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2023 The 1st National Competition of “Bloomag Cup” in CO_2 capture, conversion, and utilization

A B S T R A C T

The inaugural National Competition for Carbon Dioxide Capture, Conversion and Utilization Innovation (“Bloomag Cup”) was successfully held on July 30, 2023 in Beijing. This competition was initiated by Professor Tianwei Tan and Prof. Yongqin Lv from Beijing University of Chemical Technology (BUCT), and jointly organized by BUCT and Chongqing University. The competition is slated for annual recurrence, with a rotational hosting arrangement involving various academic institutions. The ongoing competition underscores the primacy of pioneering and exploratory facets inherent to technological innovation. Its principal objective is to catalyze the development of foundational and cutting-edge technological competencies within the realm of CO_2 capture, conversion, and utilization. The overarching goals encompass identifying promising technological breakthroughs, fostering emerging talent in scientific and technological innovation, facilitating high-quality sustainable economic growth within China, and actively contributing to global efforts towards peak carbon emissions and achieving sustainable development goals for humanity. This inaugural Bloomag Cup saw wide participation from students and researchers, generating fruitful discussions that advance the nascent field. It is hoped this competition will continue cultivating solutions that help mitigate anthropogenic climate change through innovative carbon dioxide technologies.

1. The strategic significance of coordinating national efforts in carbon dioxide mitigation technologies

In accordance with the 2015 Paris Agreement, a consensus was reached among a majority of nations worldwide to embrace diverse strategies aimed at significantly mitigating greenhouse gas emissions. Notably, carbon dioxide (CO_2) comprises the predominant share of emissions contributing to anthropogenic climate change. As the primary byproduct of fossil fuel utilization, CO_2 presents opportunities for emissions reductions across its lifecycle when leveraged as a renewable carbon resource for chemical and fuel synthesis. In the context of China’s strategic objectives around “carbon peaking” and “carbon neutrality”, researching highly efficient CO_2 utilization technologies has emerged as a critical avenue for addressing energy and environmental challenges on a global scale.

To catalyze innovation supporting these priorities, the 1st National “Bloomag Cup” Competition for CO_2 Capture, Conversion and Utilization was jointly organized by Beijing University of Chemical Technology and Chongqing University from April to July 2023 under guidance from relevant professional committees, Biochemical Professional Committee of Chemical Industry and Engineering Society of China, C1 Biotechnology Professional Committee of Chinese Society of Biotechnology, Chemical Engineering Professional Committee of Chemical Industry and Engineering Society of China, and Popularizing Science Committee of Chinese Society of Biotechnology. Spanning four months, the competition culminated in the successful finals held in Beijing on July 30th. Through nurturing emerging talents, the competition aims to advance high-quality sustainable development in China and promote transformative technological solutions. By fostering collaborative international efforts, it aspires to meaningfully contribute to the global pursuit of peak emissions and carbon neutrality in line with the Paris Agreement’s goals. The competition’s inaugural success lays a foundation for continued progress in developing foundational CO_2 technologies.

2. The opening ceremony

In the opening remarks at the inauguration ceremony (Fig. 1), Professor Tianwei Tan, President of Beijing University of Chemical Technology and Academician of the Chinese Academy of Engineering, highlighted how the bio-technological approach to CO_2 conversion, driven by green principles, has introduced pioneering frontiers for cultivating a low-carbon economy. This fundamental redefinition of energy conservation and emissions mitigation paradigms, he explained, positions the field as critically important for augmenting industrial sustainability and advancing socioeconomic viability. Expressing optimistic vision, Prof. Tan invited researchers and industry experts in biochemical engineering to leverage the “Bloomag Cup” competition as a catalyst for accelerating bio-technological innovation. He called on participants to actively contribute to attaining the carbon emission goals and engage fervently in the pursuit of environmentally sustainable, low-carbon, and high-quality economic development. Through his inspirational address, Prof. Tan aptly framed both the strategic importance and immense promise of the collaborative, cross-disciplinary work to be undertaken over the competition’s inaugural months. His framing set the stage to drive impactful progress on the technological frontlines of the “Dual Carbon” strategy.

Under the theme “Technology-Driven Visioning for a ‘Carbon’ Future,” the “Bloomag Cup” Competition is founded on principles of disruptive, forward-looking exploration and innovation. With a nationwide call, it issues a diverse taxonomy of technology-driven projects focused on strategically important CO_2 capture, conversion and use. The competition’s core is fundamental research and development of emerging techniques in these domains. Teams are encouraged to independently propose research topics, promoting novel and inventive methodologies. A wide array of technical arenas are encompassed, including separation and capture of single-carbon gases, synthetic carbon fixation cell fabrication, establishment of multi-enzyme catalytic

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Fig. 1. Prof. Tianwei Tan delivering the opening speech at the inauguration of the 1st National “Bloomag Cup” Competition for CO_2 Capture, Conversion, and Utilization.

carbon fixation systems, theories to enhance and control industrial biocarbon processes, bio-chemical coupling techniques, artificial intelligence and data-driven carbon fixation guidance, carbon fixation efficiency assessments, carbon fixation industrial equipment, engineering approaches for carbon fixation products, and various allied technologies. By bringing together diverse perspectives and problem-solving approaches, the “Bloomag Cup” competition aims to advance the frontiers of carbon technologies through an spirit of collaborative innovation.

Project submissions are divided into two tracks: “Technology Projects” and “Social Investigation Reports.” The “Technology Projects” track encompasses physical demonstrations including models, experiments, software, and designs. It encourages forward-leaning exploration and visioning informed by, but extending beyond, the current technological frontier. The aim is to uncover innovative solutions and pathways through pioneering approaches. The “Social Investigation Reports” track features reports stemming from social practice investigations and industry analyses. These reports predominantly consist of research objectives, methodologies employed, scopes of investigation, and data analysis components. They provide insights into real-world contexts, stakeholder needs, implementation considerations, and other social dimensions important for positioning promising technologies on trajectories towards meaningful applications and impact. By fostering both tech-centric and application-focused work, this dual-track structure aims to stimulate a comprehensive, interdisciplinary and collaborative approach to advance carbon technologies for a sustainable future.

The inaugural “Bloomag Cup” competition elicited an enthusiastic response from innovators across the country. In total, over 240 submissions were received involving the collaborative efforts of more than 1000 individuals tackling important challenges at the intersection of carbon management and sustainable development. All submissions first underwent an initial online review. Projects exhibiting particularly promising approaches and third-tier recognition or beyond were then identified for further evaluation. Through a rigorous final assessment process, select projects emerged that most meaningfully pushed boundaries or addressed needs. These included those bestowed the Grand Prize, First Prize, and Second Prize distinctions.

Spanning fundamental research and applied demonstrations, the award-winning projects collectively represented the full breadth of carbon capture, conversion and utilization technologies under examination. Their diverse yet complementary contributions validate both the urgent need and immense promise of these interdisciplinary solution spaces. By facilitating such a vibrant exchange of novel concepts and collaborative efforts, the inaugural “Bloomag Cup” competition has energized further progress along diverse innovation trajectories that could help maximize carbon’s value while minimizing its impact on our climate and shared environment.

3. The technology of carbon dioxide capture

The foundations of flue gas treatment and carbon separation span back decades, with early work detailing temperature swing absorption garnering particular influence. However, intensifying climate change drivers in recent years have dramatically amplified focus on, and funding into, refining capture platforms suitable for deployment at coal and industrial scales. Across solution spaces, amine-based absorption processes remain a primary focus in scientific communities and test facilities worldwide due to their current dominance in definition of baseline solvent performance.[1–4] Intensive computational and experimental streams have established detailed kinetics and mechanisms, informing optimization efforts targeting next-generation formulations. Meanwhile, alternative materials like metal-organic frameworks, covalent-organic frameworks, carbonic anhydrase mimics, and membrane separation represent vanguard directions with potential for transforming economics,[5–16] though more applied work remains crucial to demonstrate industrial maturity.

In pursuit of CO_2 capture technology, a team from Tsinghua University has developed a multi-source coupled Organic Rankine Cycle System for Power Generation (OCCS) (Fig. 2). This innovative system is grounded in the principles of harnessing waste heat from flue gases and leveraging osmotic energy to facilitate the capture of CO_2 through hydrate carbon capture technology. The OCCS system is structured into several integral modules, encompassing flue gas initial treatment, waste heat power generation, as well as desulfurization and denitrification mechanisms, harmoniously coupled with osmotic power generation. The system further includes a module for hydrate-based carbon capture, followed by CO_2 transfer, utilization, and storage. In terms of energy supply, the hydrate-based carbon capture process derives its energy from the efficient utilization of waste heat and the osmotic power generation mechanism. Regarding exhaust gas treatment, the system sequentially eliminates pollutants such as SOx, NOx, VOCs, and other contaminants. It then proceeds to capture CO_2 through the hydrate process, culminating in the subsequent phases of CO_2 transfer, utilization, and storage. This project integrates waste heat power generation, osmotic power generation, and innovative hydrate-based carbon capture technology, embodying sophisticated design concepts. It is important to note that preliminary model-based experimental research has already been undertaken, yielding promising results for the project's development and feasibility.

In response to the challenges associated with achieving regulatory-compliant treatment for high-concentration organic wastewater containing phosphorus, high-value utilization of straw and sludge, and CO_2 capture and conversion, a team from Xuzhou University of Technology has devised a technology that involves the co-pyrolysis of phosphorus-iron sludge and straw to produce biochar for CO_2 capture. This multifaceted technology comprises three principal components: the purification of high-concentration phosphorus wastewater, the co-pyrolysis of straw and phosphorus-iron sludge for biochar production, and the subsequent adsorption of CO_2 by the biochar.[17] Notably, this technology attains a phosphorus removal efficiency of 94 % and endows the biochar with a CO_2 capture capacity of 114 mg g^{-1}. The primary innovation of this approach stems from the synergistic activation of sludge and straw, resulting in enhanced adsorption capabilities of the co-pyrolyzed biochar for CO_2. Consequently, this project not only addresses the challenge of treating high-concentration organic wastewater containing phosphorus in compliance with regulations but also facilitates the high-value utilization of straw and sludge waste. It holds significant promise for practical applications and exhibits considerable potential for widespread adoption.

Addressing prevailing efficiency and regeneration energy shortcomings, a team from Beijing Institute of Technology employed a rigorous dual-strategy comprising optimized amine solvent selection as well as an intelligent control framework. Their meticulous experimental program systematically honed amine combinations exhibiting high capture capacities coupled with reduced energy needs. Implementing integrated optimizations then diminished operational costs by 20 % versus conventional systems. Moreover, their integrated artificial intelligence control architecture empowers human-machine cooperation and dynamic parameter modulation. It lays groundwork for advancing carbon capture towards true industrial intelligence. By thoroughly exploring solvent chemistry while creating an adaptable technical support platform, this initiative exemplifies how principles from diverse fields can synergize to overcome longstanding technology barriers.

In the field of CO_2 capture material development, a team from Tianjin University has successfully synthesized a material with the capability to directly absorb and utilize solar energy for the capture and subsequent conversion of CO_2 into synthesis gas (composed of CO and H_2). This pioneering advancement allows for the direct harnessing of solar energy for CO_2 capture, resulting in the production of synthesis gas and ultimately achieving a net-negative greenhouse gas emission process. The manufacturing process for this material is uncomplicated and well-suited for large-scale commercial production. Leveraging the foundation of existing industrial calcium looping CO_2 capture technology, the team has integrated it with methane dry reforming while

Fig. 2. Academicians Yingjin Yuan and Guanghui Ma presenting the award to the first prize-winning team.

introducing solar energy through enhanced equipment. This integration facilitates the substitution of calcium-based absorbents with the materials developed in this project, enabling solar-powered CO_2 capture and synthesis gas production. Another team from Zhejiang Sci-Tech University has undertaken the design and synthesis of novel metal-organic framework materials possessing a remarkable CO_2 adsorption capacity of up to 60 $cm^3\ g^{-1}$. In contrast, the adsorption capacity for acetylene is only 2 $cm^3\ g^{-1}$, underscoring the material's high selectivity for CO_2 over C_2H_2 separation.

4. The technology of carbon dioxide conversion and utilization

Once captured, effectively utilizing CO_2 represents an important pathway forward. Its conversion to high-value fuels and chemicals like carbon monoxide, methane and formic acid can help maximize carbon's value while minimizing atmospheric impacts. Current catalytic conversion technologies for CO_2 encompass thermal catalytic hydrogenation,[18,19] photocatalytic conversion,[20–24] electrocatalytic conversion[25,26] and biocatalytic approaches.[27–29] Among these, electrocatalytic reduction offers advantages such as rapid reaction kinetics under mild conditions. Biocatalytic methods leverage biotechnology to transform CO_2 into valuable end products, achieving efficient carbon utilization. Direct microbial conversion of CO_2 into fuels and chemicals via what has been termed "third-generation biorefinery" shows particular promise.[30] By serving as a feedstock for microbial synthesis, this approach realizes CO_2 reduction potentials while generating useful outputs. It thus presents a crucial avenue toward carbon neutrality objectives through innovative carbon recycling frameworks. Advancing such technologies maintains strategic importance as the means continue evolving for society to thrive within planetary boundaries.

The project entry from Beijing University of Chemical Technology exhibits cutting-edge research developing a third-generation biorefinery platform. Through targeted modification of three microbes, the team has enabled utilization of one-carbon substrates.[31–33] Studying *Saccharomyces cerevisiae*, their work coupling CO_2 and formate demonstrates enhanced fatty acid production from renewable one-carbon feedstocks. Investigation of *Yarrowia lipolytica* yielded an insightful bio-electrocatalytic system efficiently generating high-value long-chain biofuels from CO_2 and electricity. Meanwhile, initial efforts utilizing *Escherichia coli* aim to establish a formate-reliant strain. By reconstructing multiple organisms and hybrid systems, this entry represents pioneering innovation at the forefront of carbon cyclic biomanufacturing. It holds promise for advancing both scientific understanding and eventual industrial applications. Projects embracing such a collaborative, multi-pronged design philosophy are uniquely positioned to yield meaningful insights and accelerating progress in this critical field.

Nanjing Tech University researchers exhibited astute synthetic biology application through their engineered *Escherichia coli* platform. By optimizing heterologous pathway expression and energy flux, the team enhanced CO_2 fixation around the crucial RuBisco enzyme. Innovative design incorporated decarboxylase and carboxylase complexes to concentrate carbon dioxide, maximizing recovery. Methodically addressing such design constraints reflects their sophisticated understanding. Significantly, demonstrating in situ fixation in yeast models likewise improved process atom economy for biomanufactured products. These comprehensive efforts underscore both scientific merit and practical industrial potential.

Overcoming limitations in current carbon fixation approaches is paramount for enabling efficient CO_2 utilization at scale. Addressing issues like sluggish capture kinetics, energy constraints, and product selectivity will require groundbreaking solutions. In this spirit, researchers at the Chinese Academy of Sciences Tianjin Institute of Industrial Biotechnology devised an insightful chemical-biological hybrid system. By integrating CO_2 hydrogenation, enzymatic catalysis and synthetic microbial production, it presents an end-to-end conversion route generating sophisticated polymers directly from carbon dioxide. Splitting the process into specialized modules leveraging the innate strengths of both biotic and abiotic methodologies reflects nuanced technological design. This multi-step environmental carbon recycling framework warrants further exploration given its potential contributions toward realizing the low-carbon future. Additionally, microalgae demonstrate a natural proficiency for carbon capture while doubling as a biomass feedstock. Developments harnessing solar energy and low-cost carbon sources via microalgal co-cultivation similarly hold special strategic significance. They present an auspicious avenue for accomplishing "dual carbon" objectives through sustainable industrial bioengineering platforms. Innovations like these compelling examples underscore how disruptive thinking and collaborative solution spaces can help accelerate progress on complex global challenges.

A project from the Chinese Academy of Sciences Qingdao Institute of Bioenergy and Bioprocess Technology merits recognition. Through meticulous metabolic engineering and multi-species cultivation design, the team elicited new discoveries. By co-developing precision-engineered copper clusters alongside the diatom *Thalassiosira pseudonana*, their approach achieved a vital synchronization of the cellular redox state. This balanced redox poise served to elevate carbon capture alongside oxygenic photosynthesis under concentrated carbon dioxide conditions. Addressing photosynthetic inhibition challenges plaguing microalgal cultivation at industrial scales, their coupled biotechnological framework substantively lifted carbon fixation, oxygen evolution and microalgal growth efficiencies.

Microbial electrosynthesis represents an effective approach for the sequestration and transformation of CO_2 into organic compounds, offering distinct advantages including the ready availability of feedstocks, mild operational conditions, absence of toxic substances, and environmental sustainability. A team from Beijing University of Chemical Technology has made substantial advancements in enhancing succinate production within *Escherichia coli*, an electroactive microorganism. This achievement is attributed to the augmentation of cofactor NAD^+/NADH levels and the meticulous regulation of the succinate biosynthesis pathway, thus presenting a novel and viable route for the conversion of CO_2 into high-value products. Applying the principles of a bio-chemical coupling, researchers at the Qingdao Institute of Bioenergy and Bioprocess Technology, Chinese Academy of Sciences, have introduced an innovative strategy for de novo starch synthesis from CO_2, achieved through CO_2 electrocatalysis coupled with heterotrophic fermentation in microalgae (Fig. 3). The successful realization of this work holds substantial reference value for the field of catalytic conversion and the high-value utilization of CO_2.

Precisely and swiftly evaluating the carbon sequestration advantages, environmental consequences, and commercial viability of innovative low-carbon processes poses a pivotal challenge in the contemporary domain of CO_2 utilization technologies. A team from Xi'an Jiaotong University has devised LATTE, a software tool that facilitates the appraisal of whether novel processes or technologies fulfill the dual criteria of being low in carbon emissions, environmentally benign, and economically feasible. LATTE encompasses two primary modules: one devoted to assessing carbon sequestration benefits and environmental impacts, and the other focused on technical and economic feasibility analysis. This initiative draws upon process simulation data covering parameters like process quality, energy balance, and carbon sequestration potential. It then undertakes multi-faceted evaluations of the technical, economic, and environmental implications of different CO_2 capture, conversion, and utilization pathways. Specifically, the initiative assesses feasibility and impacts relating to factors such as carbon abatement achieved, life cycle emissions footprint, and cost competitiveness.

5. Summary

This inaugural "Bloomag Cup" competition has successfully

Fig. 3. Academicians Tianwei Tan and Yingjin Yuan presenting the award to the first prize-winning team.

convened leading scientists, scholars and engineers from top universities, research bodies and innovative firms. Facilitating convergence across cutting-edge CO_2 technologies and insights, it meaningfully advanced discussion among stakeholders in sustainable carbon solutions and biotechnology. By fostering knowledge exchange pertaining to carbon capture, conversion and use, the competition significantly contributed to the strategic mission of peak carbon emissions and carbon neutrality. Insights emerging from collaborative submissions have the potential to inform tangible progress. Moreover, bringing diverse perspectives together in one forum energized a well-rounded discourse and nurtured cross-disciplinary thinking around this complex challenge. New research networks and trajectories have doubtless been stimulated. The conveners, scientific committees and secretariat are commended for superbly conducting the myriad logistics of this undertaking amid a shifting research landscape. Their efforts have laid a strong foundation for continued progress. Looking ahead, the next iteration of the competition scheduled for 2024 rightfully elicits our eager anticipation. Strengthening such initiatives over time will remain integral to cultivating the leadership in building a sustainable and prosperous future for all.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Yongqin Lv is an Editorial Board Member for Biotechnology Notes and was not involved in the editorial review or the decision to publish this article.

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