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Solar-driven catalytic platforms for closed-loop carbon cycling: CO_2 assisting biomass conversion

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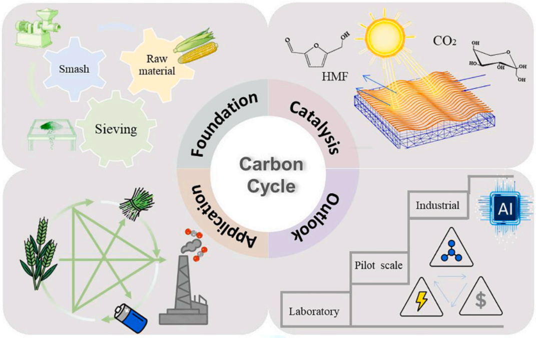
GRAPHICAL ABSTRACT



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ABSTRACT

The high-value utilization of biomass materials has emerged as a research hotspot, yet the underlying mechanisms and selectivity regulation of photothermal synergy conversion remain underexplored, especially for the CO_2 coupling with biomass molecular conversion. Sugar-based molecules, serving as critical renewable resources, have achieved large-scale applications. Based on the strategy of high-quality development around the world, this review systematically intends to conclude the high-value transformation pathways of biomass-derived materials (particularly sugar) coupled with CO_2, delving into the various product (solid, liquid, and gas) transformation features during photothermal catalysis have been explained. Through comparative solid product, this study thoroughly examines the conversion mechanisms of biomass molecule, selectivity regulation, and processes from intermediate product evolution to key species generation. Additionally, by analyzing the characteristics of different biomass resources and their market application potentials, this work provides theoretical

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and practical implications for closed-loop carbon cycles and low-carbon chemical industrial park development, driving renewable energy transitions from a 'linear economy' to a 'circular economy' via photothermal catalytic coupling of biomass and CO_2.

1. Introduction

Under the dual pressures of continuously rising global energy demands and surging carbon emissions, excessive reliance on traditional fossil fuels has intensified the greenhouse effect (Hassan et al., 2024). National strategic priorities in China are shifting toward "broad agriculture-new materials-smart chemical engineering-green catalysis" (Yu et al., 2024). Biomass holds great potential as a renewable carbon resource, yet less than 10% is currently utilized (Queneau & Han, 2022). Traditional carbon management technologies are confronted with high energy consumption, low value-added products, and indirectional carbon loss, making it difficult to achieve the goal of "carbon neutrality" (Ali et al., 2024; Millinger et al., 2025).

Recently, studies on the high-value utilization of biomass-based raw materials have demonstrated a growing trend (Dos Santos et al., 2024; Yang et al., 2023). Breakthroughs continue to spring up, particularly in the fields of biomass carbonization and the production of aviation kerosene from biomass (Ning et al., 2021; Wang et al., 2025). However, systematic reviews on the high-value transformation of glycosyl molecules in practical applications are lacking, particularly regarding multidimensional, multifaceted, and multifunctional resource pathways from a national strategy. Moreover, traditional single technologies suffer from severe carbon loss-biomass combustion releases 80% of carbon as CO_2, while single CO_2 electroreduction needs extra carbon sources, failing to form a closed loop. Such as co-firing for power generation, result in substantial CO_2 emissions, while their resource utilization procedures remain complex and energy-intensive (Fan et al., 2023; Lee et al., 2022).

Currently, biomass conversion methods based on physico-chemical-biological processes are gaining researchers' attention due to the modifiable nature of CO_2 as an intermediate during conversion (Varalakksmi et al., 2024). Compared with CO_2 catalytic conversion technologies (such as electrocatalysis and thermal catalysis), biomass-integrated CO_2 conversion processes offer superior economic viability, safety, and operational feasibility (Chang et al., 2025; Yang et al., 2024). Moreover, these processes allow for the efficient utilization of biomass resources while reducing CO_2 emissions, thus supporting energy diversification and sustainable development (Saravanan et al., 2025). Different from previous studies that mainly focused on one-sided aspects such as resource-oriented raw material processing methods, resource-based intermediate product separation paths, CO_2 conversion integration research, reactor adaptive transformation in engineering processes, one-dimensional life cycle management, and principles for constructing the backend of large-scale intelligent industrial parks, etc (Cheng et al., 2025; Selwal et al., 2025). Few reviews have comprehensively explored the entire value conversion chain of biomass-derived molecules by integrating the aforementioned multifaceted considerations (Lucas et al., 2021). Novel coupling methods integrating the value chain of biomass-derived molecules with CO_2 solvent utilization pathways must be developed to address the growing demands for green energy and smart technologies (Shan et al., 2025). Therefore, the development of efficient and sustainable carbon cycling technologies driven by light energy capable of synergistically converting CO_2 and biomass into high-value products has emerged as a critical breakthrough for addressing energy and environmental challenges (He et al., 2025; Sun et al., 2025). Utilizing photothermal effects to enhance the photothermal synergistic conversion of both components remains a central challenge in this field (Tang et al., 2025). Multidimensional comprehensive evaluations and resource-oriented approaches also need to be fully assessed to offer innovative and constructive guidance for future development (Guene Lougou et al., 2024).

This study investigates the photothermal catalytic coupling conversion of glycosyl molecules with CO_2, systematically examining physico-chemical-biological synergistic strategies for biomass resource transformation (Martín, 2022; Wu et al., 2025b). It highlights the critical role of solar-driven photothermal catalysis in facilitating the co-conversion of biomass and CO_2, while evaluating the economic feasibility and circular potential across the entire industrial chain (Bhattacharjee et al., 2024; Solar Energy in Thermochemical Processing, 2011). Firstly, in chemical processing under renewable solar energy, the claimed regulatory effects of hydrothermal synthesis conditions on glucose conversion products are comprehensively analyzed (Ramos-Fernandez et al., 2025). The structure–activity relationship between reaction environments and the transformation pathways/product distributions otheoretical underpinnings for efficient biomass depolymerization and value-added utilization (Evro et al., 2024; Li et al., 2024). At the application level, photothermal catalytic technology demonstrates potential in advancing intelligent low-carbon chemical parks within circular economy frameworks through photothermal synergistic conversion of agricultural waste and industrial CO_2 (Pereira et al., 2025; Sun et al., 2025; Xu et al., 2024). This approach presents innovative pathways for global energy transition and carbon neutrality objectives (Xie et al., 2022). Future research directions include optimizing functional photothermal material design, refining reaction kinetics control, and enhancing large-scale system integration to accelerate industrial deployment. Through multidimensional innovation spanning mechanisms, materials, systems, and industrial applications, a holistic theoretical framework and technical system for photothermal-driven biomass-CO_2 co-conversion is established (Wu, 2025), providing sustainable solutions for renewable carbon resource cycling towards carbon neutrality targets. The study aims to bridge the gap between laboratory-scale experiments and full-scale industrial implementation (Alcocer-García et al., 2025; Faaij, 2006).

To lay the foundation for this review, we propose two central scientific questions that guide the entire discussion. The first question is: at the molecular and catalytic level, what are the fundamental mechanisms and material design principles underlying the coupled photo-thermal catalytic conversion of biomass-derived sugars and CO_2? The second question is: how can photo-thermal catalytic technology be integrated into system-level processes to achieve a closed carbon cycle, and what are its sustainability potential and practical challenges in real-world applications?

2. Biomass Sugar-Based conversion mechanism

Common biomass resources convert solar energy into chemical energy through photosynthesis, storing it in the form of carbohydrates, such as glucose, cellulose, and other organic molecules (Yang & Lü, 2021; Zhang et al., 2021). Carbohydrates are classified by degree of polymerization into monosaccharides, oligosaccharides, and polysaccharides, and their structures and physicochemical properties profoundly influence the reaction pathways and product selectivity of biomass conversion (Begum et al., 2024; Tripathi et al., 2024).

The cellulose and hemicellulose components of biomass mainly consist of sugar units. The current waste rate of biomass resources remains high, estimated by the industry at approximately 30%-40% (Sant'Ana Júnior et al., 2025; Uzun, 2022). The chemical energy stored in this wasted biomass is equivalent to 300–500 million tons of standard coal, sufficient to meet the annual energy needs for hundreds of millions of people (Chen et al., 2024). Their conversion processes encompass critical stages including physical pretreatment, chemical catalysis, and biological fermentation (Jędrzejczyk et al., 2019; Zhang et al., 2023). These stages fundamentally determine biomass availability, conversion efficiency, as well as the quality and potential applications of the end products.

2.1. *Classification and treatment methods*

In the conversion of biomass-derived sugars, physical pretreatment is employed as a crucial initial step to enhance accessibility and reactivity by modifying the structural characteristics of biomass (Lorenci Woiciechowski et al., 2020). As shown in Fig. 1a, physical pretreatment includes processes such as washing, drying, mechanical grinding, and sieving, aimed at disrupting the inherent stubbornness of biomass (Worku et al., 2024). These physical operations can significantly enhance the penetration efficiency of acid/alkali reagents by reducing biomass crystallinity and increasing specific surface area, thereby creating structural advantages for subsequent saccharification (Amicucci et al., 2020; Liu et al., 2021). These structural modifications create favorable conditions for the following chemical treatment.

The chemical catalysis stage involves treating biomass with acidic or alkaline reagents to break its chemical bonds and release soluble sugars (Cruz-Casas et al., 2021; Oehlenschläger et al., 2024). As shown in Fig. 1b polysaccharides into monosaccharides such as glucose and xylose (Yin et al., 2023). The study on corn stover indicates that hydrolysis conditions must be strictly controlled: dilute sulfuric acid treatment at 120°C for 30 min achieves a total sugar yield of 72%, but HMF increase sharply, and the yield decreases by more than 20% (Wang et al., 2023). Therefore, hydrolysis conditions must be strictly controlled to prevent excessive degradation of sugar products.

The bio-fermentation stage utilizes enzymatic saccharification and microbial fermentation to convert sugar-based compounds into biofuels or other high-value products (Yang, et al., 2021; Liu et al., 2025). In Fig. 1c, cellulase and hemicellulase act synergistically to break down cellulose and hemicellulose into soluble sugars. The synergistic effect of enzyme systems in this process can enhance polysaccharide degradation efficiency by 40%, while genetically engineered microorganisms can achieve over 90% conversion of sugars to ethanol (Chen et al., 2024; Long et al., 2024; Zhang et al., 2025). These sugars are subsequently metabolized by microorganisms into target compounds such as ethanol and lactic acid. This stage not only enables high-value utilization of biomass but also highlights its significant potential in energy and chemical production (Feng & Guanghua, 2011; Gutierrez-Blanco & Mejuto, 2025).

The efficiency and selectivity of biomass-derived carbohydrate valorization are determined by the complex interactions among physical pretreatment, chemical catalytic depolymerization, and biological upgrading, highlighting the need for integrated process optimization (Li et al., 2022; Ndlwana et al., 2021). Demonstrate the high-value utilization of monosaccharides and fermentation products, and establish a full-chain utilization paradigm from biomass raw materials to functional products (Shen et al., 2024).

2.2. *Multistage hydrothermal synthesis technique*

As a sustainable chemical processing paradigm, hydrothermal synthesis has made significant progress in reconciling mild reaction conditions with molecular precision (Kammoun et al., 2019; Questell-Santiago et al., 2018). Notably, it enables the selective dissolution of carbohydrates and the formation of target products under solvent-free

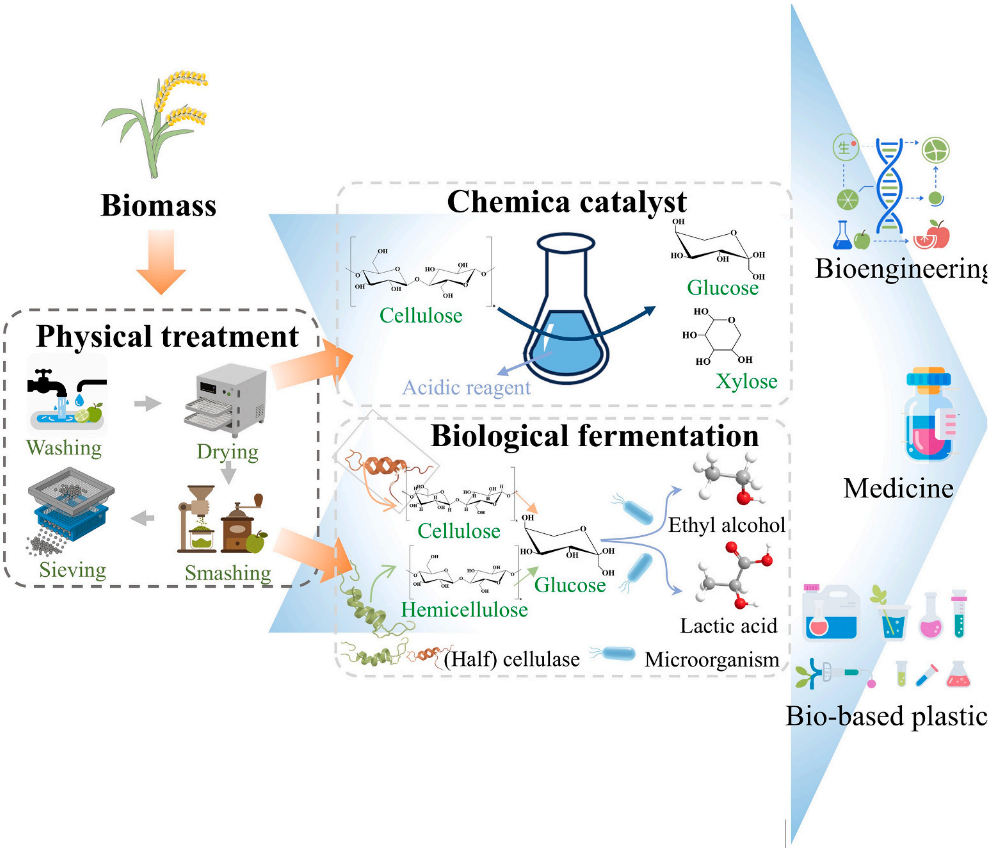

Fig. 1. Flow chart of biomass conversion and treatment. a) Preliminary regulation of biomass raw materials can be achieved through pretreatment to provide a homogenized substrate for subsequent conversion. b) Monosaccharide products are directionally generated through cellulose depolymerization catalyzed by acidic reagents. c) Cellulose is degraded into glucose by enzyme systems secreted by microorganisms, followed by fermentation to produce chemicals.

condition (Alonso-Riaño et al., 2024). Under typical hydrothermal conditions (100–200 ℃, 1–5 MPa), water with its strong hydrogen bond network and high polarity, governs the hydrolysis reaction pathway during glycosyl conversion (Tempelman et al., 2021). As depicted in Fig. 2a, monosaccharides like glucose and xylose are decomposited-polymized in the hydrothermal reactor and subsequently undergo dehydration reactions at 150–200 ℃ (Baruah et al., 2025; Lara-Serrano et al., 2022; Tongtummachat et al., 2020). Specifically, glucose is converted into 5-hydroxymethylfurfural (HMF) via 1,2-enolization, while xylose is transformed into furfural(Gan et al., 2020). In a highly polar environment, glucose is isomerized into fructose, a key intermediate that enables the yield of HMF to reach 60% at 200 ℃ (Ahmad et al., 2025; Liu et al., 2020; Yu et al., 2022). However, at high temperatures, the aldehyde group of HMF easily reacts with unreacted glycosyl groups through condensation, forming humic-like polymers and causing carbon loss. Additionally, although ordinary hydrothermal synthesis can initially depolymerize glycosyl groups, the cellulose conversion rate is relatively low at 150°C. When the temperature exceeds 200°C, side reactions become prominent, and the formation rate of humus surpasses that of HMF.Since ordinary hydrothermal synthesis requires external heating to above 150°C, it consumes a relatively large amount of energy (He et al., 2023; Wu et al., 2017). This has prompted the upgrade of research to subcritical hydrothermal conversion.

Under subcritical hydrothermal conditions, at a temperature range of 150-374°C and a pressure range of 5–22.1 Mpa, the dielectric constant of water gradually drops from ~ 80 (for liquid water at 25°C) to 20–50 (dimensionless) under subcritical conditions (Cui et al., 2020). This gradient change in physicochemical properties significantly impacts the glycosyl conversion pathway. A moderate dielectric constant not only maintains water's ability to dissolve carbohydrates but also strengthens its affinity for HMF, driving the reaction to shift from a hydrolysis-dominated mechanism to a "hydrolysis-dehydration" synergistic mechanism (Brunner, 2014; Lachos-Perez et al., 2022). For example, when glucose undergoes dehydration in subcritical water at 180°C, the yield of HMF can reach 60% (Kaur et al., 2024). The reaction pathway is as follows: glucose first isomerizes into fructose, and then HMF is produced through β-hydroxy elimination. It is worth noting that the supercritical hydrothermal technology, which is parallel to subcritical hydrothermal technology, exhibits a unique rate advantage in the depolymerization of biomass glycosidic bonds, but its applicability needs to be comprehensively evaluated in combination with the requirements of target products (Bueno et al., 2023; Zunita et al., 2022). In terms of reaction efficiency, in the supercritical hydrothermal environment, the dielectric constant of water molecules further decreases to 5–10, approaching the polarity characteristics of organic solvents, which can significantly accelerate the bond-breaking process of cellulose (Sayed et al., 2020). This characteristic makes it have potential in scenarios requiring rapid processing of high-solid-content biomass.

Compared with the supercritical region, the relatively high polarity of subcritical water suppresses the condensation reaction between HMF and glycosyl, significantly reducing the carbon loss rate. Under the low-temperature subcritical conditions of 150 − 200°C, hydrolysis products predominate (Menegazzo et al., 2018). For instance, xylan is converted into xylose, with a small amount of dehydration products accompanying, which makes it suitable for the preparation of high-purity monosaccharides. Under the high-temperature subcritical conditions of 200-374°C, the dehydration reaction takes the lead. The yield of converting glucose to HMF reaches a peak when the temperature rises to 220°C (Guo et al., 2021b; Sun & Li, 2004). When the temperature continues to rise to 300°C, the yield of HMF declines due to ring-opening degradation, and levulinic acid and formic acid are produced simultaneously (Chen et al., 2025). Some studies have indicated that at the same

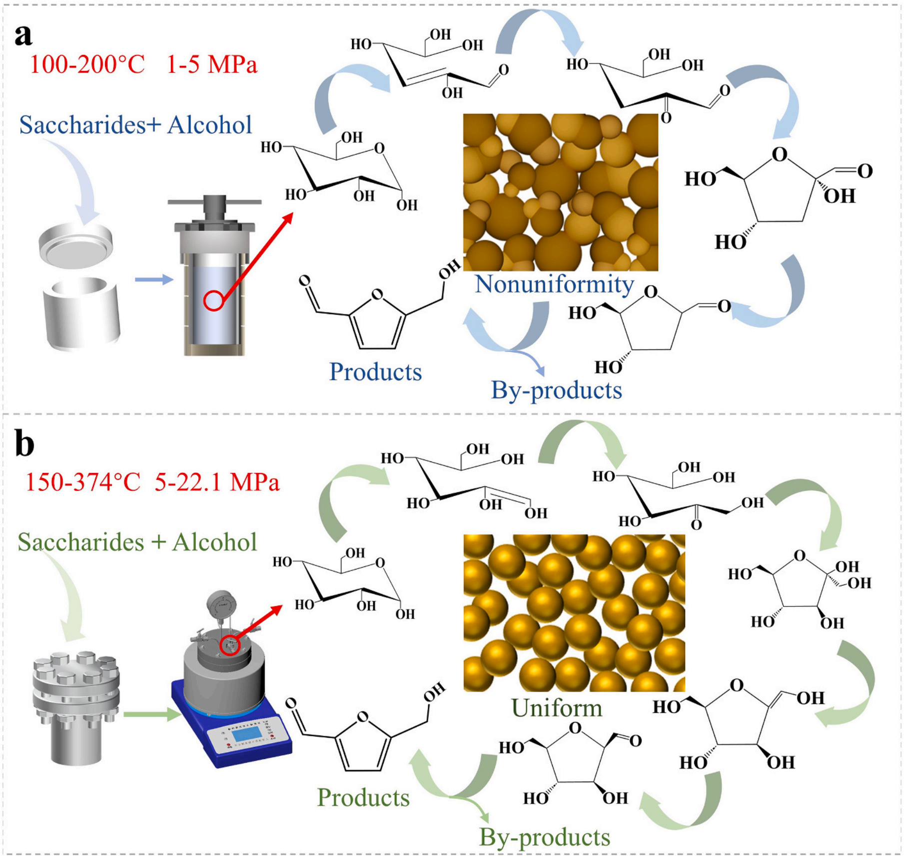

Fig. 2. Hydrothermal Synthesis: Pathways of Glycose Transformation and Product Characteristics under Varied Conditions. a) Hydrothermal synthesis under normal circumstances. b) Hydrothermal synthesis in subcritical states.

temperature, the trends of concentration changes of products like glucose and fructose under different pressures are similar. However, the reactions of isomerizing glucose to fructose and dehydrating fructose to form HMF are significantly influenced by pressure changes. At subcritical temperatures, an increase in pressure has no significant effect on the kinetics of glucose hydrolysis into monosaccharides. However, under high temperature and highpressure conditions, an increase in pressure inhibits glucose isomerization and dehydration reactions but enhances the reverse aldol reaction of glucose (Kierans & Taylor, 2024; Tafolla-Arellano et al., 2024; Zou et al., 2024).

Although hydrothermal technology demonstrates high efficiency in sugar depolymerization, the elucidation of its reaction mechanism still faces significant limitations-currently, the hydrothermal process is still regarded as a "black box", making it difficult to directly capture key information such as multiphase interfacial interactions, dynamic evolution of intermediate species, and side reaction pathways within the reaction system (Chen et al., 2022). Moreover, due to the coupled influence of multiple factors including temperature, pressure, substrate concentration, and the dielectric properties of water, precise control of the reaction poses considerable challenges. This also necessitates in-depth investigation of hydrothermal technology relying on in situ characterization techniques, which enable real-time tracking of structural changes and chemical state evolution of substances during the reaction process, thereby providing direct experimental evidence for elucidating the reaction mechanism.

Meanwhile, its industrial application also faces practical challenges: for example, corrosion of alloy materials by acidic media under high temperature and high pressure, and engineering challenges in thermal-mass transfer matching for continuous reactor design. Most current studies remain at the laboratory scale, lacking thermal-mass transfer coupled optimization models required for engineering scale-up. High energy consumption and corrosion issues in conventional and subcritical hydrothermal processes, combined with control difficulties arising from the "black box" nature, have prompted researchers to explore more efficient and sustainable technological pathways. In fact, the "black box" nature of hydrothermal reactions originates from the nonlinear and coupled effects between key operational parameters and dynamically changing solvent properties (Shelonchik et al., 2024). This complex interplay poses significant challenges for predicting and controlling reaction pathways under current levels of understanding. To transform this "black box" into a "transparent reactor" and rigorously assess the potential of photo-assisted regulation, future research must move beyond single-variable optimization strategies. The development of quantitative kinetic models and dynamic phase diagrams that express product selectivity as functions of temperature, pressure, and time is essential. Such tools will enable visualization of reaction pathways and identification of optimal process windows for target products. Achieving this goal requires the integration of in situ spectroscopic techniques to directly monitor the evolution of intermediates under realistic conditions, coupled with machine learning algorithms to interpret complex high-dimensional data and thereby establish predictive relationships between input parameters and output metrics. This also provides a new research dimension for the green upgrading of hydrothermal technology.

The "black box" nature of hydrothermal reactions primarily stems from the nonlinear coupling between operational parameters (temperature, pressure, time) and the dynamically evolving solvent properties (Liu et al., 2023), which complicates the establishment of clear condition-pathway relationships using existing methodologies. Future research should focus on integrating in situ spectroscopic techniques with machine learning to decipher these complex interactions, visualize intermediate evolution, and ultimately develop quantitative kinetic models capable of predicting and controlling product selectivity.

2.3. *Conversion of CO2 coupled with bio-based molecules*

The coupling conversion of bio-based molecules and CO_2 is a crucial step in constructing the chain of “biomass fixation of CO_2 to high-value products to carbon cycle” (Ramli et al., 2025). Thanks to its mild oxidation properties, CO_2 can subtly regulate the selectivity of biomass reaction pathways during the conversion. Currently, biocatalysis, thermal catalysis, and electrocatalysis are the main approaches to achieving this key conversion, but each approach has obvious limitations.

Biocatalysis utilizes the high selectivity and specificity of microorganisms or enzymes to convert biomass platform compounds into high-value-added products (Liu et al., 2016). Taking glucose as an example, Fig. 3a shows that it is first converted to pyruvate via glycolysis and then reduced to lactate by lactate dehydrogenase; in parallel, enzymes or microbial communities can facilitate CO_2 activation and its coupling with biological substrates (Xia et al., 2025). For example, Zeng et al. constructed (Zeng et al., 2024) engineered *Escherichia coli* strains to reconstruct the glycolysis-carbon fixation metabolic network, enabling co-metabolism of glucose and CO_2, and achieved a 40% improvement in lactic acid production efficiency compared to the wild type. However, biocatalysis faces issues such as poor thermal stability of enzymes, low reaction rates, and high costs of cofactor regeneration. Thermal catalysis drives the chemical reaction between biomass and CO_2 under high-temperature and high-pressure conditions (Li et al., 2025c), primarily relying on metal catalysts to modulate electron transfer pathways. In Fig. 3b, when glucose and CO_2 interact on the catalyst surface, CO_2 initially binds to active sites on the glucose molecule, followed by dehydrogenation and addition reactions that produce oxalic acid, succinic acid, and other chemicals. Li et al. designed a Ni-Fe bimetallic catalyst to regulate the electron transfer pathway between glycosyl molecules and CO_2, effectively suppressing carbon deposition, with a succinic acid yield of 65% (). However, this technology suffers from high energy consumption, and the elevated temperatures can promote side reactions, leading to catalyst deactivation through carbon deposition – thus limiting its use in low-energy applications.

In Fig. 3c, the electrochemical method drives the conversion of biomass and CO_2 through electrode reactions. By adjusting the potential and current density, one can precisely control the reaction rate and product selectivity. At the cathode, the applied potential drives electrons to transfer from the electrode surface to CO_2 molecules, forming CO_2^- intermediates. These intermediates then react with glycosyl molecules to yield substances like formic acid and methanol. At the anode, an oxidation reaction takes place, usually producing oxygen or organic acids. Commonly used electrode materials are carbon-based materials and metal oxides, which feature good electrical conductivity and catalytic activity, thus enhancing the reaction efficiency and stability. Developed a nitrogen-doped hierarchical porous carbon electrode that precisely guides the coupling of CO_2^- intermediates with sugar radicals by modulating interfacial charge distribution, increasing formic acid yield to 82% while reducing the competing hydrogen evolution side reaction. Electrochemical conversion also encounters challenges such as high overpotential, limitations in scaling up, and competition from the hydrogen evolution reaction.

The performance differences among the three catalytic technologies can be intuitively quantified by the radar chart in Fig. 3d, with reaction efficiency, cost-effectiveness, mildness of reaction conditions, energy consumption, and product selectivity as core dimensions. From the perspective of practical application performance, the three catalytic technologies exhibit significant differences in their key parameters (Wan et al., 2025). Biocatalysis using engineered *Escherichia coli* achieves 92% glucose conversion and 88% lactic acid yield, but suffers from poor enzyme thermal stability (Avci et al., 2013). Thermocatalysis with a Ni-Fe bimetallic catalyst attains 85% glucose conversion and 65% succinic acid yield at 300°C (Gao et al., 2021), yet is prone to carbon deposition under high-temperature conditions. Electrocatalysis employing nitrogen-doped hierarchical porous carbon electrodes achieves 90%

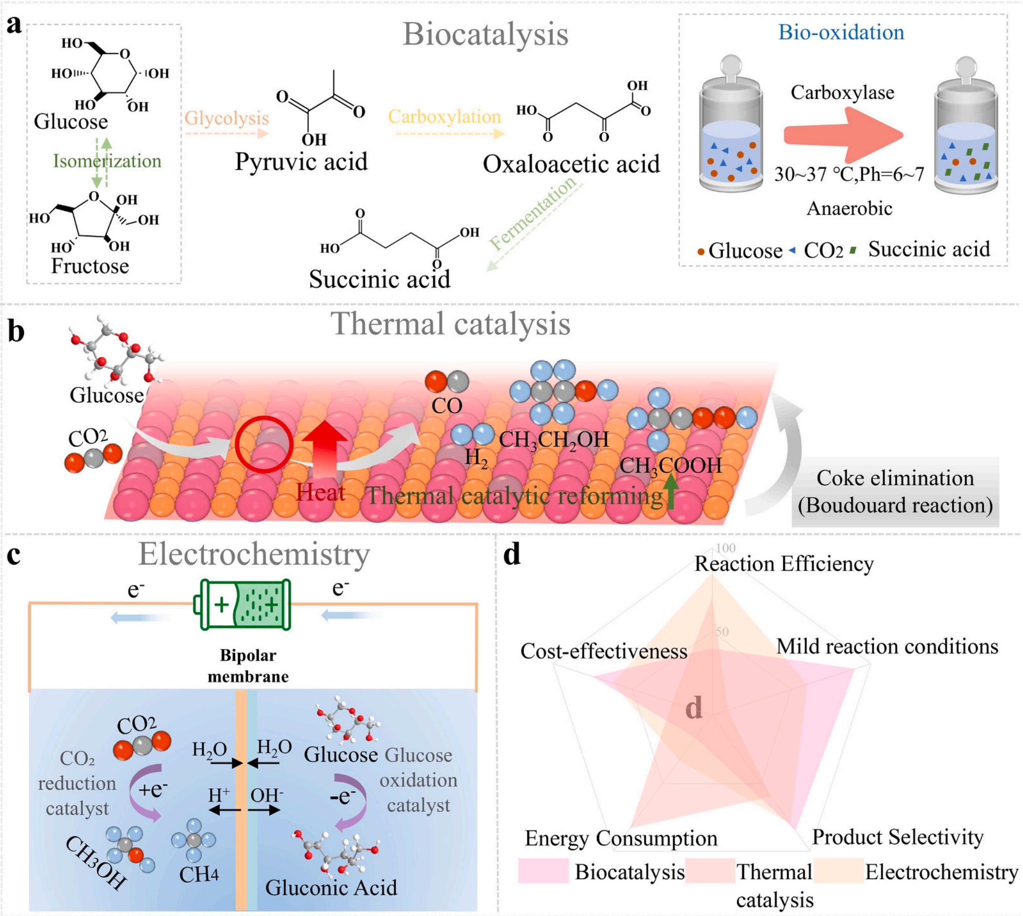

Fig. 3. Catalytic Technologies for Biomass Sugar Conversion: Mechanistic Differences and Multidimensional Performance Comparison. a) Enzyme-mediated glucose biocatalytic pathway. b) Thermally driven glucose-CO_2 reaction network.c) Electrically driven sugar-based-CO_2 electrochemical conversion system. d) Radar comparison chart of performance among three types of catalytic technologies.

glucose conversion and 82% formic acid yield (Sun et al., 2020), while suppressing the hydrogen evolution side reaction to 15%. Each technology presents distinct trade-offs among efficiency, stability, and scalability (Jiang et al., 2024). This multidimensional comparison clearly reveals that none of the three technologies is absolutely superior; catalytic strategies must be customized according to the priority of “selectivity-cost-energy consumption” for the target product. These problems need to be solved through material design and optimization of reaction conditions.

Although biocatalysis, thermal catalysis, and electrocatalysis have achieved certain applications in biomass-CO_2 coupled conversion, each faces inherent limitations that are difficult to overcome. These limitations make it challenging for any single technology to efficiently construct a complete chain of "biomass carbon fixation-conversion-carbon cycle," where the core of carbon cycling lies in "carbon-atom-level coupling without carbon loss," which is precisely the key shortcoming of existing technologies. The emergence of photothermal catalysis offers an innovative solution to the above issues: driven by solar energy, it possesses the dual advantages of "precise cleavage of chemical bonds by photo-generated carriers" and "LSPR thermal field lowering reaction energy barriers." It can not only utilize photo-generated carriers to selectively activate the C—O/C—C bonds in biomass sugar units and the C═O bond in CO_2, but also regulate the evolution pathways of intermediates through mesoscopic thermal fields, thereby avoiding the random degradation and carbon loss associated with conventional thermal catalysis. Moreover, photothermal catalysis can directly utilize solar energy as the energy input, without requiring additional consumption of fossil fuels, thus aligning with the goal of carbon neutrality. Therefore, photothermal-promoted biomass–CO_2 coupling conversion opens a new pathway to overcome existing technical bottlenecks and achieve low-carbon, efficient carbon cycling, demonstrating significant theoretical and practical value.

2.4. *Summary of key control variables for glycosyl conversion selectivity*

The directional conversion of biomass sugar-based molecules into target products is not determined by a single factor, but relies on the synergistic interaction of four control variables: temperature, solvent, key intermediates, and catalysts (Yuan et al., 2023). Together, they form a core framework that governs the selectivity of reaction pathways.

Temperature serves as the macroscopic switch for pathway selection. Low temperatures favor hydrolysis to form monosaccharides, moderate temperatures drive dehydration to generate furan platform molecules (such as HMF), while high temperatures trigger ring-opening degradation and condensation, leading to carbon loss. The solvent governs the dissolution, activation, and stabilization of reactants. Moderate polarity facilitates the synergy between hydrolysis and dehydration, whereas extreme polarity conditions tend to favor a single pathway or induce undesirable side reactions. The subsequent pathways of reactive intermediates such as HMF represent a critical juncture for selectivity. Rapid conversion or timely removal from the reaction system can effectively suppress their condensation, which is essential for enhancing carbon efficiency and preventing humin formation. The active sites of catalysts function as molecular tools for precise control. They guide the reaction network by selectively polarizing specific chemical bonds and can be engineered to activate co-reactants, thereby opening new pathways for value-added transformations (Suvarna et al., 2024).

Mastering conventional regulation of the aforementioned variables forms the foundation for achieving selective conversion. However, these variables are often coupled in conventional thermal catalysis and challenging to optimize independently. The breakthrough potential of photothermal catalysis lies precisely in its ability to provide a new dimension for addressing this complex regulatory challenge.

3. Photothermal-driven biomass conversion coupled with CO_2

3.1. Photothermal-driven biomass conversion

The efficiency and selectivity in the directional conversion of biomass sugar-based molecules are fundamentally governed by the synergistic regulation of four key variables: temperature, solvent, critical intermediates, and catalysts. However, in conventional thermal catalysis, these variables are often coupled, making independent optimization challenging. The breakthrough potential of photothermal catalysis lies precisely in its introduction of a new dimension to address this complex regulatory challenge: the photogenerated carriers and localized thermal fields it introduces serve as synergistic “precision tools.” Through selective activation of chemical bonds and spatiotemporal management of the reaction microenvironment, they enable superior control over the aforementioned key variables, thereby establishing a multiscale, highly efficient conversion system spanning from molecular to reactor levels.

Photothermal catalysis establishes an innovative system for the efficient conversion of biomass, with its core originating from the “sugar-alcohol dual-pathway feedstock network” in Fig. 4a (Wang et al., 2024c), hemicellulose depolymerizes into monosaccharides such as xylose and glucose, which further generate lactic acid and pyruvic acid in aqueous phase; cellulose is converted via fermentation or catalysis into alcohols including methanol, ethanol, furfuryl alcohol, and HMF, which subsequently form aldehydes, carboxylic acids, and acetals through oxidation and condensation. This network lays the material foundation for photothermal catalysis, supporting multiscale synergy across microscale bond control, mesoscale field regulation, and macroscopic cascade (Song et al., 2024).

Photothermal catalysis is an emerging technology that combines light and thermal energy, providing an innovative approach for the efficient conversion of biomass (Zhang et al., 2023). At the microscale (0.1–10 nm) shown in Fig. 4b, the synergistic effect of photo-generated carriers and thermal activation enables selective cleavage of recalcitrant chemical bonds in biomass (such as cellulose β-1,4-glycosidic bonds) and activation of CO_2 (Morales et al., 2024). This synergy is based on a fundamental principle: photo-generated carriers act as “molecular scissors” that directly attack the electronic structure of target bonds. Specifically, high-energy hot electrons can occupy the antibonding orbitals

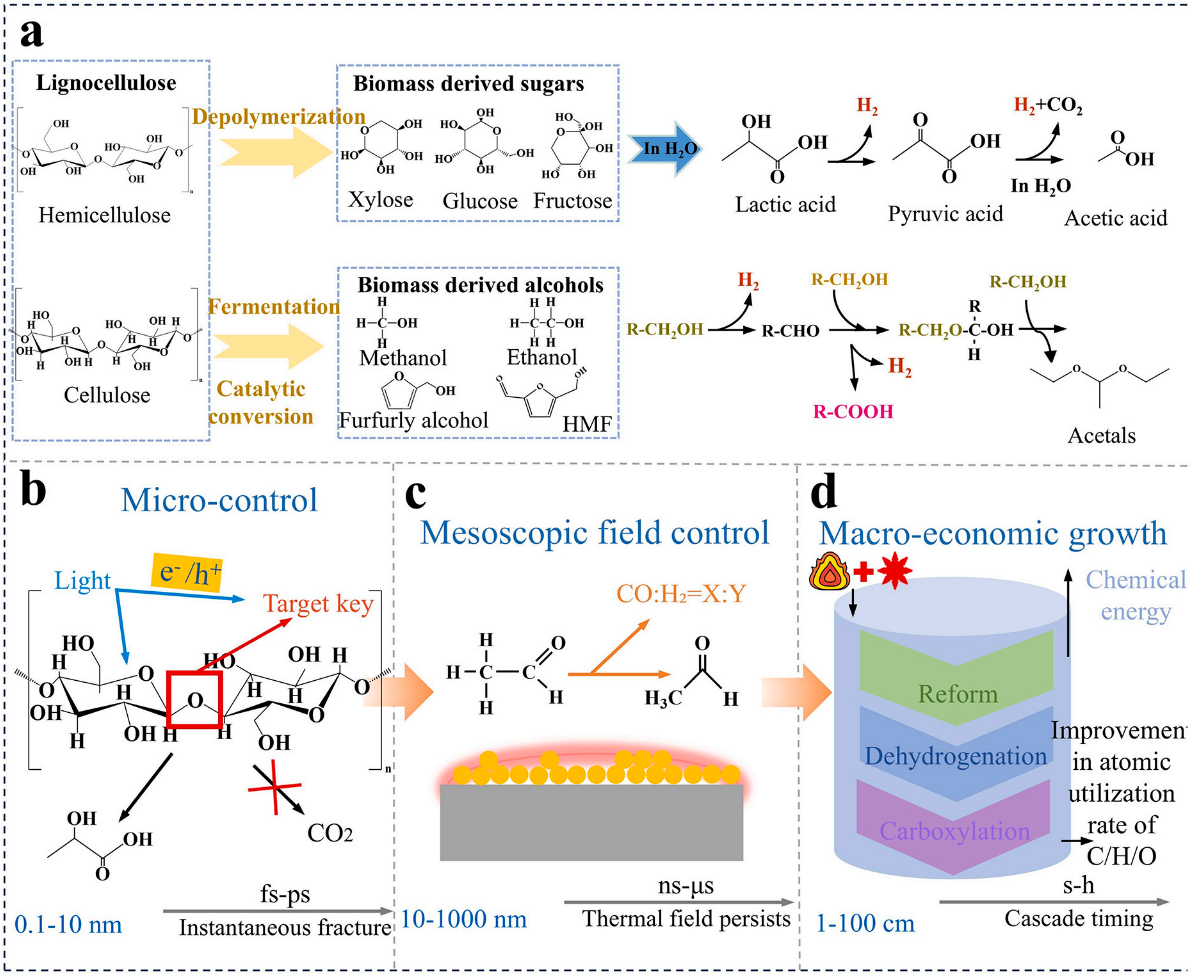

Fig. 4. Multiscale Regulation System for Photothermal Catalysis of Biomass. a) Depolymerization and transformation network of biomass-based carbon sources. Source: Reprinted with permission from ref (M. Wang et l., 2024). b) Molecular-scale synergistic regulation of photoexcited carriers and chemical bonds. c) Mesoscopic aggregate dynamic regulation of thermal field and intermediates. d) Cascade reactions and atom economy construction at the reactor scale.

of C—O or C═O bonds, significantly weakening their bond strength and thereby reducing the activation energy required for bond cleavage. Meanwhile, the localized thermal field, primarily generated by non-radiative relaxation of carriers and LSPR effects, plays the role of a "molecular activator" (Lin et al., 2025), it provides the thermal energy required to overcome the remaining reaction energy barrier, enhances the mobility of reactants and intermediates on the catalyst surface, and promotes proton-coupled electron transfer processes. For example, in activating inert CO_2 molecules, photoelectrons are crucial for the initial single-electron reduction to form the bent $CO_2\bullet^-$ intermediate, while the local thermal effect effectively suppresses the competing hydrogen evolution reaction by accelerating the desorption of key intermediates (such as *CO), thereby steering the reaction pathway toward specific C—C coupling. In Fig. 4c, extending to the mesoscale, 10–1000 nm, nanosecond to microsecond level, the localized surface plasmon resonance (LSPR) effect of photothermal catalysts establishes a sustained thermal field: this both accelerates proton–electron transfer and precisely regulates intermediate pathways. By optimizing the CO/H_2 ratio through oxygen vacancies or sulfate clusters, as shown in Fig. 4c with dynamic tuning of $CO:H_2$ = X: Y, or by promoting dehydration condensation of aldehyde intermediates for fuel additive production, it becomes the core bridge connecting microscopic bond cleavage with macroscopic products.

At the macro-engineering scale, as shown in Figs. 4d, 1–100 cm, second to hour level, photothermal catalysis exhibits unique advantages: in the Au/CdS catalytic system, lignin monomers undergo dehydrogenative coupling of phenyl C—C bonds to directly generate C_{16}-C_{18} cycloalkanes with simultaneous H_2 release, circumventing the complex separation issues of conventional pyrolysis (Yan et al., 2025). More critically, the oxygen-containing functional groups in lignocellulose undergo a "reforming-dehydrogenation-decarboxylation" cascade reaction: reforming breaks the stubborn structure, dehydrogenation releases H_2, and decarboxylation suppresses CO_2 emissions, ultimately transforming oxygen atoms from "structural constraints" into "reaction advantages".Through the co-production of H_2, lactic acid, acetic acid, and others, full-chain utilization of carbon, hydrogen, and oxygen atoms is achieved, providing a typical model for high-value utilization of biomass resources under the "dual carbon" goal.

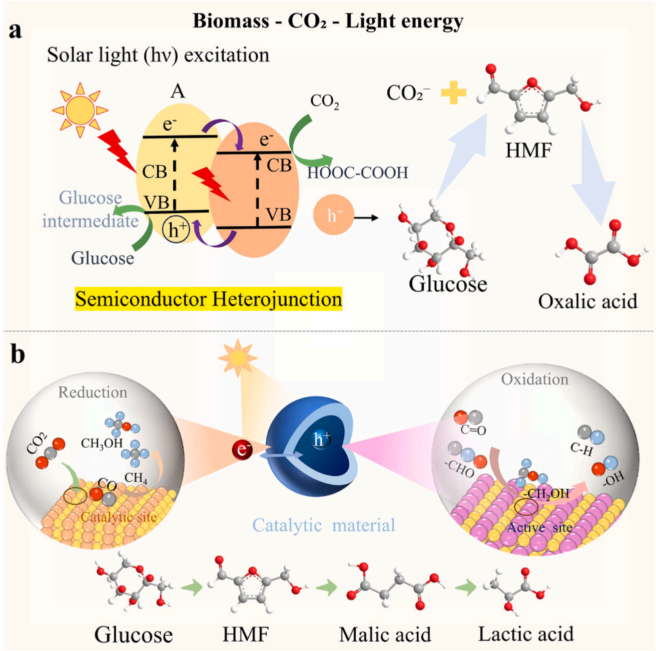

Fig. 5. Light-driven biomass – CO_2 conversion: schematic illustration of two photocatalytic pathways. a) Semiconductor heterojunction photocatalysis of Glucose and CO_2 conversion. b) Photocatalytic redox dual process of Glucose and CO_2 conversion.

While the cross-scale logic spanning from charge carriers to reactor synergy is compelling, several critical knowledge gaps persist between theoretical appeal and practical implementation. At the molecular level, direct real-time observation of short-lived radical intermediates in photothermal reactions remains challenging. On the mesoscale, quantitatively distinguishing the respective contributions of localized surface temperature and bulk reactor temperature presents significant experimental difficulties (Aranda-Ruiz et al., 2025). Furthermore, at the reactor scale, intertwined challenges—such as light distribution, thermal management, and mass transport in high solid-content biomass systems under irradiation—render reliable scale-up exceedingly complex. Addressing these interconnected gaps is essential for translating this conceptual framework into a quantitatively validated and industrially viable technology.

3.2. Photothermal-Driven coupling of glycosyl for CO_2 conversion

Photothermal catalysis offers an innovative technological pathway for the coupled conversion of biomass-derived sugar molecules and CO_2. Its high efficiency is fundamentally rooted in the precisely engineered active sites on the catalyst surface. Modern in situ characterization studies have revealed that specific sites, such as oxygen vacancies, Lewis acid-base pairs, and metal step edges, play pivotal roles in this process (Lin et al., 2025). For instance, oxygen vacancies have been demonstrated to serve as preferential anchoring sites for CO_2 molecules; by donating electrons into the π^* antibonding orbitals of CO_2, they induce a structural transformation from the linear to a bent chemisorbed configuration, significantly weakening the C═O bonds and thereby facilitating subsequent carboxylation reactions. Meanwhile, Lewis acid sites (Hao et al., 2023) on the catalyst surface polarize the C-OH bonds within sugar molecules and, in cooperation with adjacent basic sites, stabilize key reaction intermediates. This synergistic interaction directs the selective dehydration of sugar molecules, suppressing random degradation pathways and enabling controlled transformation. These oxygen-containing functional groups can facilitate the activation of CO_2 through proton-coupled electron transfer, and this is the core advantage of photothermal catalysis in achieving the co-conversion of "biomass-CO_2" (Lan et al., 2023).

Photothermal catalysis provides an innovative technical approach for the coupled conversion of biomass sugar-based molecules and CO_2 (Balapure et al., 2024; Feng et al., 2024). Fig. 5 clearly presents the complete pathway of photothermal catalytic coupled conversion of sugar-based molecules and CO_2. The dehydration-carboxylation cascade reaction of sugar-based raw materials is deeply integrated with the "light energy-thermal energy-chemical energy" conversion mechanism of photothermal materials, constructing a microscopic model for the closed-loop utilization of carbon resources.

Starting with glucose as the raw material, on the surface of the semiconductor heterojunction catalyst, through processes such as carrier-assisted functional group activation, –OH undergoes dehydration to form the furan ring structure of HMF (Verma et al., 2024). As shown in Fig. 5a, when the semiconductor heterojunction absorbs light energy in the ultraviolet–visible/near-infrared (UV–vis/NIR) wavelength range, two key processes are triggered. Firstly, e^- (conduction band CB) and h^+ (valence band VB) generated by photoexcitation undergo separation and migration, accelerating the conformational adjustment of sugar molecules and enhancing the activity of functional groups, thereby promoting the directional conversion of sugar-based carbon chains into HMF (Cui et al., 2023). Secondly, carriers release thermal energy through non-radiative relaxation, further reducing the reaction energy barrier and enhancing conversion kinetics. Meanwhile, the high selectivity of this transformation pathway is attributed to the synergistic regulation of photogenerated carriers and the localized thermal field at the molecular scale. Time-resolved spectroscopic studies

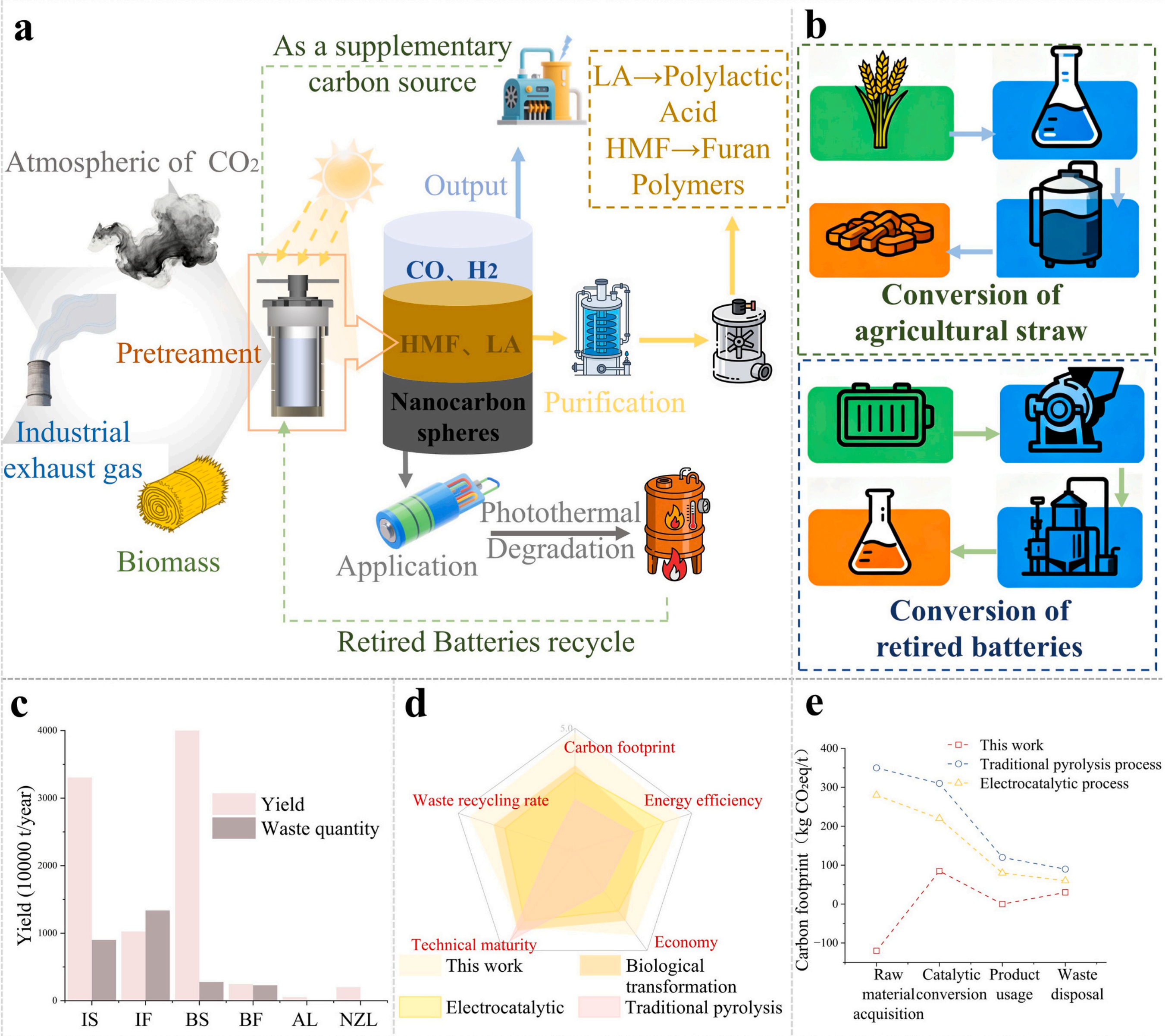

Fig. 6. Comprehensive Utilization of Multiple Resources: Flow, Transformation, and Performance Carbon Footprint Analysis Diagram. a) Schematic diagram of multi-resource comprehensive utilization process based on industrial waste gas, biomass and retired battery recycling. b) Schematic diagram of conversion process of agricultural straw and retired batteries. c) Comparison chart of output and waste number of different categories of products. d) Multi-dimensional performance radar chart comparison of different conversion technologies. e) Comparison chart of carbon footprint at each stage of different conversion processes.

indicate that hot electrons generated by plasmonic metals upon photoexcitation can be injected into the conduction band of adjacent semiconductors on a femtosecond timescale, directly participating in attacking the antibonding orbitals of CO_2 or cleaving specific C — O bonds in sugar molecules. The localized thermal field generated by the LSPR effect does not merely provide bulk heating; its more critical role lies in accelerating the kinetics of key steps and suppressing side reactions by modulating the microenvironment at the reaction interface (Biswas et al., 2023). For instance, on Cu catalysts with well-defined stepped-edge structures, the unique electronic properties of these sites have been demonstrated to simultaneously stabilize CO_2 activation intermediates and furfural molecules, significantly promoting C—C coupling reactions and thereby enabling highly selective conversion of CO_2 to multi-carbon carboxylic acid products. (Wu et al., 2019; Zhang et al., 2025). Moreover, the photothermal effect enables a unique asynchronous synergy between hydrolysis and dehydration steps, which is difficult to achieve in conventional thermal processes. Photothermal catalysis exhibits higher-order precision in bimolecular activation and coupling. It holds distinct advantages in driving C—C coupling between CO_2 and sugar molecules (Cheng et al., 2025).

In Fig. 5b, driven by light energy, the catalytic material exhibits excellent bifunctional catalytic properties, synergistically mediating the efficient progression of reduction and oxidation reactions (Zhang et al., 2024). First, CO_2 reduction undergoes reductive transformation at Co catalytic sites, generating high-value chemicals such as CH_3OH and CH_4; second, substrates containing carbonyl, aldehyde, and hydroxymethyl functional groups at the oxidation end undergo oxidation processes; meanwhile, glucose derived from biomass is progressively converted through intermediates such as HMF and malic acid, ultimately forming lactic acid, constructing an efficient conversion pathway from biomass to high-value platform compounds, providing a typical paradigm for the synergistic resource utilization of CO_2 and biomass under photocatalytic driving (Wang & Yuan, 2026).

The core mechanism of photothermal catalytic coupling conversion can be attributed to the synergistic transformation of light energy, thermal energy, and chemical energy, enabling precise control over bond breaking and formation at the molecular level. The cascade regulation from atomic to nanoscale dimensions collectively establishes the theoretical foundation for high efficiency and selectivity in photothermal catalysis.Whether it is the “photogenerated carriers and thermal energy” synergy of semiconductor heterojunctions or the “direct driving by photothermal effect” of photothermal materials, both can effectively reduce the energy barriers of “glycosyl dehydration” and “CO_2 activation”, provide power for the coupling conversion of glycosyl molecules and CO_2, and ultimately achieve the efficient conversion from biomass sugars to high-value carboxylation products (He et al., 2025). The properties of photothermal catalytic materials directly determine their application potential. Semiconductor heterojunctions (e.g., TiO_2/ZnS) can enhance carrier separation (Xiao et al., 2025), but exhibit a narrow photoresponse range. Plasmonic metal materials achieve photothermal conversion efficiencies exceeding 85%, yet suffer from high cost and susceptibility to sintering. Single-atom supported materials enable 100% atom utilization, but face challenges in scalable synthesis (Tian et al., 2025). The selection of an appropriate material system must be based on the target product and reaction conditions in practical applications. Through rational design of catalytic sites, competing reaction pathways can be selectively promoted, thereby providing a powerful strategy for precise control over the CO/H_2 product ratio. The selection of photothermal catalysts presents a clear trade-off. For industrial applications, future research must prioritize the development of replacement materials based on earth-abundant elements and robust, scalable synthesis methods to achieve kilogram-scale production with stable performance, which represents a critical research gap currently hindering the economic viability of photothermal biorefinery.

Biomass and its derived saccharides (such as glucose and xylose) can not only provide electron donors for photothermal catalytic reactions to drive H_2 generation, but also serve as carbon sources to participate in reactions such as carboxylation and dehydration, synthesizing high-value-added chemicals like oxalic acid, malic acid, and HMF (Li et al., 2025d). This photothermal synergistic conversion mode of “hydrogen production and high-value chemical synthesis” not only endows photothermal catalysis with economic feasibility in the closed-loop utilization of carbon resources, but also provides technical support for carbon–neutral cycles. For example, by constructing semiconductor heterojunctions or photothermal catalysts loaded with single atoms, the directional conversion of biomass sugars to HMF, CO_2 carboxylation to carboxylic acid products can be simultaneously achieved under the ultraviolet–visible/near-infrared broad spectrum, accompanied by H_2 generation, which provides a technical paradigm for the efficient storage and multiple utilization of “solar energy-chemical energy” (Guo et al., 2025).

Photothermal catalysis, with “light energy capture-thermochemical driving-catalytic regulation” as its core logic, precisely activates the inert C—C and C-OH bonds of glycosyl molecules and the C=O inert bond of CO_2, realizing the directional and multiproduct photothermal synergistic conversion from biomass to high value-added chemicals such as carboxylic acids and furans, and opening up a new path for efficient and environmentally friendly recycling of carbon resources. In the future, focus can be placed on the precise design of photothermal materials and the engineering optimization of reaction processes to promote the technology from laboratory to industrialization, thereby laying a foundation for global resource utilization.

4. Global resource utilization: Transformation from linear conversion to closed-loop networks

After systematically analyzing the mechanism and pathway of the photothermal catalytic-driven coupling conversion of CO_2 coupling biomass, we will reveal the sustainability potential and practical challenges of this technology in building a closed-loop carbon economy from the perspectives of full-space resource recycling and life cycle assessment (Wan et al., 2024).

4.1. Full-space resource utilization

Deploying a photocatalytic system at the park level requires selecting a robust and scalable core process. Among the pathways investigated, the direct photothermal catalytic coupling of biomass-derived sugars with CO_2 represents the most viable foundation. This pathway serves as the ideal chemical heart of a circular carbon park, as it simultaneously accomplishes waste valorization and carbon fixation within a single solar-driven reactor, eliminating the complexity associated with coupled systems (Wang et al., 2025). The essence of full-scale resource utilization is to construct a full-chain carbon cycle of “biomass fixation of CO_2 to high-value conversion to recycling” through the photothermal catalytic interface. Driven by the local surface plasmon resonance effect of photothermal materials, the glycosyl molecules in agricultural waste (such as cellulose in straw) selectively cleave the C—O/C—C bonds, generating carbon-containing intermediates like HMF and lactic acid. Through the C—C bond coupling reaction under photothermal catalysis, these intermediates react with industrially captured CO_2 and are converted into high-value-added chemicals such as oxalic acid and levulinic acid, releasing hydrogen at the same time. The reaction by-product, nanocarbon spheres, can be regenerated into catalytic carriers through photothermal reconstruction, with a recycling rate of over 90%, thus forming a cross-scale carbon cycle closed-loop of “depolymerization-fixation-regeneration” (Barbhuiya & Das, 2023; He et al., 2025; Zhang et al., 2021).

Fig. 6a illustrates an integrated biorefinery system centered on the photothermal catalytic co-conversion of agricultural waste with CO_2. Compared with conventional thermochemical processes, this system offers notable advantages: first, solar energy serves as the primary energy input (Li et al., 2024), directly replacing the fossil-derived heat required for pyrolysis or gasification, thereby substantially reducing process energy consumption; second, the photothermal effect enables lignin carbohydrate complex depolymerization and CO_2 activation to proceed at temperatures significantly lower than those in purely thermal catalysis, thus avoiding excessive degradation and directing carbon skeletons toward high-value chemicals such as HMF and lactic acid, rather than low-value syngas or bio-oil (Jiao & Wang, 2025). The sustainability of this system hinges on the inherent photothermal regeneration mechanism of the nanocarbon sphere (NCS) catalyst, thereby establishing a cross-scale carbon closed loop of “depolymerization-fixation-regeneration.” Specifically, the straw is initially depolymerized into reactive carbon intermediates (Ban et al., 2025). These intermediates then couple with industrially captured CO_2 on the surface of NCS to form high-value acids and fuels. Although the used NCS deactivates due to carbon deposition or passivation, its intrinsic photothermal properties enable rapid self-heating under light irradiation in an inert atmosphere. This eliminates the need for an external furnace, allowing carbon deposits to be combusted off and the catalyst’s structure and activity to be restored. As a result, NCS not only serves as a catalytic medium but also functions as a recyclable carbon carrier. Ultimately, this solar-driven process achieves a fully closed-loop cycle spanning from biomass waste to product molecules and back to the catalyst itself (Bartling et al., 2021).

The platform compounds can be catalytically polymerized into furan-based bioplastics and other environmentally friendly polymeric materials, aligning with the academic focus on replacing conventional fossil-based materials with bio-based alternatives. The solid product, nanocarbon spheres, after surface functional group modification, serves dual functions: one, facilitating photothermal-assisted leaching of cathode materials from spent batteries to enhance selective separation efficiency of valuable metals; and two, supporting the preparation of battery-related functional materials. Meanwhile, certain intermediate products are recycled back into the reaction system as supplementary carbon sources, establishing a cross-chain synergistic closed loop encompassing “carbon capture – biomass conversion – solid catalyst application – resource recycling.” Its innovation lies in overcoming the limitations of single-waste resource utilization by establishing an energy-matter coupling mechanism across multiphase resources, with comprehensive resource utilization as the core, providing a systematic process paradigm for collaborative treatment of cross-sectoral wastes (Meinrenken et al., 2020; Tripathi et al., 2019).

Fig. 6b focuses on two central issues: breaking through technological bottlenecks in single-waste resource utilization and filling the academic gap in cross-category waste holistic synergy. Centered on fractionated and targeted conversion of biomass such as agricultural straw, the design simultaneously extends the application of solid catalysts in end-of-life battery recycling. For agricultural straw, the process encompasses three key units, feedstock pretreatment, catalytic conversion, and product separation and purification, clarifying the transformation mechanism of lignocellulose into C5/C6 sugar derivatives and high-value chemicals, thereby offering a replicable technical framework for large-scale lignocellulosic biomass valorization and addressing the shortcomings of conventional pyrolysis technologies, such as poor product selectivity and low added value. For end-of-life batteries, leveraging the previously generated solid catalyst (modified nanocarbon spheres), a stepwise pathway of “mechanical disassembly – photothermal-assisted leaching – solvent extraction – material reconstruction” is adopted to achieve efficient separation of cathode materials from current collectors, enabling targeted recovery of valuable metals such as Li^{+} and Co^{2+} and their reformation into cathode precursors or catalytically active components, thus overcoming the traditional bottlenecks in end-of-life battery recycling characterized by high energy consumption, secondary pollution, and low recovery rates.The two transformation pathways respectively establish a core model for biomass waste valorization and an extended cross-scenario application model for solid catalysts, providing a basis for process design in the targeted conversion of wastes with different occurrence forms and laying a methodological foundation for academic exploration of holistic resource utilization.

Beyond integration with existing industrial infrastructure, the combination of photothermal catalysis with downstream biological processes also demonstrates significant potential. Biocatalysis offers unique advantages, including exceptionally high product selectivity and suitability for synthesizing complex fine chemicals. However, its major limitation lies in the difficulty of directly and efficiently utilizing untreated recalcitrant biomass feedstocks. In perfect complement, photothermal catalysis serves as an efficient abiotic pretreatment technology, capable of rapidly depolymerizing stubborn biomass such as lignocellulose and CO_2 into a range of bioavailable reactive intermediates. Therefore, integrating the efficient degradation capability of photothermal catalysis with the precise synthetic capacity of microbial conversion holds promise for establishing a novel tandem biorefining model characterized by “photothermal degradation → microbial upgrading”.

The photothermal catalytic strategy demonstrates excellent compatibility with existing biomass processing infrastructure. In traditional sugarcane mills, low-value streams such as molasses and bagasse can serve as ideal raw materials for photothermal-coupled CO_2 conversion, enabling the upgrading of process residues into high-value chemicals while utilizing the plant’s own CO_2 emissions (Daiyan et al., 2020). This integrated approach not only enhances resource efficiency but also reduces the overall carbon footprint of the sugar production process. The primary challenge lies in engineering adaptability, specifically the optimization of photothermal reaction conditions for handling complex industrial feedstocks (Yang, et al., 2024). From a sustainability perspective, it directly integrates carbon capture and utilization into the bio-industry by employing CO_2 generated from the plant’s own fermentation or combustion units, sequestering it into products and thereby reducing the carbon footprint across the entire sugar production chain.

Beyond integration with thermochemical processes, coupling photothermal catalysis with microbial conversion offers a promising hybrid strategy. The photothermal process serves as an upstream abiotic pretreatment, efficiently depolymerizing recalcitrant biomass into bioavailable intermediates (Xiu et al., 2023). These intermediates subsequently function as refined substrates for downstream microbial fermentation, where engineered strains selectively upgrade them into more complex products. Bridging this abiotic-biological interface through substrate compatibility and process integration remains a critical research frontier for future circular biorefineries. This closed-loop carbon cycle fully adheres to the core concepts of cross-scale material cycling and full-life-cycle value extraction in the concept of full-domain resource utilization (Chen, et al., 2025). In the future, by integrating multiple technological systems and conducting intelligent optimization, we can establish an intelligent zero-waste park with a coupling of “photothermal catalysis-biological conversion-energy cascade utilization”. We can use the Smart internet technology to regulate the temperature field distribution and the CO_2 capture-conversion rate of the photothermal reactor in real time. By combining with blockchain technology to trace the carbon flow trajectory, we can achieve the collaborative conversion of multisource wastes such as straw and industrial exhaust gas. Ultimately, a closed-loop ecological paradigm of “resources-products-wastes-recycled resources” will be formed, offering a replicable engineering model for the circular economy under the dual-carbon goal.

Despite outlining a promising blueprint for a circular carbon economy, the practical implementation of photothermal catalysis on a large scale must address several inherent engineering challenges in reactor design and operation (Rivadeneyra-Romero et al., 2023). Limited light penetration depth poses a fundamental constraint during reactor scale-up, as light intensity decays exponentially when passing through the catalyst bed. To mitigate this issue, innovative reactor designs, such as those incorporating internal light distribution systems or cascading thin-film reactor concepts, are being actively investigated to ensure efficient photon delivery throughout the reaction space. Furthermore, thermal and mass transport management becomes particularly challenging in systems involving solid biomass raw materials, gaseous CO_2, and solid catalysts (Li et al., 2025b). Effective solid–liquid-gas three-phase mixing is crucial to prevent mass transfer limitations. Engineering solutions such as photothermal fluidized bed reactors or mechanically agitated systems can enhance interfacial contact and reactant-catalyst interactions. Addressing these intertwined challenges of light, heat, and mass transfer represents a key frontier in translating the potential of photothermal catalysis into large-scale, industrially viable processes.

4.2. Life cycle assessment

On this basis, the full-chain environmental impact of the system from raw material acquisition, catalytic conversion to product utilization and byproduct regeneration should be further quantified through life cycle assessment (LCA)(Sun et al., 2025). This assessment analyzes resource consumption, carbon emission characteristics, and socio-economic benefits across key processes, including photothermal material preparation, CO_2 capture, and nanocarbon sphere regeneration. By integrating environmental and economic dimensions, the LCA provides a scientific decision-making basis for the sustainable optimization of intelligent waste-free parks (Yang et al., 2021).

Inefficient utilization and high waste of biomass sugar resources are among the core pain points in the carbon cycle chain (Jeuken et al., 2024). Fig. 6c visually presents the differences in sugar production waste among typical countries globally. In India, fructose waste even exceeds its production, and sucrose waste reaches one-third of its output, revealing problems of cold chain deficiencies and insufficient processing; Brazil leads the world in sugarcane production, yet its waste amounts to only 7% of its output, demonstrating the efficiency advantages of large-scale processing; the United States has a lactose waste rate of nearly 18%, while New Zealand, due to its export-oriented industry, has a waste rate of less than 2%. Such national and category-specific differentiation in sugar resource production waste highlights the urgent need for high-value conversion of biomass. Reducing waste and closing the carbon loop through catalytic technologies is precisely the core mission of photothermal catalysis.

In Fig. 6d, when comparing electrocatalysis, biotransformation, and traditional pyrolysis processes, photothermal catalysis exhibits significant comprehensive performance advantages in energy conversion efficiency, catalyst stability, and closed-loop carbon management. It realizes a dual-effect balance between negative carbon conversion and resource regeneration through the synergistic regulation of light, heat, and mass. This approach not only quantifies the carbon emission reduction benefits of the photothermal catalytic system but also highlights its technological competitiveness through multidimensional comparison. From the perspective of the full-life cycle carbon footprint, the photothermal catalytic system shows significant advantages in carbon emission reduction (Li et al., 2023; Zhang et al., 2024; Zhu et al., 2022).

Beyond macroscopic performance comparisons, quantitative life cycle assessment (LCA) plays a crucial role in clarifying the environmental benefits of photothermal catalytic pathways (Guo et al., 2024; Xiong et al., 2025; Zhang et al., 2023). However, comprehensive LCA studies focusing specifically on photothermal catalytic biomass conversion remain extremely limited, representing a significant research gap in this field. Existing data derived from related processes indicate that photothermal routes utilizing agricultural waste may achieve favorable global warming potential (GWP), primarily attributed to the carbon-negative nature of biomass feedstocks. In contrast, conventional thermochemical routes for producing similar products exhibit significantly higher GWP due to their heavy reliance on fossil energy sources (Vuppaladadiyam et al., 2023). Electrocatalytic processes powered by renewable energy also possess a carbon footprint, partly stemming from emissions associated with electrode manufacturing. A critical limitation in current assessments lies in the failure to comprehensively account for the complete life cycle carbon footprint of the photothermal catalyst synthesis itself, encompassing both functional material production and spent catalyst disposal (Ge et al., 2025). Consequently, future research must prioritize conducting comprehensive LCAs that quantitatively incorporate these frequently overlooked stages.

5. Conclusion and perspective

This study establishes a theoretical framework for photothermal catalysis based on a ternary coupling system of biomass-derived sugars, CO_2, and solar energy, achieving selective cleavage of glycosidic bonds, functional group modification, and CO_2 fixation/reduction through photothermal synergistic effects, thereby constructing carbon conversion pathways with unique spatiotemporal resolution under mild conditions. This strategy starts with sugars from agricultural waste, which undergo photothermal depolymerization to generate carbon-containing reactive intermediates that couple with industrial waste CO_2 via carboxylation to produce high value chemicals such as HMF and lactic acid. The solid byproducts are regenerated and restructured into catalytic supports through photothermal treatment, establishing a cross-scale closed-loop carbon cycle of "production-consumption-regeneration". From a life cycle perspective, the carbon footprint of its raw materials is significantly lower than that of fossil-based routes, and its economic feasibility will continue to improve in regions with abundant sunlight and under scenarios of declining CO_2 capture costs. This technology not only overcomes the bottleneck of biomass-derived sugar conversion but also drives a paradigm shift in renewable carbon utilization from a "linear economy" to a "circular economy": by innovating photothermal materials and optimizing reaction engineering, it bridges the gap between fundamental research and industrial application, providing transformative solutions for carbon neutrality and a circular bioeconomy.

However, from laboratory to industrial implementation, a series of critical scientific and engineering challenges remain to be addressed. At the material derivation and coupling level, the matching mechanism between photothermal active components and biomass-based supports during derivation is still unclear; it is necessary to elucidate the regulatory rules of precursor chemistry on cross-scale coupling of structure-performance, as well as the synergy between active component derivation and CO_2 fixation pathways. At the reaction engineering spatiotemporal matching level, there is a lack of systematic correlation between the catalyst's microscopic growth behavior and the reactor's macroscopic conditions; a quantitative relationship between microscopic parameters and macroscopic design must be established. At the chemical process interference level, the influence mechanisms of impurities in biomass sugar conversion on solid–liquid-gas three phase interfacial reactions and the impurity "tolerance threshold" for asymmetric structures remain undefined; in-depth studies on in situ characterization and multiscale simulation are required. Solving the aforementioned issues will further consolidate the theoretical foundation of ternary coupling, promote the transition of photothermal catalysis from "proof-of-concept" to "engineering application," and provide stronger scientific support for global energy transition and carbon neutrality goals.

Compared to other advanced photothermal strategies, such as photothermal-electrocatalytic coupling or photothermal-biological hybrid systems, the direct photothermal coupling of biomass and CO_2 proposed in this work demonstrates unique advantages in terms of system simplicity, high energy efficiency, and operational feasibility. Although integrated systems may achieve superior performance in certain metrics, our approach offers a more straightforward and potentially lower-cost pathway for solar-driven carbon cycling, making it particularly suitable for near-term implementation.

Looking ahead, the industrialization of photothermal catalysis hinges on addressing a series of compelling research frontiers that integrate advanced materials engineering with smart system design. A central challenge lies in the rational design of low-cost, scalable, and stable photothermal materials to resolve economic viability concerns. Moreover, bridging the 'material-to-system' gap is critical; this requires synergistic advances in reactor engineering to manage light, heat, and mass transport at scale, alongside the development of intelligent process control systems. The integration of real-time sensing, machine learning for dynamic optimization, and blockchain-based carbon flow tracking can enable the creation of 'smart zero-waste parks', yet the effective implementation of these digital tools remains a crucial area for future research. Finally, exploring synergies with existing industrial ecosystems must be integrated with rigorous interdisciplinary collaboration. Conducting comprehensive techno-economic life cycle assessments and developing frameworks aligned with carbon trading mechanisms are essential yet underdeveloped steps for verifying the technology's sustainability claims and ensuring its economic competitiveness. Addressing these challenges will establish photothermal catalysis as a cornerstone technology for a sustainable, circular carbon economy.

To bridge the gap between the conceptualization and industrialization of photothermal catalysis, future research should focus on three critical directions:

(1) Interfacial mass and energy transport: Elucidating the dynamic coupling mechanism between photothermal energy transfer and the transport of reactants/intermediates at the solid–liquid–gas interface, which represents a major bottleneck limiting reaction efficiency and selectivity.
(2) Intelligent system integration: Overcoming mass and heat transfer limitations in photothermal reactors, exploring their smart coupling with bio-/electro-catalytic processes, and establishing digital twin systems for carbon cycling at the industrial park level.

(3) Interdisciplinary convergence: Conducting comprehensive techno-economic and life-cycle assessments, promoting integration with carbon trading mechanisms, and ultimately supporting the achievement of carbon neutrality goals.

CRediT authorship contribution statement

Jingwen Jiang: Writing – review & editing. **Yiheng Wang:** Conceptualization. **Yuanjie Li:** Investigation. **Junxi Huang:** Investigation. **Weiping Zhang:** Supervision. **Dan Wang:** Writing – review & editing. **Dong Xu:** Supervision. **Dong Fu:** Supervision. **Pan Zhang:** Supervision. **Lemeng Wang:** Supervision. **Kun Zhao:** Supervision.

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.

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Data availability

The authors declare that all data supporting the findings of this study are available within the paper and Supplementary Information files. Source data are provided with this paper.

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