasis on reducing the energy demand associated with separation steps.

» **Other Fields:** Various ideas could not be classified according to the Technology Field mentioned above. These are summarised as “Other Fields”.

» **Main Principles Biologisation and Bio-inspiration:** are defined based on the Whitepaper of acatech, Deutsche Akademie der Technikwissenschaften, Materials Research Inspired by Nature, Innovation Potential of Biologically Inspired Materials.<sup>[11]</sup> The main principles are summarized in the following section.

» **Biotechnological Methods:** Modern biotechnology in materials science refers to the use of biological systems and principles, such as self-organisation and self-assembly,

to develop new, high-precision materials. It focuses on understanding and utilizing natural building blocks like proteins, polysaccharides, nucleic acids, and biominerals (e.g., in bone or shells) to create functional materials under mild conditions that preserve sensitive structures of proteins, polysaccharides, and the like. Through biotechnological processes, such as fermentation using host organisms like bacteria or yeast, both natural and modified biopolymers can be produced. These materials offer unique properties, including high strength and adaptability.

- » **Bioteemplating:** A Materials synthesis approach that uses natural biopolymer structures, such as plant tissues or biological architectures, as templates to create inorganic functional and structural materials. These biological templates guide the deposition of durable inorganic substances, enabling the fabrication of complex, hierarchically structured materials with cross-scale functionality. This method allows for the replication of intricate natural designs, such as porous ceramics modelled after plant cell walls, and is particularly valuable in industrial and biomedical applications.
- » **Hierarchical Structures:** A key characteristic of natural materials is their multi-scale hierarchical structure, which spans from the molecular to the macroscopic level. This architecture allows for the integration of multiple functions, which can emerge at individual hierarchical levels or through interactions across several levels.
- » **Interactive and Adaptive Systems:** Interactive and adaptive materials are material systems that respond to environmental stimuli. Interactive materials exhibit passive, non-specific responses, while adaptive (or smart) materials actively adjust to changes in their surroundings. These materials often possess intrinsic self-X properties, such as self-healing, self-cleaning, or self-assembling, which enable them to maintain or restore functionality autonomously.
- » **Multifunctionality:** Today's materials are expected to go beyond serving single functions like mechanical strength or specific electrical, optical, or magnetic characteristics. Instead, there is a growing demand for materials that integrate multiple functions and exhibit adaptive, interactive, and stimulus-responsive behaviours.
- » **Other Principles:** Various ideas could not be classified according to the Main Principles mentioned above. These are summarised as Other Principles.

All ideas were classified according to the classes described above.<sup>[11]</sup> This classification step enabled thematic clustering and identification of cross-cutting concepts.



### c) Foundations used for the Technology Assessment

The technology assessment was inspired by the previous work of Armin Grunwald.<sup>[12]</sup> Each idea was rated on three key dimensions with a rating value between 1 and 5. Ratings were given on a subjective basis, considering the nature of the idea versus the state of the art:

- ▶ Potential **Environmental advantage**: lower environmental impact, better resource efficiency, better energy efficiency, reduced emissions
- ▶ Potential **Economic advantage**: cost saving, scalability, competitiveness
- ▶ Potential **Technical advantage**: higher performance, compatibility, reliability

Other aspects, such as social and applicability/usability advantages as well as legal and ethical advantages, were not considered for the evaluation of the World cafés. The ratings were assigned by the World café leaders, resulting in a composite score for prioritisation. To reduce the subjective character of the evaluation process, the top-scoring 20% of ideas from each World café session were selected for a subsequent comparative, detailed analysis. While the ratings reflect individual assessments by the World café leaders and are inherently subjective, the internal thematic consistency of technical topics discussed within each session enables a meaningful comparison across the World cafés, which later on guides the recommendations for future funding programmes.

### d) Research demand classification

Ideas were also evaluated for their research horizon:

- ▶ **Short-term** (1–2 years)
- ▶ **Mid-term** (3–5 years)
- ▶ **Long-term** (5+ years)

Each idea received a rating from 1 to 5, indicating the urgency and maturity of the research required.

### e) Statistical data evaluation

The final step involved statistical data evaluation:

- ▶ Quantitative analysis of ratings across all dimensions
- ▶ Visualisation of trends
- ▶ Identification of high-potential clusters and gaps in research focus

## 5. Workshop evaluation

The workshop evaluation is based on three participant groups with carrying research background, three World cafés, 9 interactive sessions, 50 participants, and 199 ideas for evaluation.

**Group 1:** Catalysis and Process Chemistry → referred to as **Catalysis** in the evaluation

**Group 2:** Inorganic Functional Materials → referred to as **Inorganic** in the evaluation

**Group 3:** Polymers and Functional Materials → referred to as **Polymer** in the evaluation

**World café 1:** Bio-Intelligence

**World café 2:** Bio-Interfaces

**World café 3:** Bio-Transition

### 5.1 Overview across all World cafés and Categorisation

World café 1: Bio-Intelligence featured the highest total number of ideas, with Group 3: Polymer contributing over half of the ideas in this category. This indicates a strong thematic alignment between polymer-related research and approaches relating to Bio-Intelligence. In contrast, the other World cafés exhibited a more balanced distribution of ideas coming from the three groups. Notably, Group 2: Inorganic was consistently the least represented across all sessions, suggesting a weaker alignment with the evaluated principles in this workshop context. Figure 3 and Table 1 summarize the number and group affiliation of the ideas.

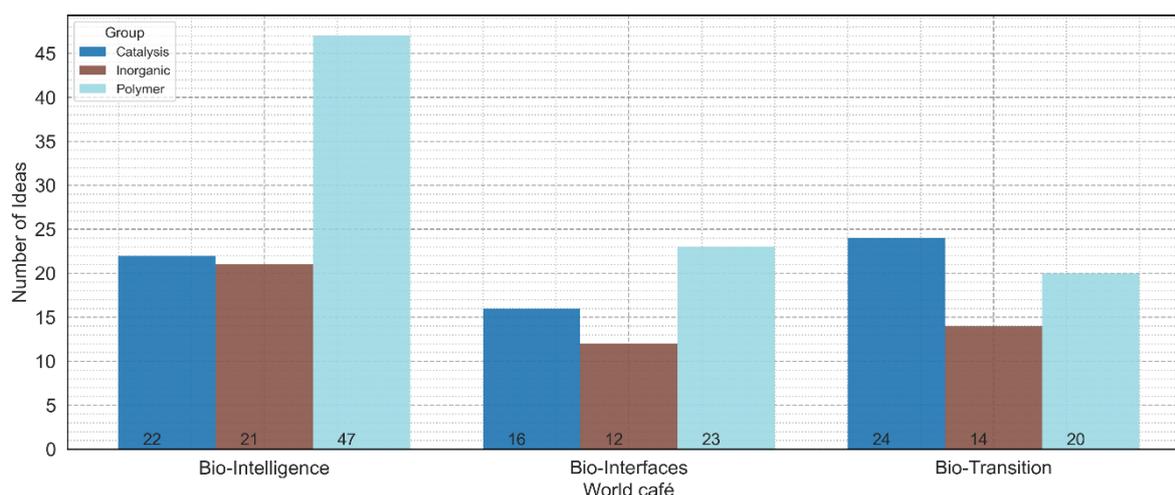


Figure 3: Number of ideas in each **World café** categorised by **Group**.

Table 1: Number of ideas in each **World café** and **Group**.

Number of ideas	World Café 1: Bio-Intelligence	World Café 2: Bio-Interfaces	World Café 3: Bio-Transition	Total
Group 1: Catalysis	22	16	24	62
Group 2: Inorganic	21	12	14	47
Group 3: Polymer	47	23	20	90
<b>Total</b>	<b>90</b>	<b>51</b>	<b>58</b>	<b>199</b>

To ensure clarity and depth in the evaluation, the following discussion of the ideas is organised throughout the individual World cafés. This approach allows for a more focused analysis of thematic trends, group representation, and alignments within each context. It also helps to identify category-specific strengths and gaps, which are essential for guiding future strategic decisions.

## 5.2 Overview World café 1: Bio-Intelligence

### 5.2.1 Distribution across Group, Main Principle, and Technology Field

In World café 1: Bio-Intelligence, the distribution of ideas is notably concentrated on one guiding principle, as can be seen in Figure 4.

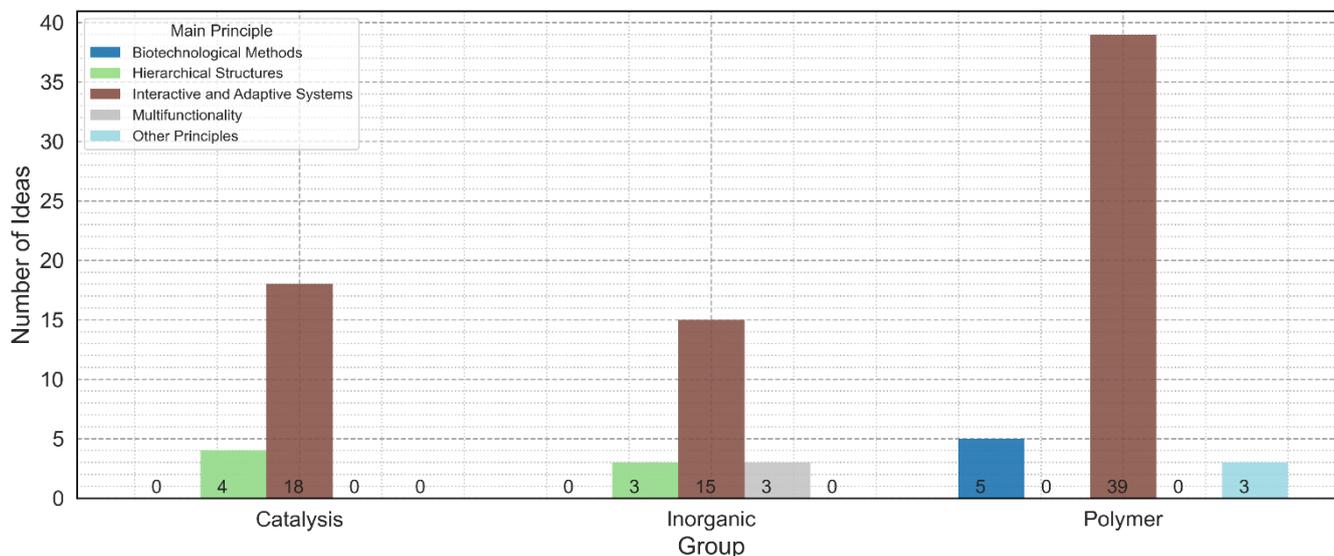


Figure 4: Number of ideas in **World café 1: Bio-Intelligence** categorized by **Group** and **Main Principle**.

A significant majority of the 90 ideas are categorised under the Main principle: Interactive and Adaptive Systems, with only 18 ideas falling outside this classification. This strong thematic focus suggests a clear conceptual alignment within the Bio-Intelligence World café.

A similar pattern is observed for the Technology Field distribution. Most ideas of Group 1: Catalysis are aligned with the Technology Field: Catalysis, all Group 2: Inorganic ideas can be classified under the Technology Field: Advanced Materials, and for Group 3: Polymer ideas can be predominantly associated with the Technology Field: Functional Polymers. Figure 5 shows the number of ideas categorized by the respective Group and Technology Fields.

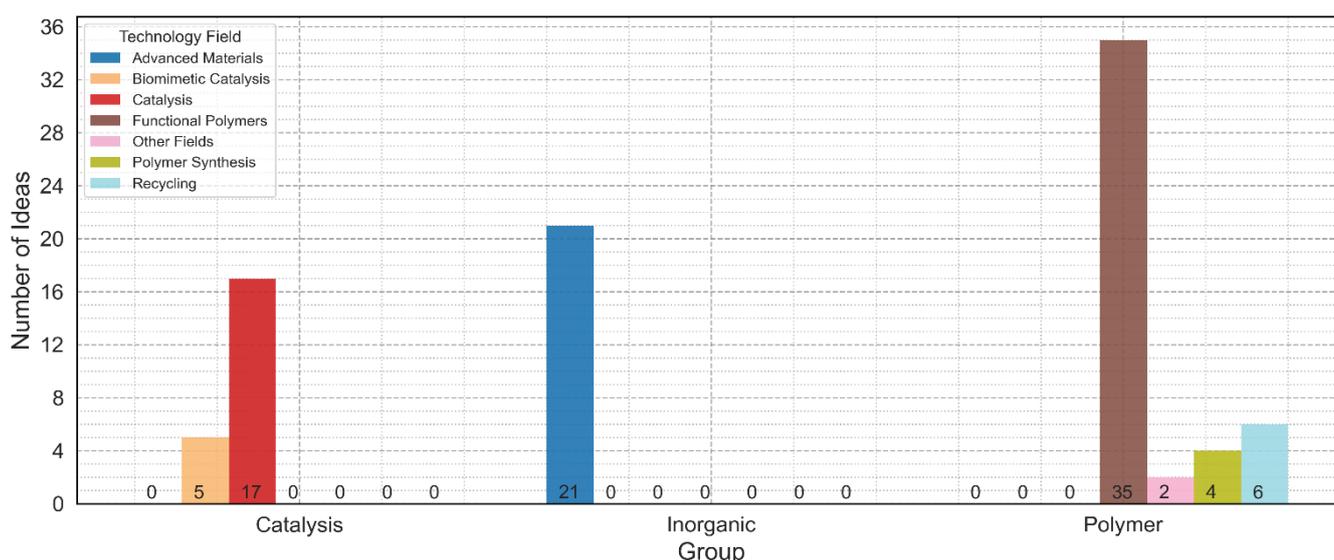


Figure 5: Number of ideas in **World café 1: Bio-Intelligence**, categorized by **Group** and **Technology Field**.

This narrow spread across both the Main Principle and the Technology Field highlights a high degree of internal consistency within this World café.

### 5.2.2 Technology assessment of ideas by Group

World café 1: Bio-Intelligence shows more consistent trends of ideas with high technical advantages across all Groups, contrasted by moderate to low economic and environmental advantages. The average scores of the respective advantages, as well as the most frequent rating (mode) for each Group, can be seen in Figure 6. The ideas of Group 1: Catalysis stand out with average technical scores above 4, and economic and environmental scores around 3. However, both non-technical evaluations exhibit higher standard deviations, indicating greater variability in the perceived value of the ideas. Notably, the most frequent score across all three categories is 5, suggesting a strong concentration of top-rated ideas. Ideas in Group 2: Inorganic follow a similar pattern in technical advantages, but show lower economic and environmental ratings, with the mode for both being 1, reflecting limited perceived advantage in these dimensions. Ideas of Group 3: Polymer also maintain high technical scores on average, but their economic and environmental advantage averages are

closer to 2, with a mode of 1 in both categories, indicating a consistent challenge in demonstrating broader impact.

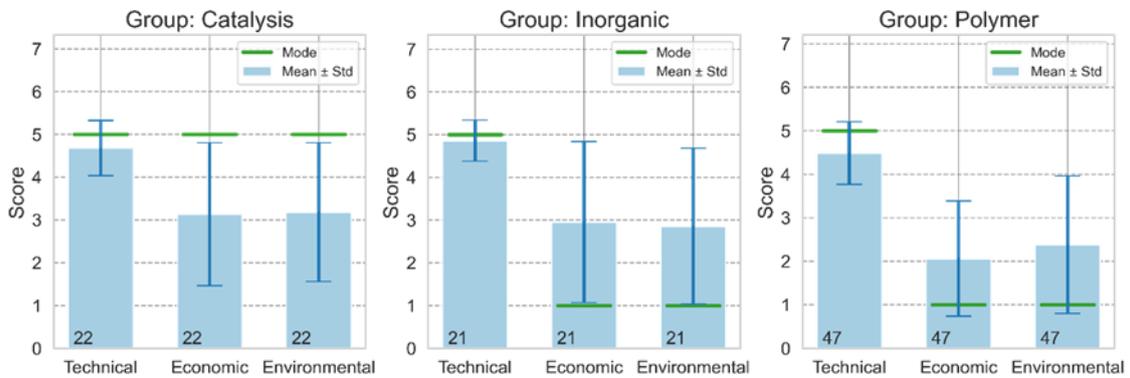


Figure 6: Average evaluation of the technology assessment scores received in each evaluation category (light blue), standard deviation (blue), and mode (green) by **Group** in **World café 1: Bio-Intelligence**. The number of ideas in each Group is shown in the bottom left of each bar.

### 5.2.3 Technology assessment ratings

Across World café 1: Bio-Intelligence, ideas consistently received high technical advantage scores, with very few ideas rated below 3, indicating strong perceived feasibility and a high degree of innovation. A notable pattern emerges between economic and environmental advantage evaluations, which appear to correlate strongly. Ideas with low economic advantages often score also low on the aspect of environmental advantage, and vice versa. World café 1: Bio-Intelligence also contains the highest number of ideas receiving the maximum score across one or more categories. The breakdown of the score into each evaluation criterion and the number of ideas that received full marks in each criterion is shown in Figure 7.

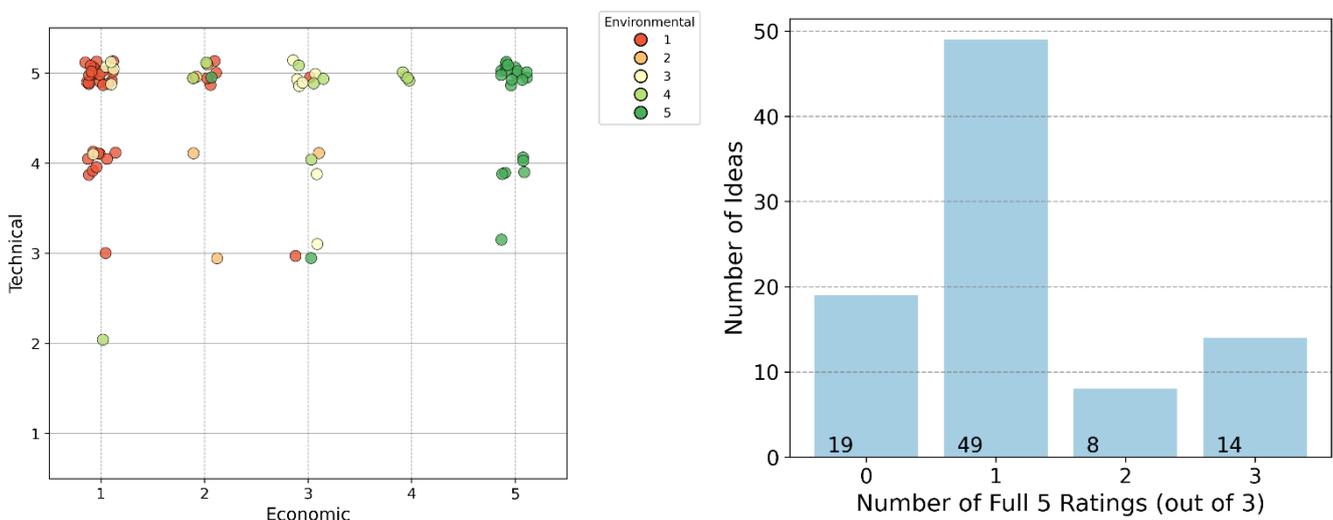


Figure 7: Evaluation score breakdown of the ideas in **World café 1: Bio-Intelligence**. Left: Score received in each category. Right: Number of ideas that received a maximum rating in zero, one, two, or three evaluation categories.



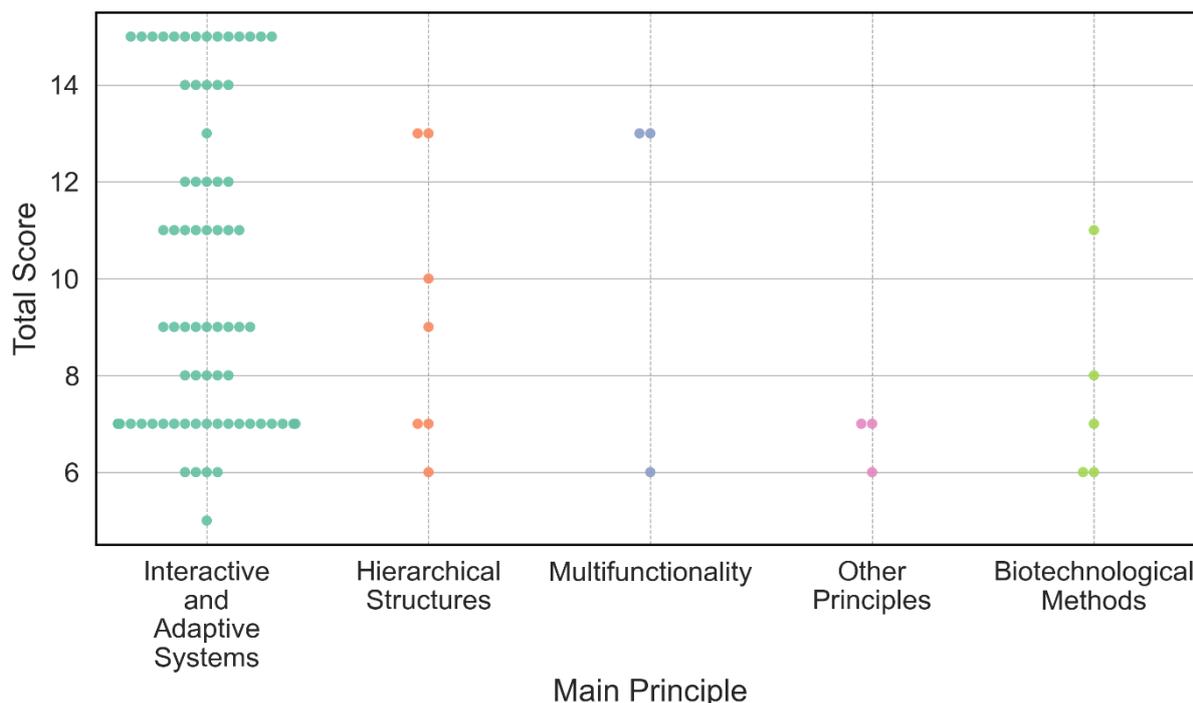


Figure 9: Distribution of ideas in **World café 1: Bio-Intelligence** by total evaluation score, categorized by **Main Principle**. Each dot represents an individual idea in that category.

In World café 1: Bio-Intelligence, most ideas could be categorised under the Main Principle: Interactive and Adaptive Systems, which also encompasses all top-scoring submissions. This concentration suggests a strong alignment between perceived innovation potential and the adaptability of biological systems, possibly reflecting current research trends or evaluator preferences. The other Main Principles are sparsely populated, limiting meaningful comparative analysis; notably, biomimetic catalysis is absent. Figure 9 shows the idea spread by Main Principle.

From the Technology Field perspective, illustrated in Figure 10, the distribution is more balanced, although the Technology Field: Separation Technology is not represented at all. The highest-ranked ideas are concentrated in the Technology Fields: Catalysis, Advanced Materials, and Functional Polymers, indicating clear pathways to implementation.

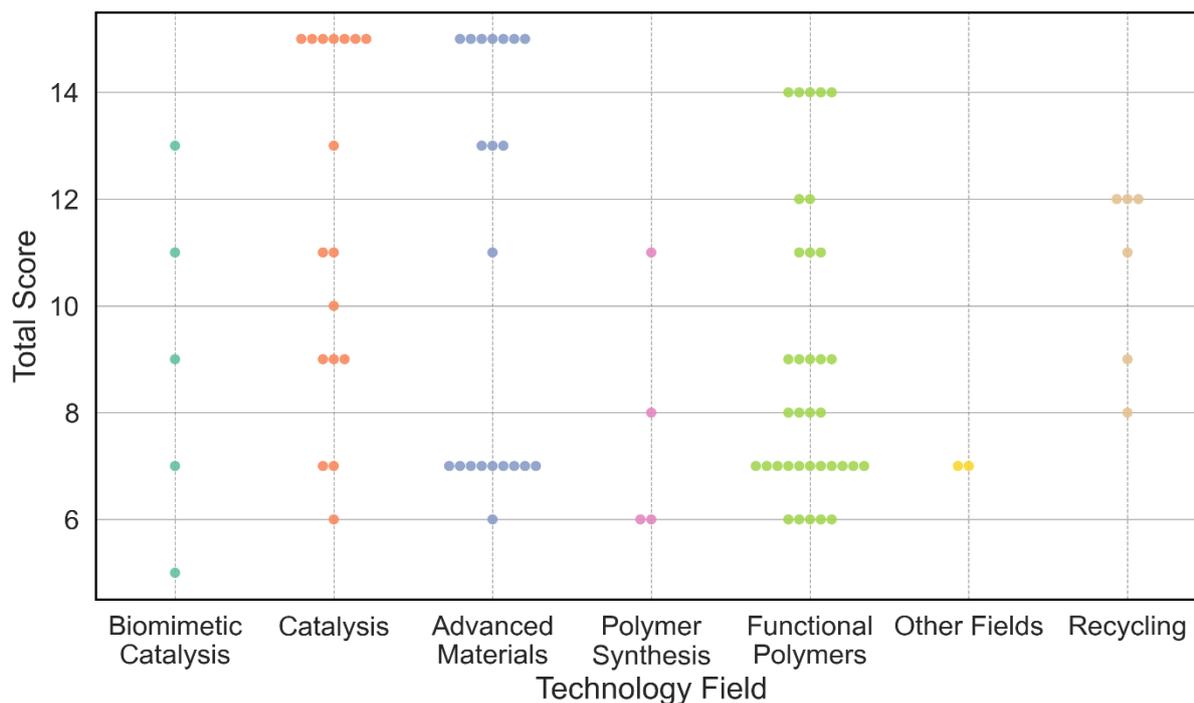


Figure 10: Distribution of ideas in **World café 1: Bio-Intelligence** by total evaluation score, categorized by **Technology Field**. Each dot represents an individual idea in that category.

### 5.2.5 Characteristics of Top-Rated Ideas

In order to evaluate the most promising concepts from World café 1: Bio-Intelligence, the top 20% of ideas, along with any additional entries sharing the same technology assessment score, were analysed across their assigned Main principle, Technology Field, and Group (19 in total). Through this strategy, the aim is to evaluate the World cafés more robustly and comparably. This strategy aims to enhance the comparability of evaluations conducted during the World cafés by establishing consistent criteria and a shared understanding across all discussion groups. This approach resulted in a subset of 19 ideas, 14 of which received the highest evaluation. All top-rated ideas were categorised under the Main Principle: Interactive and Adaptive Systems, and were distributed across the Technology Fields: Catalysis, Advanced Materials, and Functional Polymers. This strong clustering suggests that the Main Principle: Interactive and Adaptive Systems currently represents the most compelling conceptual framework within this World café. However, the underrepresentation of other Main Principles, particularly the complete absence of the Main Principle: Biomimetic Catalysis, warrants caution. It remains unclear whether this imbalance reflects a true lack of relevance or simply a gap in idea generation or submission diversity. Notably, all three Groups, Catalysis, Inorganic, and Polymer, are represented within these top ideas, indicating that high-impact potential is not confined to a single disciplinary domain but spans across diverse technological foundations. Table 2 summarizes the distribution of the top-scoring ideas in World café 1: Bio-Intelligence.

Table 2: Distribution of high-scoring ideas of **World café 1: Bio-Intelligence** across **Group**, **Main Principle**, and **Technology Field**. The Groups are color-coded: **Catalysis** (green), **Inorganic** (orange), and **Polymer** (purple).

World café 1: Bio-Intelligence	Bio-technological Methods	Biotemplating	Hierarchical Structures	Interactive and Adaptive Systems	Multi-functionality	Other Principles
Biomimetic Catalysis						
Catalysis				7		
Advanced Materials				7		
Polymer Synthesis						
Functional Polymers				5		
Other Fields						
Recycling						
Separation Technology						

## 5.3 Overview Word café 2: Bio-Interfaces

### 5.3.1 Distribution across Groups, Main Principle, and Technology Field

In World café 2: Bio-Interfaces, the distribution of ideas closely mirrors that of World café 1: Bio-Intelligence, with a dominant concentration in the Main Principle: Interactive and Adaptive Systems. Additionally, isolated instances appear for the Main Principles: Biotechnological Methods and Biotemplating that resonate across all three Groups, indicating some conceptual diversity, albeit at lower representation levels. The number of ideas in each Group categorized by the Main Principles is shown in Figure 11.

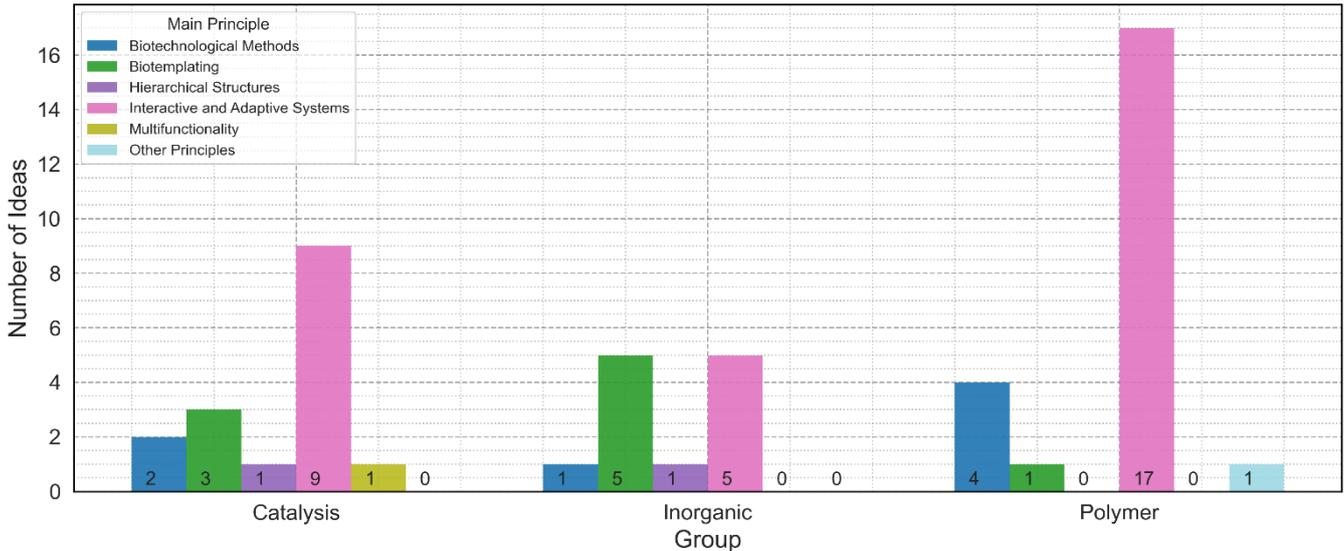


Figure 11: Number of ideas in **World café 2: Bio-Interfaces** categorized by **Group** and **Main Principle**.

When analysing the ideas by Technology Field, Group 1: Catalysis generated ideas primarily and not surprisingly associated with the Technology Field: Catalysis. Ideas of Group 2: Inorganic align typically with the Technology Field: Advanced Materials. For Group 3: Polymer, most ideas could be linked to the Technology Field: Functional Polymers. This alignment between Group identity and Technology Field suggests a coherent thematic structuring of ideas, potentially reflecting disciplinary strengths or evaluator expectations. Figure 12 shows the distribution of ideas across Group and Technology Field.

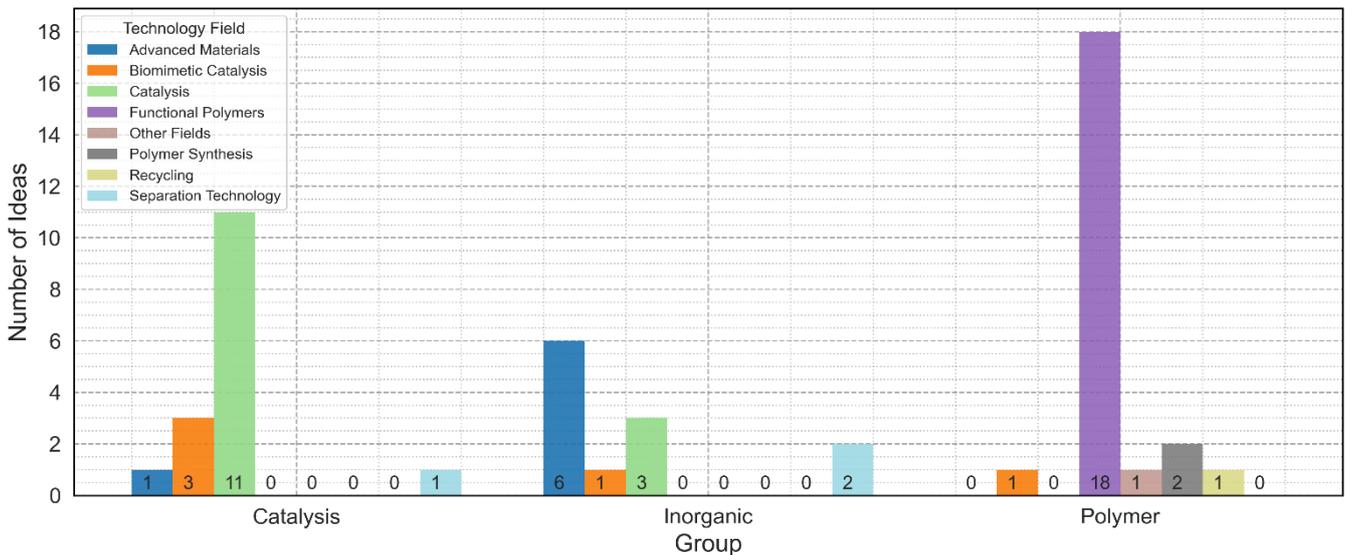


Figure 12: Number of ideas in **World café 2: Bio-Interfaces** categorized by **Group** and **Technology Field**.

### 5.3.2 Technology assessment of ideas by Group

An analysis of the average evaluation scores across groups in World café 2: Bio-Interfaces reveals distinct scoring profiles, which are displayed in Figure 13. For Group 1: Catalysis, it can be seen that a high technical advantage score is achieved, averaging around 4, a medium environmental score with notable variability, and a low economic score averaging approximately 1,5. The mode of evaluations, 5 (technical), 1 (economic), and 1 (environmental), suggests a strong technical appeal but limited perceived economic and environmental viability of the ideas. For Group 2: Inorganic, it is perceived that the results stand out with a consistently high technical score of 5 and minimal standard deviation, indicating strong consensus on technical merit for the ideas. The environmental score averages around 3, with a mode of 5, while the economic score remains low, with a mode of 1. For Group 3: Polymer, a balanced technical and environmental score is seen averaging around 4, with a mode of 5, suggesting moderate strength across these dimensions. However, its economic score mirrors that of Group 1: Catalysis, averaging 1,5 with a mode of 1. These patterns highlight a recurring challenge: while technical merit is consistently rated high, economic viability remains a limiting factor across all groups, and environmental assessments vary more widely.

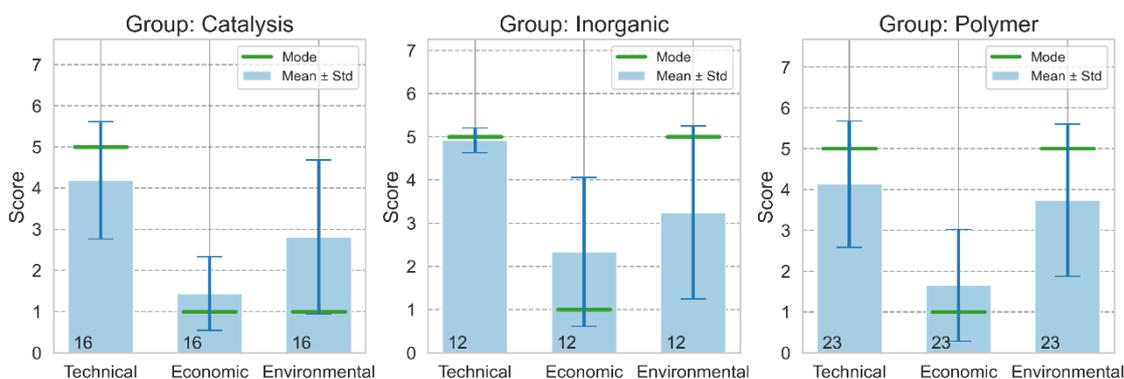


Figure 13: Average evaluation scores received in each evaluation category (light blue), standard deviation (blue), and mode (green) by **Group** in **World café 2: Bio-Interfaces**. The number of ideas in each Group is shown in the bottom left of each bar.

### 5.3.3 Technology assessment ratings

An analysis of the 51 submitted ideas within the World café 2: Bio-Interfaces reveals that most ideas tend to aggregate in either one or two evaluation categories, achieving top scores in these. Specifically, 25 ideas received the highest possible score regarding specific advantages in at least one criterion, and 19 ideas achieved full marks in two criteria. This distribution suggests that many concepts exhibit strong ratings in either technical feasibility or environmental sustainability, but rarely in all three dimensions simultaneously.

The attributes “technical advantage” and “environmental advantage” are frequently rated highly, indicating a strong emphasis on innovation and ecological impact. In contrast,

economic viability was less commonly rated at the highest level, pointing to a potential gap in the integration of market-oriented considerations during early-stage ideation.

“No ideas” demonstrated moderate scores across all three criteria, suggesting that balanced, integrative approaches are underrepresented. This pattern may reflect the early development stage of many concepts, where focused excellence in one domain is prioritised over holistic feasibility. Figure 14 illustrates this trend, highlighting the skewed distribution of evaluation scores and the prevalence of domain-specific strengths over cross-dimensional robustness.

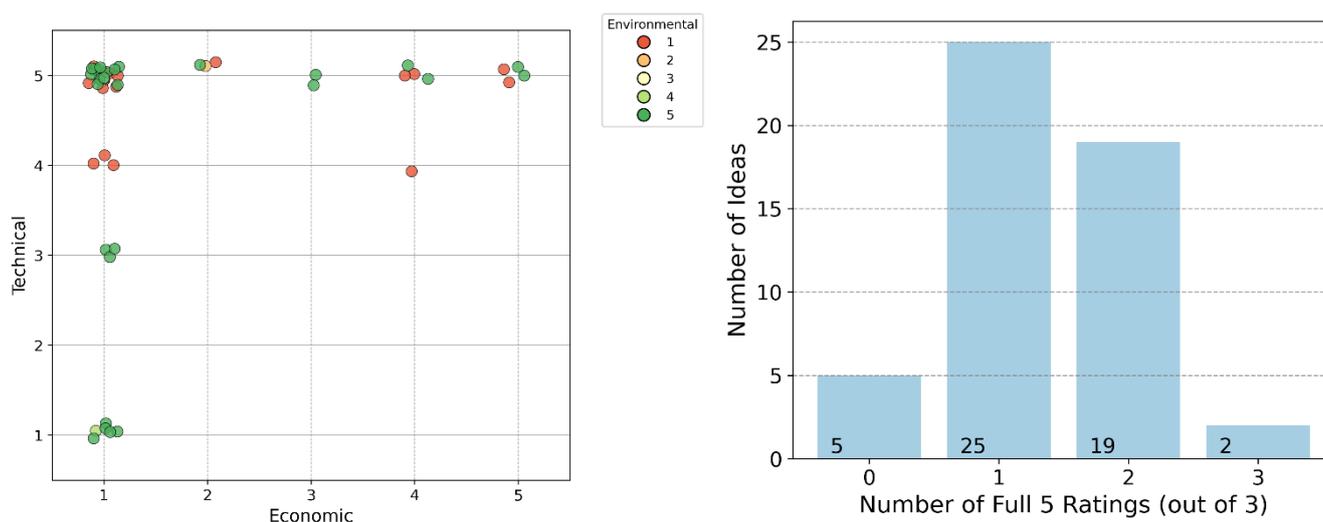


Figure 14: Evaluation score breakdown of the ideas in **World café 2: Bio-Interfaces**. Left: Score received in each category. Right: Number of ideas that received a maximum rating in zero, one, two, or three evaluation categories.

### 5.3.4 Technology assessment across Group, Main Principle, and Technology Field

The distribution of total scores across the three disciplinary groups, Group 1: Catalysis, Group 2: Inorganic, and Group 3: Polymer, appears to be relatively balanced, with each group contributing ideas across the full scoring spectrum. However, distinct patterns emerge:

Group 1: Catalysis is characterised by a predominance of low-scoring ideas, interspersed with a few high-scoring outliers, indicating selective excellence within a generally weaker performance profile.

Group 2: Inorganic shows a concentration of ideas with mid-range scores, suggesting consistent but moderate performance across submissions.

Group 3: Polymer spans both lower and medium score ranges, while also featuring several high-scoring outliers, highlighting its potential for impactful contributions despite variability.

The distribution of the total score by Group is shown in Figure 15.

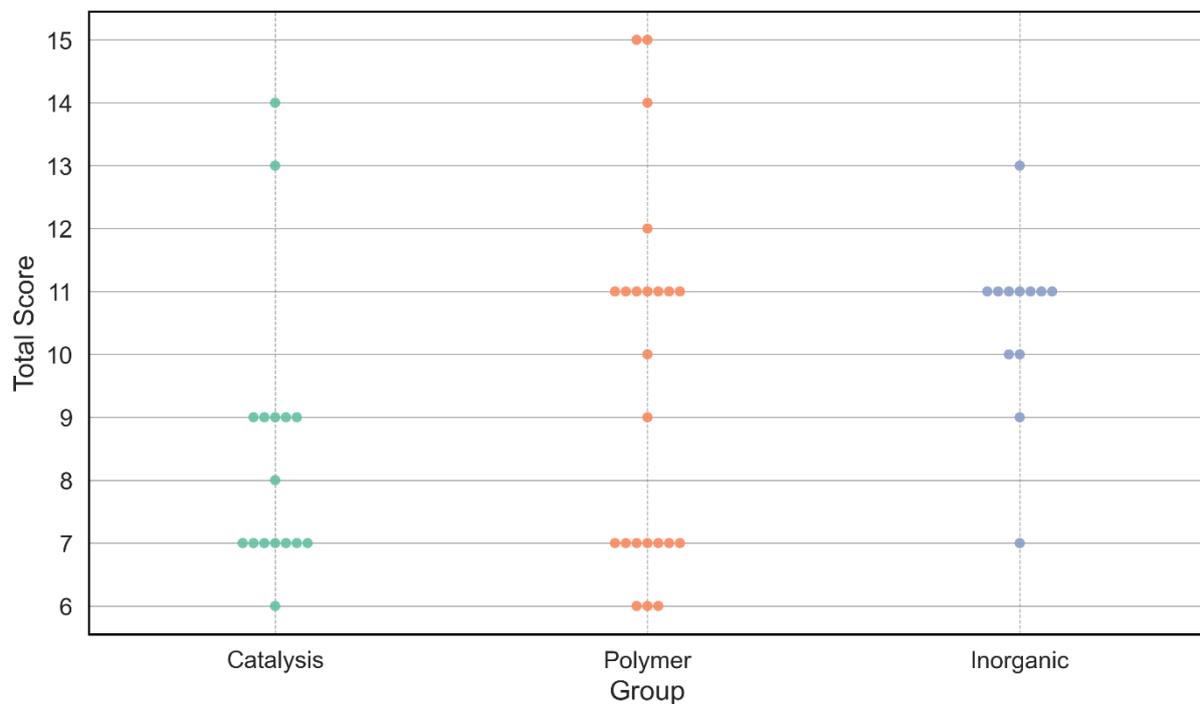


Figure 15: Distribution of ideas in **World café 2: Bio-Interfaces** by total evaluation score, categorized by **Group**. Each dot represents an individual idea in that category.

Ideas could predominantly be aligned with one Main Principle: Interactive and Adaptive Systems, followed by the Main Principle: Biotemplating and the Main Principle: Biotechnological Methods, as can be seen in Figure 16. The Main Principle: Interactive and Adaptive Systems accounted for the majority of submissions. However, their total scores skew toward the lower end, with only a few ideas achieving top evaluations. This suggests a high level of conceptual interest but limited maturity or feasibility in current implementations. The Main Principles Biotemplating and Biotechnological Methods, both exhibited a more equilibrated distribution of scores, encompassing both low and high-performing ideas. This balance indicates a broader range of development stages and potential for refinement.

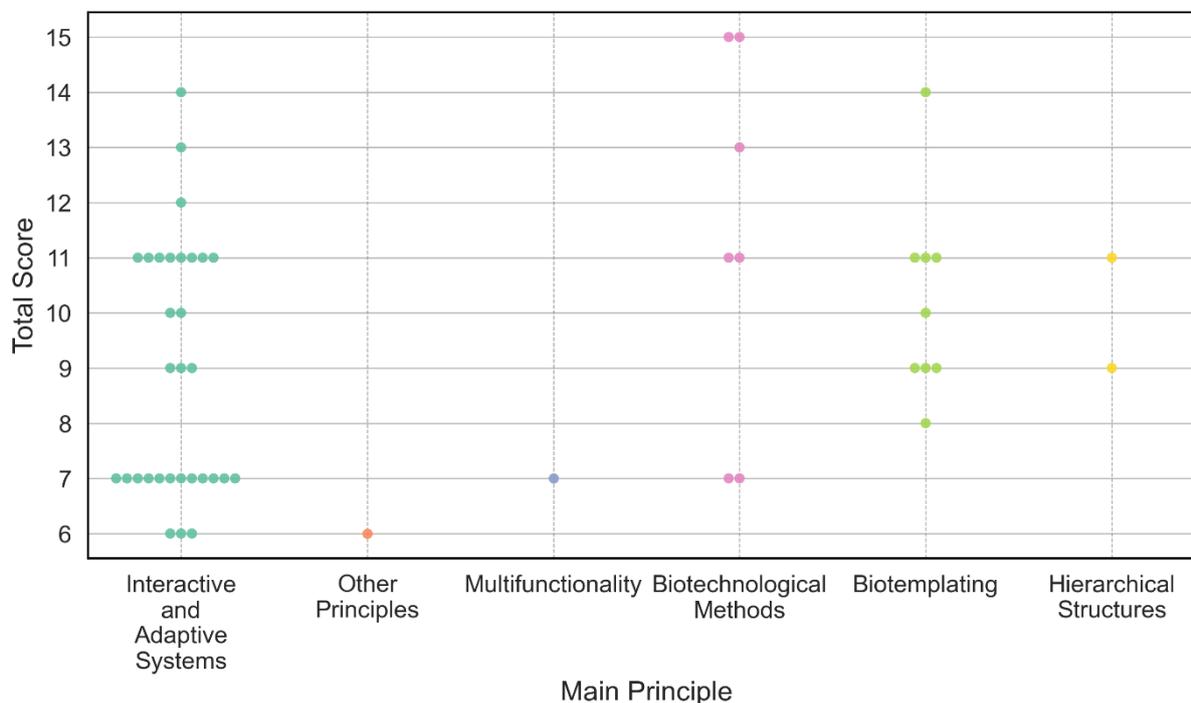


Figure 16: Distribution of ideas in **World café 2: Bio-Interfaces** by total evaluation score, categorized by **Main Principle**. Each dot represents an individual idea in that category.

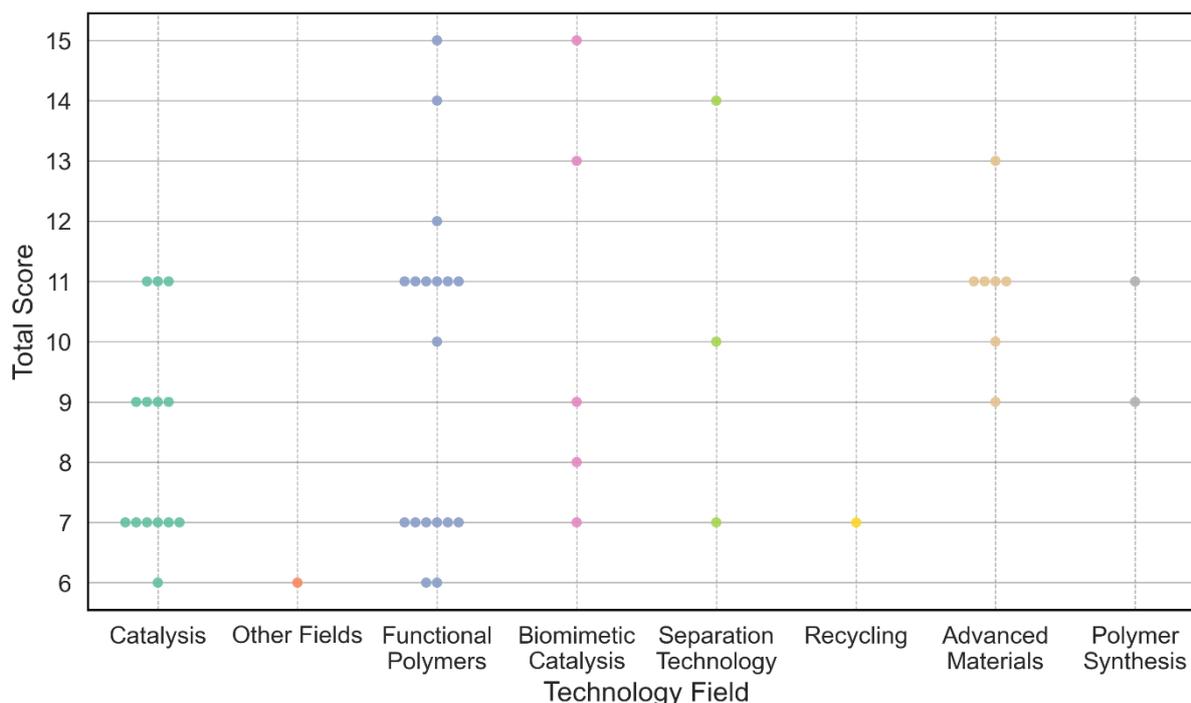


Figure 17: Distribution of ideas in **World café 2: Bio-Interfaces** by total evaluation score, categorized by **Technology Field**. Each dot represents an individual idea in that category.



Figure 17 depicts the distribution of the total score for all the Technology Fields. All defined Technology Fields were represented among the submitted ideas, with notable performance in specific areas. The highest total scores were observed in ideas associated with the Technology Field: Functional Polymers, Technology Field: Biomimetic Catalysis, and Technology Field: Separation Technology. Despite being represented by only five ideas, Separation Technology included several medium-scoring to high-scoring submissions. This concentration of high performance within a small sample size suggests significant potential and warrants further exploration.

### 5.3.5 Characteristics of Top-Rated Ideas

Table 3: Distribution of high-scoring ideas of **World café 2: Bio-Interfaces** across **Group**, **Main Principle**, and **Technology Field**. The Groups are color-coded: **Catalysis** (green), **Inorganic** (orange), and **Polymer** (purple).

World café 2: Bio-Interfaces	Bio-technological Methods		Biotemplating	Hierarchical Structures	Interactive and Adaptive Systems	Multi-functionality	Other Principles
Biomimetic Catalysis	1				1		
Catalysis			2		1		
Advanced Materials	1	1	1	1	1		
Polymer Synthesis	1						
Functional Polymers	1				8		
Other Fields							
Recycling							
Separation Technology			1				

An analysis of the top 20% highest-scoring ideas (21 in total), along with those just meeting the threshold score, reveals distinct thematic and technological trends within World café 2: Bio-Interfaces. The Main Principle: Interactive and Adaptive Systems was most frequently identified, particularly in combination with the Technology Field: Functional Polymers, indicating a strong alignment between adaptivity and advanced polymer technologies. The Main Principle: Biotechnological Methods also emerged, appearing across a wide range of

conceptual frameworks and linking to multiple Technology Fields. Furthermore, the Main Principle: Advanced Materials was found to span nearly all Technology Fields, underscoring its foundational role and broad impact in contributing to high-performance ideas in World café 2: Bio-Interfaces. Table 3 summarizes the distribution of the top-scoring ideas in World café 2: Bio-Interfaces.

## 5.4 Overview World café 3: Bio-Transition

### 5.4.1 Distribution across Groups, Main Principles, and Technology Fields

The distribution of Main Principles amongst the ideas generated in World café 3: Bio-Transition shows a broad thematic spread across all three groups of participants. The ideas of Group 1: Catalysis feature a balanced representation of all principles. This is in contrast to the ideas generated by Group 2: Inorganic, which focuses primarily on the Main Principles of Biotemplating and Interactive and Adaptive Systems. Ideas of Group 3: Polymer are dominated by the Main Principle: Biotechnological Methods, with additional contributions from the Main Principle: Interactive and Adaptive Systems. This varied allocation is visualized in Figure 18 and reflects the diverse conceptual approaches present in the ideas across disciplinary boundaries.

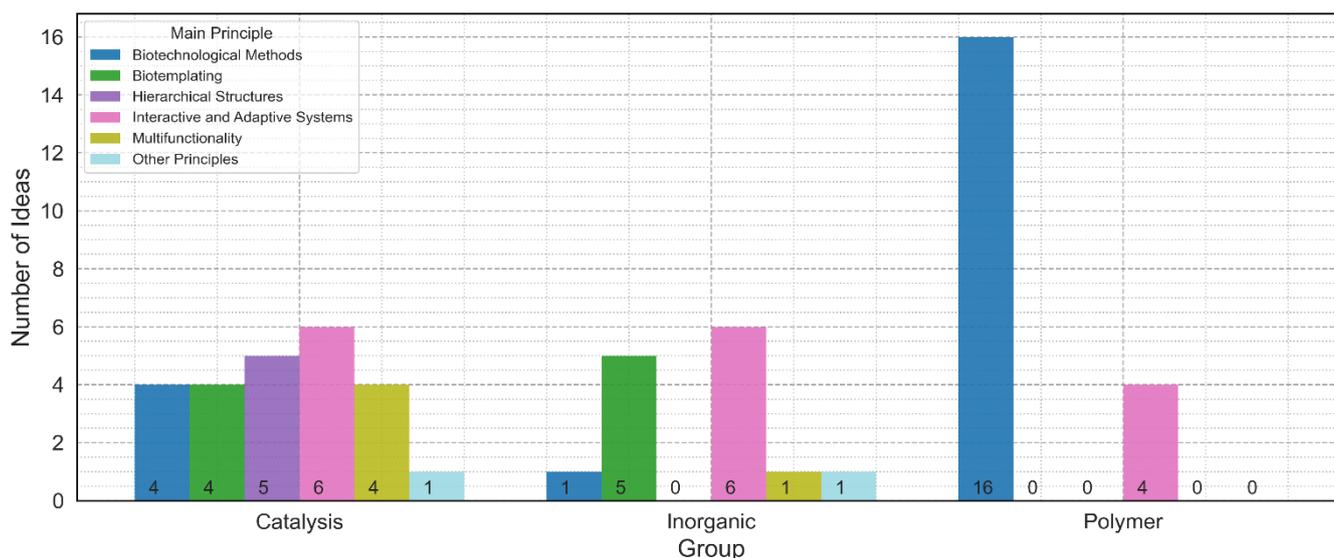


Figure 18: Number of ideas in **World café 3: Bio-Transition** categorized by **Group** and **Main Principle**.

The Technology Fields identified in the ideas generated in the Bio-Transition World café are distributed across all groups, with distinct focal areas. Ideas of Group 1: Catalysis emphasize the Technology Fields Biomimetic Catalysis and Catalysis, and also include the Technology Field: Separation Technology. Group 2: Inorganic generated ideas that are limited to the Technology Fields Advanced Materials and Recycling, while ideas of Group 3: Polymer are

almost exclusively associated with the Technology Field: Polymer Synthesis. The allocations, shown in Figure 19, illustrate the technological orientations of the ideas of each group without excluding any major category.

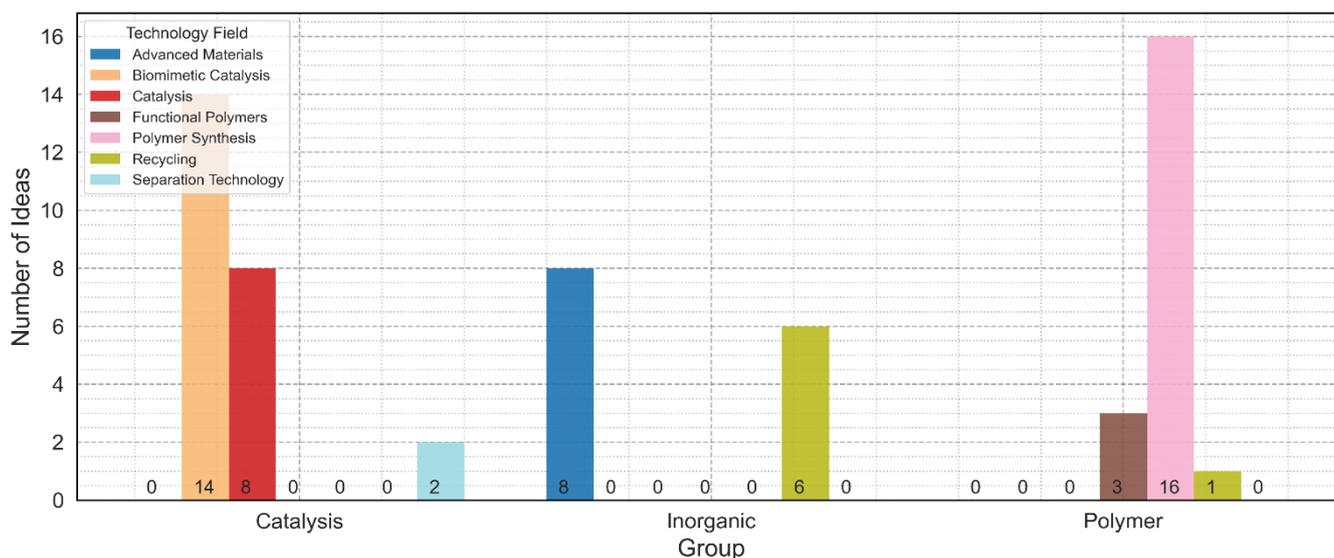


Figure 19: Number of ideas in **World café 3: Bio-Transition** categorized by **Group** and **Technology Field**.

### 5.4.2 Technology assessment of ideas by Group

The evaluation of average scores for the ideas reveals distinct patterns across the three disciplinary groups, which is shown in Figure 20. Ideas of Group 1: Catalysis and Group 2: Inorganic follow a consistent trend, with ideas typically rated highest for technical advantage (mode: 5), moderately for environmental advantage (mode: 1), and lowest for economic advantage (mode: 1). Ideas of both groups exhibit broad standard deviations in the ratings, indicating variability in individual assessments. In contrast, the Ideas of Group 3: Polymer show a different profile: the attribute environmental advantage receives the highest average score (mode: 5), while technical and economic advantages are rated lower (mode: 1). Here too, the standard deviations are broad, suggesting a wide spread of perceived value across submissions.

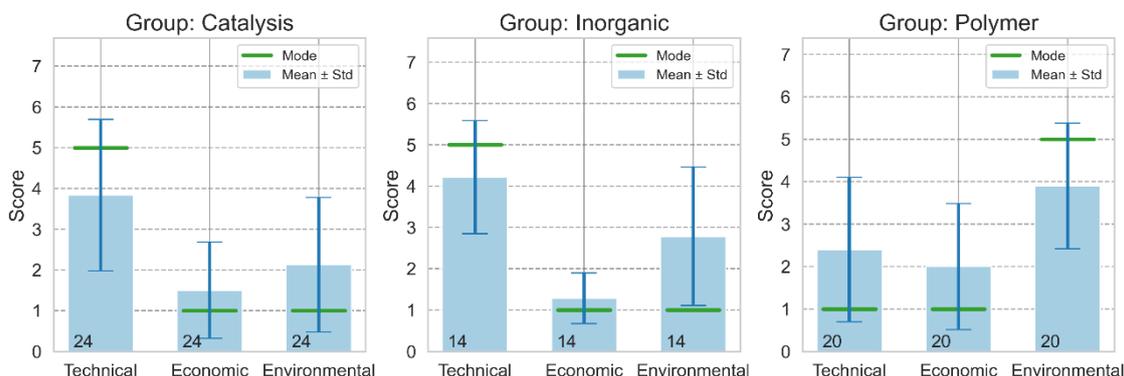


Figure 20: Average evaluation scores received in each evaluation category (light blue), standard deviation (blue), and mode (green) by **Group** in **World café 3: Bio-Transition**. The number of ideas in each Group is shown in the bottom left of each bar.

### 5.4.3 Technology assessment ratings

The overall distribution of evaluation scores for the ideas shows clear clusters of ideas that can be linked into underlying groups with similar features, which is shown in Figure 21.

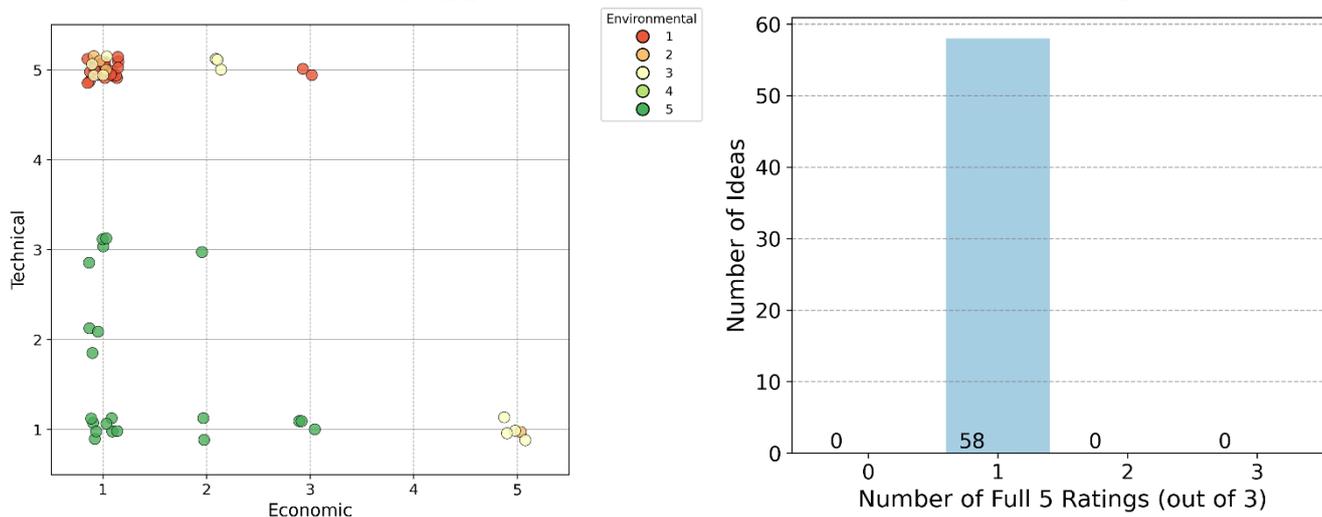


Figure 21: Evaluation score breakdown of the ideas in **World café 3: Bio-Transition**. Left: Score received in each category. Right: Number of ideas that received a maximum rating in zero, one, two, or three evaluation categories.

One cluster of ideas displays high technical, medium to low environmental, and low economic advantages. This pattern is identical in Group 1: Catalysis and Group 2: Inorganic, where technical feasibility remains the dominant strength. In contrast, there is a noticeable concentration of ideas emphasizing environmental advantage, often accompanied by medium to low technical and economic scores. This suggests a thematic focus on sustainability, albeit with trade-offs on technical maturity or economic viability. Most of these ideas stem from Group 3: Polymer. The grading approach appears to have been relatively strict, as only ideas that received full marks (score of 5) in at least one of the three evaluation criteria are present. No ideas scored zero, two, or three in any category, indicating a polarized scoring

pattern and a possible emphasis on identifying standout strengths rather than balanced performance.

#### 5.4.4 Technology assessment across Groups, Main Principles, and Technology Fields

The distribution of total scores for ideas across groups, seen in Figure 22, reveals distinct patterns. Ideas of Group 1: Catalysis are characterised by a predominance of lower-scoring ideas, with a few high-scoring outliers. In contrast, ideas of Group 2: Inorganic and Group 3: Polymer show a more even spread between high and low scores, with both groups exhibiting a slight top-heaviness, indicating a concentration of stronger ideas in the scoring.

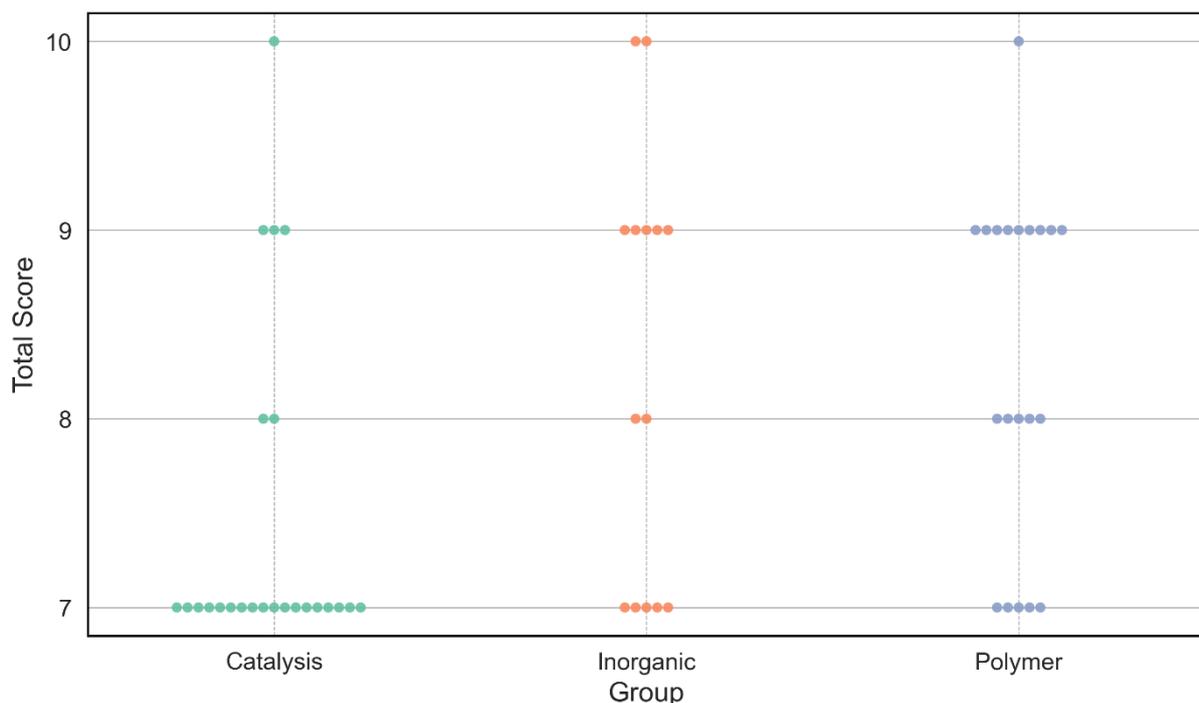


Figure 22: Distribution of ideas in **World café 3: Bio-Transition** by total evaluation score, categorized by **Group**. Each dot represents an individual idea in that category.

Among the Main Principles, the majority of ideas can be associated with the Main Principle: Biotechnological Methods and the Main Principle: Interactive and Adaptive Systems, both showing a balanced score distribution. Ideas with the Main Principle: Biotemplating, while present, tend to feature lower-scoring ideas, whereas the Main Principle: Multifunctionality displays a split profile, with ideas clustering at both ends of the scoring spectrum. The total score distribution is shown in Figure 23.

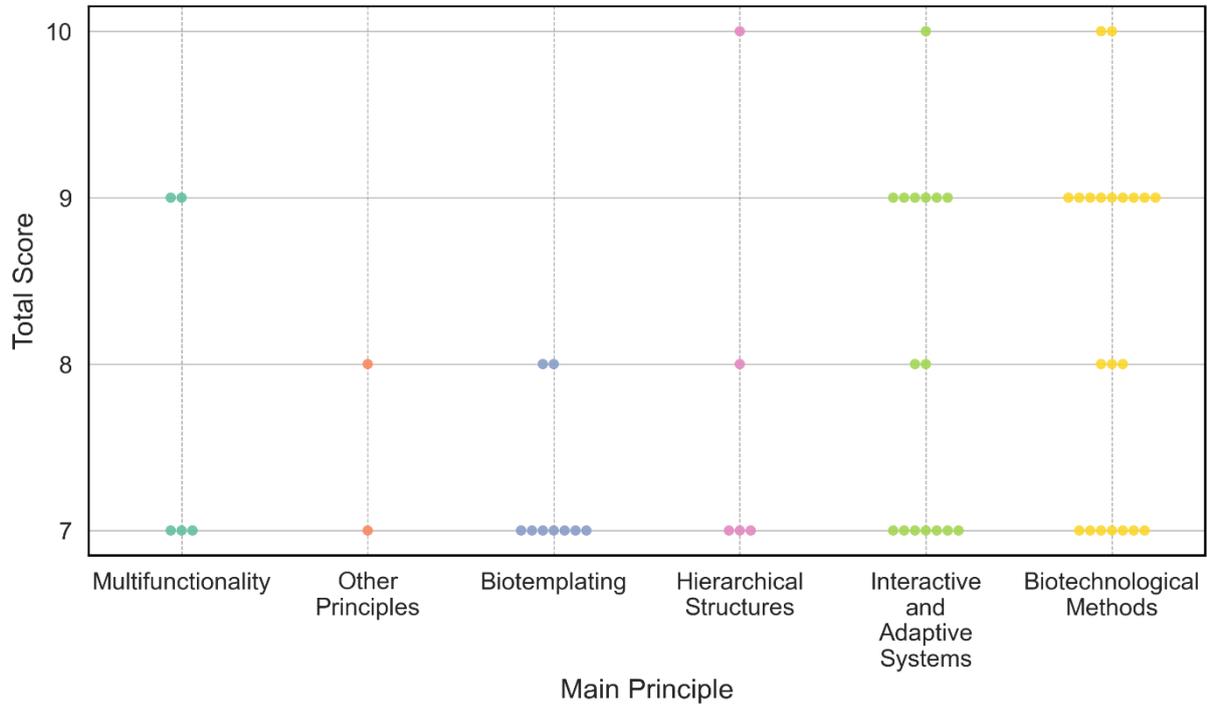


Figure 23: Distribution of ideas in **World café 3: Bio-Transition** by total evaluation score, categorized by **Main Principle**. Each dot represents an individual idea in that category.

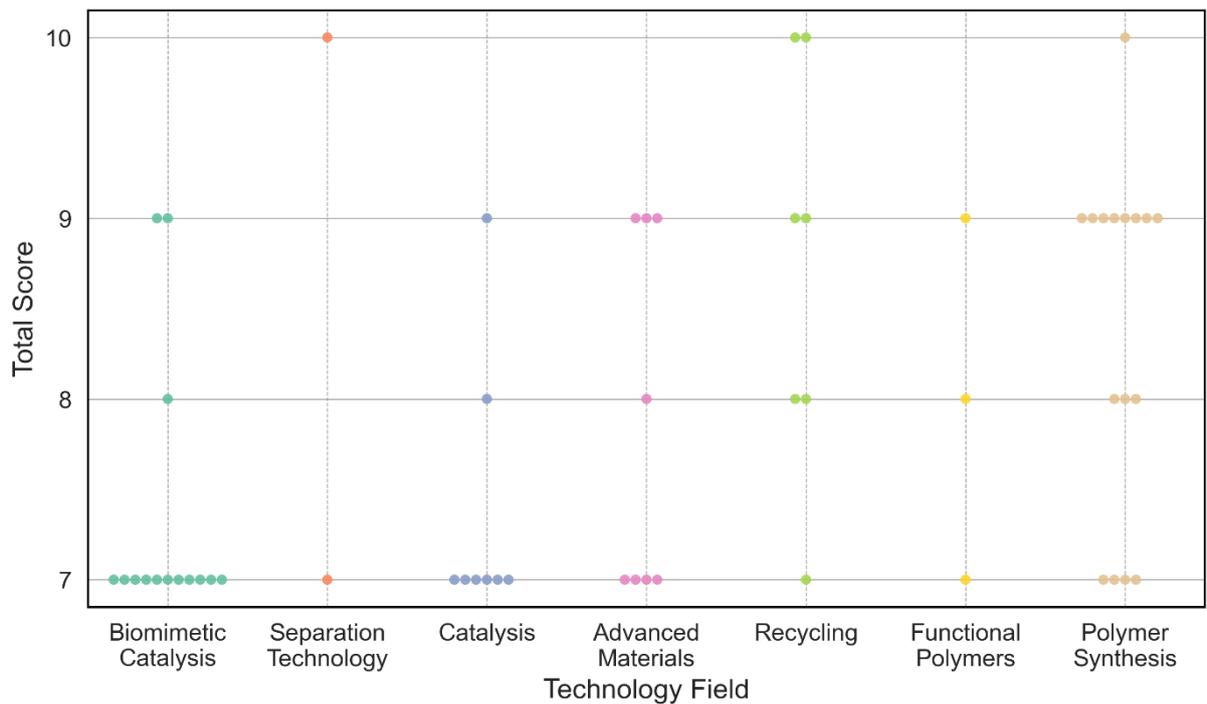


Figure 24: Distribution of ideas in **World café 3: Bio-Transition** by total evaluation score, categorized by **Technology Field**. Each dot represents an individual idea in that category.

In terms of idea rating according to the Technology Field, the Technology Field: Polymer Synthesis stands out with a high concentration of top-scoring ideas, while the Technology Field: Recycling is evenly distributed across the score range over the ideas. Ideas labelled with the Technology Field: Separation Technology show a distinct gap between high and low scores, though only a few ideas are available to formulate a robust conclusion. Ideas associated with the Technology Field: Biomimetic Catalysis generally feature lower scores, though it includes a few notable high-scoring outliers. Figure 24 displays the total score distribution for the ideas based on the respective Technology Field.

### 5.4.5 Detailed Characteristics of Top-Rated Idea

Table 4: Distribution of high-scoring ideas of **World café 3: Bio-Transition** across **Group**, **Main Principle**, and **Technology Field**. The Groups are color-coded: **Catalysis** (green), **Inorganic** (orange), and **Polymer** (purple).

World café 3: Bio-Transition	Bio-technological Methods	Bio-templating	Hierarchical Structures	Interactive and Adaptive Systems	Multi-functionality	Other Principles
Biomimetic Catalysis				1	1	
Catalysis	1					
Advanced Materials				2	1	
Polymer Synthesis	9					
Functional Polymers				1		
Other Fields						
Recycling	1			3		
Separation Technology			1			

An analysis of the top 20% of the highest-scoring ideas in World café 3: Bio-Transition (21 in total), including those meeting the threshold score, reveals an inclusive distribution across both the Main Principles and Technology Fields. All defined Technology Fields and all Main Principles, except the Main Principle: Biotemplating, are represented among the top-performing ideas, underscoring the wide applicability of bio-transition concepts. A recurring and promising combination of ideas is the Main Principles: Biotechnological Methods paired with the Technology Field: Polymer Synthesis, suggesting a strong alignment. Additionally,



ideas within the Main Principle: Interactive and Adaptive Systems, in conjunction with the Technology Field: Recycling, emerge as another high-potential area, reflecting the growing relevance of circularity and responsiveness in transition-oriented innovations towards a more circular economy. These findings highlight that while certain Main Principle–Technology Field pairings in ideas stand out, the overall diversity of high-scoring ideas points to a robust and multifaceted innovation landscape within World café 3: Bio-Transition. A summary of the top-scoring ideas of Word Café 3: Bio-Transition is shown in Table 4.

## 5.5 Summary of Top-Rated Ideas of all World cafés

While the analysis of top-scoring ideas, in terms of technology assessment, across the World café sessions provides valuable insights into thematic and technological trends that are anticipated to contribute to value creation, several methodological limitations must be acknowledged. The evaluation process was inherently subjective, with each World café being assessed by a different evaluator (World café leader), potentially introducing variation in scoring standards. To mitigate this, the top 20% of ideas from each session were analysed separately, idea by idea, ensuring relative comparability across differing grading baselines. With this approach, the aim was to reduce the inherent subjective character of the data analysis based on personal scores and draw more general conclusions on a text basis. Additionally, the uneven distribution of ideas across the Main Principles and Technology Fields presents a challenge for statistical interpretation, particularly in sparsely populated categories, where single high scores may disproportionately influence the perceived relevance. The dominance of certain Main Principles and Technology Fields discovered in the ideas may reflect not only conceptual maturity but also the underrepresentation of alternative approaches, limiting the generalizability of findings. Also, the research-driven background of all collaborators may have likely contributed to a stronger emphasis on technical feasibility and weakened the attention given to environmental and economic dimensions in the ideation. To more accurately assess the relevance and perceived merit of specific Main Principles and Technology Fields, we have therefore considered the percentage of ideas within each category that achieved top technology advantage scores, offering a normalized view that accounts for category size and helps to identify areas of concentrated excellence.

Out of 199 evaluated ideas, 61 were identified as top performers, representing the top 20% across all World café sessions. In total, this correlates to 30% of the whole ideas, yet due to several ideas having the same total score, more are recognized as the top performers. This subset includes ideas from every Main Principle, every Technology Field, and all three disciplinary groups, except for the residual other, indicating that each defined category has produced at least one high-impact concept. Notably, Group 2: Inorganic contributed the highest proportion of top-scoring ideas, suggesting a strong performance relative to its total submissions. Among the Main Principles, Biotechnological Methods led with 50% of its ideas achieving top scores, followed by Interactive and Adaptive Systems (31%), Multifunctionality and Biotemplating (both 22%), and Hierarchical Structures (14%). In terms of Technology Fields,



Polymer Synthesis ranked highest with 45% of its ideas in the top tier, though all were linked exclusively to Biotechnological Methods, indicating a high degree of specialisation. Advanced Materials followed with 42%, showing a broader distribution across several Main Principles, particularly Interactive and Adaptive Systems, but also appearing in other contexts. Separation Technology, despite being represented by only five ideas, achieved a 40% share in the top scorers, highlighting its potential. Recycling, Catalysis, and Functional Polymers contributed 29%, 28%, and 27% of their ideas to the top tier, respectively, predominantly in combination with Interactive and Adaptive Systems. Finally, Biomimetic Catalysis, while achieving only 17%, stands out as the only Technology Field represented by top-scoring ideas across all three groups, underscoring its cross-disciplinary relevance and integrative potential.

Table 5: Overview of high-scoring ideas from all **World cafés**, categorized by **Group**, **Main Principle**, and **Technology Field**, including total idea count and the percentage share of each **Main Principle** and **Technology Field**. The Groups are color-coded: **Catalysis** (green), **Inorganic** (orange), and **Polymer** (purple).

World cafés	Biotechnological Methods		Bio-templating	Hierarchical Structures	Interactive and Adaptive Systems		Multi-functionality	Other Principles	Total (% of)
Biomimetic Catalysis	1				1	1	1		4 (17%)
Catalysis	1		2		7	1			11 (28%)
Advanced Materials	1	1	1	1	10		1		15 (42%)
Polymer Synthesis	10								10 (45%)
Functional Polymers	1				14				15 (27%)
Other Fields									
Recycling	1				3				4 (29%)
Separation Technology			1	1					2 (40%)
Total (% of)	16 (50%)		4 (22%)	2 (14%)	37 (31%)		2 (22%)		61

## 6. Summary of the Analysis

The analysis of 199 evaluated ideas across biologisation-focused World café sessions identified 61 high-rated concepts (top 20%). These ideas span all major Main Principles, Technology Fields, and disciplinary groups, highlighting the broad applicability and innovation potential of biologisation approaches discussed during the workshop. Among the top-rated



ideas were self-healing systems, such as catalysts, coatings, and polymers, as well as bio-inspired concepts for direct CO<sub>2</sub> capture, cellular agriculture, and membrane-based cellular filtration. These ideas reflect a broad spectrum of innovative biologisation-driven solutions to contemporary challenges.

### 1. Summary of Main Principles in High-rated Ideas

**Biotechnological Methods:** Half of the ideas in this Main Principle received top scores in the evaluation categories. Notably, Biotechnological Methods emerged as a versatile component, appearing across every group and nearly all Technology Fields, though predominantly paired with Polymer Synthesis.

**Interactive and Adaptive Systems:** This Main Principle achieved a top-score rate of 31% and is represented across ideas of all groups. It is particularly associated with the Technology Fields Recycling, Advanced Materials, Catalysis, and Functional Polymers, indicating a strong interdisciplinary relevance and recurring thematic linkage.

**Multifunctionality & Biotemplating:** Both at 22%, showing emerging relevance.

**Hierarchical Structures:** 14%, indicating niche but promising potential.

### 2. Summary of Technology Fields in High-rated Ideas

**Polymer Synthesis:** For ideas associated with the Technology Field: Polymer Synthesis, a top-score rate of 45% was identified, exclusively paired with the Main Principle: Biotechnological Methods. This finding suggests that many new ideas show prospects in this specialized Technology Field.

**Advanced Materials:** With 42% of its ideas being high rated, this Technology Field holds a broad distribution of Main Principles. It appears especially often with the Main Principle: Interactive and Adaptive Systems.

**Separation Technology:** Although this Technology Field shows a comparatively lower overall representation, it achieved a notable top-score rate of 40%. Its emergence in the context of biologisation is particularly interesting, as the application of biologisation and bio-inspired concepts to Separation Technology appears to be a novel and underexplored approach. This suggests promising potential for future interdisciplinary research and innovation.

**Recycling, Catalysis, and Functional Polymers** each achieved top-score rates in the range of approximately 27–29%. These fields are predominantly associated with the Main Principle: Interactive and Adaptive Systems. This correlation suggests that the Main Principle: Interactive and Adaptive Systems demonstrates strong relevance across multiple Technology Fields and may contribute positively to the perceived merit of ideas, as reflected in their scoring outcomes.



17% of the ideas in the Technology Field: Biomimetic Catalysis were evaluated with a top-score, placing it below other high-performing Technology Fields extracted from the group of ideas. However, it stands out methodologically as the only Technology Field represented across all three participant groups (Group 1: Catalysis, Group 2: Inorganic, Group 3: Polymer). This widespread adoption and presence suggest a high potential for cross-disciplinary integration and relevance within diverse research contexts.

### 3. Top-Performing Combinations of Main Principles and Technology Fields

Biotechnological Methods and Polymer Synthesis show a high degree of accumulation within ideas originating from Group 3: Polymer. Notably, all high-rated ideas related to Polymer Synthesis are categorised under Biotechnological Methods. This indicates a strong methodological overlap and highlights the relevance of biotechnological approaches in polymer-focused innovation concepts.

The Main Principle: Interactive and Adaptive Systems demonstrates broad applicability across multiple Technology Fields and participant groups. Not surprisingly, the Technology Field: Catalysis is the main representative for Group 1: Catalysis, showing the potential merit of biologisation within catalytic systems. The ideas within Group 2: Inorganic, show a strong alignment with the Technology Fields Advanced Materials and Recycling, indicating a thematic focus on material responsiveness and circularity. In Group 3: Polymer, Interactive and Adaptive Systems appear in combination with Functional Polymers, suggesting its relevance for dynamic and functional material systems. These recurring associations across distinct Technology Fields and disciplinary groups underline the integrative potential of Interactive and Adaptive Systems in biologisation-oriented innovation.

## **7. Data Basis and Links**

All supplementary data is given under [Additional data for the Whitepaper "Biologisation and Bio-Inspiration in Materials Science and Process Chemistry" - Single publications](#) in the NFDI4Cat Central Data Repository.

Additionally, the defined needs of the respective groups are given in Table 6, Table 7 and Table 8.

Table 6: Needs of the Group **Catalysis**.

<b>Overarching Topic</b>	<b>Potential Realisation</b>	<b>Need - Technical Target Corridor</b>
biologically inspired interfaces for selective and active heterogeneous catalysis	chemically bound surface ligands as inductors	new concepts for protein enzyme mimics (activity and selectivity enhancement)
biologically inspired interfaces for selective and active heterogeneous catalysis	chemistry in compartments or micelles	new concepts for catalysis in confined spaces (activity and selectivity enhancement)
new concepts for enzyme immobilisation	heterogenisation of bio-molecules active as catalysts	new concepts - versatile support systems - low-cost systems
transfer of concepts of bio-mineralisation to inorganic functional materials	stabilisation of heterogeneous catalysts through bio-mineralisation concepts	new versatile concepts for enhancement of mechanical stability of heterogeneous catalysts
self-healing and self-cleaning of heterogeneous catalysts	nature analogous self-cleaning and self-healing	new concepts for longer-lived catalysts - new concepts for the regeneration of catalysts
biologically inspired catalysts and catalyst-supports for the synthesis of chiral compounds	nature as example for the synthesis of enantiomerically and diastereomerically pure products	new concepts for heterogeneous catalysts with novel functionalities
use of heterogeneous catalysts as electrodes to directly couple electricity into fermentation processes	analogy to NAD/NADH: fermentation under direct use of electricity	new concepts for electrocatalysis
bio-inspired membranes for product separation in combination with heterogeneous catalysis or electro catalysis	Selective membranes for complex separations coupled to reactions	new concepts in heterogeneous catalysis and electro catalysis, separation of complex mixtures during reaction, shifting of equilibria through continuous separation

Table 7: Needs of the Group **Inorganic**.

<b>Overarching Topic</b>	<b>Potential Realisation</b>	<b>Need - Technical Target Corridor</b>
inorganic and hybrid materials which are safe and sustainable by design	re-design inorganic and hybrid functional materials	non-nano, non-microplastic-containing, non-toxic inorganic or hybrid functional materials
hybrid (organic - inorganic) materials that do not produce or release microplastic during and after their lifetime	re-design inorganic and hybrid functional materials - develop new coating strategies	non-nano, non-microplastic-containing, non-toxic inorganic or hybrid functional materials
inorganic raw materials based on recycling / recycling-based recovery of inorganic raw materials	new bio-inspired recycling processes	cost-efficient, low emission and scalable bio-inspired recycling and urban mining for inorganic (raw) materials
non-precious metals based on recycling / recycling-based recovery of non-precious metals	new bio-inspired recycling processes	cost-efficient, low emission and scalable bio-inspired recycling and urban mining for inorganic (raw) materials
cost effective metal-recycling of black mass	new bio-inspired recycling processes	cost-efficient, low emission and scalable bio-inspired recycling and urban mining for inorganic (raw) materials - particularly black mass
new adsorbents (inorganic - hybrid) for CO <sub>2</sub> -capture	bio-inspired inorganic and hybrid materials for efficient CO <sub>2</sub> -capture and release	cost and energy efficient CO <sub>2</sub> -capture materials
self-healing inorganic functional materials	bone and skin inspired inorganic materials, surfaces and coatings	cost-efficient production and sustainable use of self-healing surfaces and components
transfer of concepts of bio-mineralisation to industrial production of inorganic functional materials	stabilisation of specific crystalline phases or mesophases	new concepts for the targeted synthesis of inorganic phases under mild conditions

biologically inspired selective junction of layered materials to bulk materials	targeted structuring and synthesis of thin inorganic layers	new concepts for surface modification, protection or transformation
biologically inspired interfaces for inorganic synthesis	synthesis of materials in micelles	new concepts for the synthesis of highly defined particles

Table 8: Needs of the Group **Polymer**.

<b>Overarching Topic</b>	<b>Potential Realisation</b>	<b>Need - Technical Target Corridor</b>
new and alternative processes for polymer production	autonomous self-regulating processes for polymer synthesis	flexible and low energy processes based on fluctuating energy and raw material input
fermentation as production process for polymers	new fermentation processes	cost-efficient and scalable fermentation
fully circular polymer materials	example: structural colours in nature through refractory properties of nanoscopic crystals	materials with tuneable properties also suitable for full circularity based on non-fossil raw materials
fully circular polymer materials	hierarchical materials design based on only building blocks leading to a plurality of properties	materials suitable for full circularity based on non-fossil raw materials
self-healing polymers and composite materials	nature analogues self-healing - vitrimers or thermoplastic composites	new concepts for durable composite materials - composite materials that withstand stronger fluctuations of conditions (temperature, light, atmosphere, ...)
use of lignin for corrosion protection	derivatisation of lignin	bio-based raw materials for corrosion protection
functional polymers of non-fossil origin	sequence controlled synthesis of bio-based and degradable polymers	bio-based and degradable functional polymers based on renewable raw materials

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