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Synthesis of organonitrogen compounds via heterogeneous electrocatalytic C-N coupling

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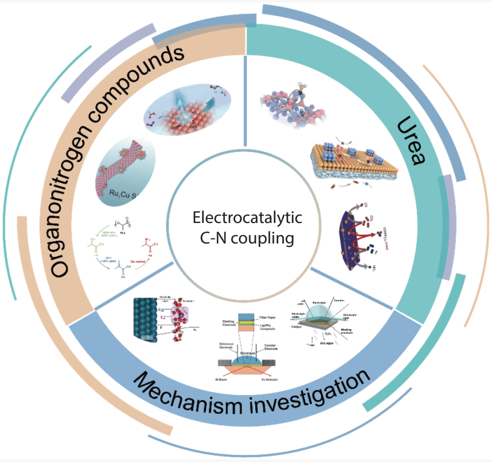
The traditional energy-intensive heterogeneous thermochemical processes have historically yielded a substantial quantity of high-value chemicals, but it simultaneously results in significant emission of carbon dioxide (CO_2) and nitrogen oxide (NO_x) species, and a heavy reliance on fossil resources. A promising strategy to address it is to utilize CO_2 greenhouse gases and NO_x pollutants as feedstocks for production of high-value chemicals under ambient conditions driven by renewable energy sources. To achieve the objectives, it is essential and highly desirable to focus on the development of electrocatalytic technology for construction of C-N bonds beyond the C-O or N-O cleavage and formation. To date, however, the ambiguous reaction mechanism and severe competitive side reactions has greatly constrained the activity and selectivity of the electrocatalytic C-N coupling reactions. This review is devoting to summarizing the recent progress of electrocatalytic C-N coupling processes in synthesizing urea, amides, amines, and related compounds with an emphasis on understanding of the fundamental design principles of electrocatalysts and insightful perspectives of modulating heterogeneous electrocatalytic processes. It is expected to be constructive for the electrosynthesis of a wide range of high-value chemicals containing C-N coupling.



The chemical industry propels the advancement of contemporary society by bringing a wide range of chemicals to ensure and enhance human life, such as medications, fertilizers, fuels, polymers, and paints.[1] All types of fossil fuel-based refinery processes, including Fischer-Tropsch, Harbor Bosch, catalytic hydrocracking, and methane reforming, may transform basic fossil resource materials into a variety of commercial chemicals for future use. However, the conventional chemical industry depending on fossil fuels has two sides to it. Thermocatalytic refineries contribute to the prosperity of human civilization, but they simultaneously produce a significant quantity of CO_2 emissions and exhaust NO_x emissions (e.g., NO_3^-, NO_2^-, NO), leading to a range of environmental issues and damages to the human respiratory system, special for global warming crisis.[2] The international climate aim of keeping the average global temperature below 2 degrees Celsius necessitates an energy system with net-zero CO_2 emissions, especially in the chemical industry, but it is still unable to meet the sustainable goal.[3] To attain the net-zero CO_2 emission target, it is essential to create alternative low-carbon and sustainable refinery processes driven by renewable energy sources.

The production of some small molecule chemicals, such as H_2, H_2O_2, CH_4, CO, HCOOH, C_2H_4, NH_3, through water splitting,[4] O_2 reduction,[5] CO_2 reduction,[6] and nitrogen reduction,[7] powered by electricity under ambient conditions has been made achievable in recent decades through the electrocatalytic reduction and oxidation process. These tiny molecules are involved the breaking of chemical bonds to make O-H, C-O, C-C, N-H, N-O, and other links via electrosynthesis. However, certain more useful and complicated molecules, such as urea, amines, amides, and amino acids, are challenging to be efficiently created by electrocatalytic process because of the intricacy of the reaction and ambiguous mechanism.[8] Therefore, it is highly desirable to couple the CO_2 with nitrogen-contain molecules (such as NO_3^-, NO_2^-, NO, N_2) via electrochemical co-reduction process to address the emission of CO_2 gas and exhaust NO_x emissions, also it appears to be a viable option to achieve the production for high-valuable chemicals under an environmental condition.

Urea, and other C-N bond-containing compounds, such as amines and amides, which have promoted the development of human society.[9] However, they were produced under high temperatures, high pressures, severe, and strongly acidic reaction conditions, necessitates large capital inputs.[10] Besides, because of the long-distance transportation and a lack

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of infrastructure, it is necessary to build in industrialized, reasonably stable, energy-rich regions and countries, leading to raised price of chemicals in emerging countries and remote places.[11] The electrochemical synthesis of urea, amines, amides, and other compounds derived from nitrogen (e.g., NO_3^-, NO_2^-, NO, N_2), CO_2, and H_2O using renewable electricity provide an alternative solution, which not only favors distributed and miniaturized production, but also provides significant environmental, economic, and social benefits.[12] Noteworthy, biomass was another potential organic carbon source except for CO_2 due to its abundance and renewable nature. And biomass can produce more kinds of precursor, which can coupl with nitrogen-containing species via electrochemical C-N coupling process to produce amino and other monomer chemicals, further enrich this product spectrum of this field.[13] Moreover, the gentle reaction conditions facilitate precise control of the C-N coupling process, rendering it more conducive to industrial applications compared to harsh conditions characterized by elevated temperature and pressure.

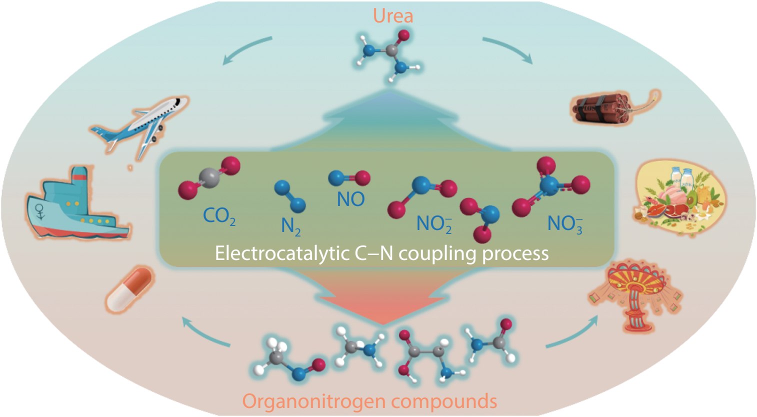
Although substantial efforts have been recently devoted to the electrosynthesis of organonitrogen, it is still impeded by the low selectivity and small current density.[14] The intricacy of the reaction pathway, multiple electron transfer, and confusing reaction mechanism are the key challenges.[15] It should be noted that competitive reaction is hardly unavoidable during the electrochemical co-reduction process of nitrogen and carbon. Herein, the construction of multifunctional catalyst with multi active sites that could not only simultaneously activate the nitrogen and carbon to yield the key intermediates, but also favor the coupling of them.[16] To date, it is still challenging to integrate multiple active sites into individual catalyst to complete the catalytic process independently, and the mechanism also remains unclear.

In this review, we will first summarize mechanistic foundation of the analogous established thermochemical, molecular, and enzymatic catalytic process. Subsequently, we will present recent advancements in electrochemical C-N coupling for the synthesis of urea, amines, amides, and so on, elucidating the corresponding mechanisms governing C-N bond formation (Scheme 1). Emphasis will be placed on delineating an efficient catalyst design strategy that integrates multi-active sites to achieve heightened selectivity and activity in the production of organonitrogen compounds, guiding the electrocatalytic process. Lastly, we will consolidate our discussion by addressing current challenges within this field, and we will propose a diverse range of efficient strategies to steer the future electrolysis of high-value chemicals.

Mechanism of C-N coupling reaction

The mechanism of C-N synthesis has been extensively studied in thermochemical, enzymatic, and molecular catalytic research. Since numerous reaction pathways for forming C-N bonds have been proposed, this discussion will be focused on several representative mechanisms considering the content limitation. The objective is to provide guidelines for electrocatalytic C-N bond coupling.

The industrial thermochemical heterogeneous catalytic process is often conducted under high temperature and pressure conditions, facilitating the generation of highly reactive radical intermediate species that subsequently participate in the C-N coupling reaction.[17] The reductive amination mechanism has been employed to achieve the industrial synthesis of primary amines under milder conditions. The pivotal C-N coupling step in this process involves the conversion of nitro-precursors into nucleophilic amines and the transformation of alcohols into electrophilic aldehydes.[18] The high-yield formation of corresponding amines and aldehydes is consistently attributed to the synergistic effects of dual metal sites. The nucleophilic attack of amines to aldehydes, resulting in the formation of targeted C-N-containing products, represents a thermodynamically spontaneous reaction.[19] The analogous reaction mechanisms also demonstrated in enzymatic catalytic and molecular processes for the construction for C-N bonds. The differences for enzymatic catalysis lie in the catalytic pocket characterized by active sites and a tunable microenvironment where the catalytic reaction takes place. Common enzymes catalyze reductive amination route including amine dehydrogenases and amino acid dehydrogenases, manipulating the local environment of catalytic pockets at the microlevel enables the stabilization of intermediates and the modulation of reaction equilibria towards the desired products.[20] In the realm of molecular catalysts, a key advantage lies in the diversity of available metal centers and ligands.



Scheme 1 Heterogeneous electrocatalysis for C-N coupling towards urea and others organonitrogen compounds via co-reduction CO_2 and N_2/NO/NO_2^-/NO_3^- feedstocks.

Take Buchwald–Hartwig amination as an example, which is a frequently used Pd(0)-catalysed cross-coupling reaction for the synthesis of aryl amines. These components can be designed and tuned to modulate the reaction landscape through electronic and/or steric effects, further facilitate the nucleophilic attack of amines on electrophilic carbon, a pivotal step in the C-N coupling reaction. Attention must be directed towards optimizing reaction conditions, including the solvent, temperature, reducing agents, and catalyst.[21]

Inspired by the aforementioned strategies for C-N coupling, these can be translated into a heterogeneous electrocatalytic process and summarized as follows: (1) The construction of bifunctional or multifunctional active sites is imperative for C-N coupling, given the adsorption and activation of multi-reactant molecules involved. (2) Optimization of the binding energy of various reactive intermediates on the active sites ensures the preferential activation of the first carbon or nitrogen species, subsequently coupling with the second reactant. (3) The local environment of the active sites and the reaction microenvironment can also play a role in electrocatalytic reactions, allowing for tuning of adsorption strength and reaction equilibrium.

Electrosynthesis of urea

Urea, is one of the most popularly used N-contained fertilizer, which has a market size of more than 200 million metric tons annually.[14] Moreover, it has gained tremendous attention as a potential material for energy storage applications.[22] The noteworthy Harbor-Bosch and Bosch-Meiser processes, involving thermocatalytic reaction of NH_3 with CO_2 via an ammonium carbamate intermediate at 200 ºC and 210 bar, are the mainstays of traditional industrial urea synthesis. The urea industry totally utilized 1%-2% of global energy consumption.[23]

Therefore, the development of an energy-efficient, environmentally friendly, and highly efficient method for urea synthesis is necessary and desirable. One alternative pathway for urea synthesis is the electrochemical co-reduction of CO_2 and nitrogen-containing species (such as N_2, NO, NO_2^-, NO_3^-), utilizing renewable electricity sources like wind or solar energy. However, during this process, the C-N coupling step faces competition from reactions such as the reduction of carbon-containing, nitrogen-containing species, and water, which greatly limits its selectivity towards the desired urea product.[24] The mechanisms underlying the C-N coupling reaction are not fully understood due to involved multiple intermediates and complex reactions, with requirement of further investigation.[25] Recent research studies in the fields of electrochemical CO_2 reduction and nitrogen-containing species have made significant contributions to deepen our knowledge in developing novel strategies for constructing C-N bonds to produce valuable chemicals, although the current C-N coupling is still too challenging to deliver efficient conversion.

Detection methods

Diacetylmonoxime-thiosemicarbazide method (DAMO-TSC)

The DAMO-TSC method, is a widely used analytical method for the quantification of urea.[27] It involves the reaction of urea with diacetyl-monoxime in an acidic environment, in the presence of ferric chloride and thiosemicarbazide. This reaction leads to the formation of a pink color in the solution. By measuring the chromogenic response of the reaction solution using colorimetry within the wavelength range of 520-530 nm, the concentration of urea can be accurately determined.[28] The DAMO-TSC method relies on detecting changes in absorbance at 525 nm, which have been found to increase proportionally with the concentration of urea. The relationship between absorbance and urea concentration follows a linear trend, enabling precise calibration and accurate quantification of urea levels. In the context of electrosynthesis, the concentration of urea is often relatively low, necessitating accurate quantification to ensure the reliability of experimental results. Experimental quantification limits are crucial in determining the minimum concentration that can be reliably measured. In a study, a linear correlation with an R^2 value of 0.9993 was observed between absorbance and urea concentration within the range of 0.1 to 10.0 μg mL^{-1}.[29] However, once the urea concentration exceeds 10 μg mL^{-1}, the linear correlation breaks down. The DAMO-TSC attained an experimental limit of quantification of (LOQ) urea was 0.1 μg mL^{-1}. To accurately measure higher concentrations of urea using DAMO-TSC, dilution of the solution is necessary, especially when dealing with high urea concentrations. The accuracy of the DAMO-TSC method can be influenced by some interference factors, leading to potentially inaccurate results. One significant interference factor is the presence of NO_2^-.[30,31] During the electrochemical CO_2 and NO_3^- co-reduction reaction, it is inevitable for NO_2^- to be produced as a by-product. Recently, Wang's group reported a modified DAMO-TSC method (M-DAMO-TSC) through using sulfamic acid solution (4%) reacted with NO_2^- via a nitrogen release reaction that can render the error of urea detection to be located within 3% and 5% when the concentration of NO_2^- below 30 ppm and 50 ppm, respectively.[29] It demonstrates that this modified detection protocol offers a relatively accurate urea detection by overcoming the NO_2^- interference.

Besides the NO_2^- interference, it is indeed important to consider the presence of other reducing reagents (e.g., S_2O_3, thiourea, and thiosulfate) and metal ions in the electrolyte when using the DAMO method for urea quantification.[32] While some metal ions (Co^{2+}, Fe^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, Ru^{3+}, Fe^{3+}, In^{3+}, Pd^{2+}, Mn^{2+}) may have a negligible impact on the DAMO-TSC method, however caution should still be exercised. To ensure reliable and accurate results, it is advisable to develop and utilize alternative urea detection methods that are less susceptible to interference from these substances, achieving more accurate urea quantification.

Urease decomposition method

The principle underlying the urease method for quantifying urea is based on the catalytic reaction between urea and the urease. Within this method, urea molecules are enzymatically hydrolyzed by urease, resulting in the formation of one molecule of carbon dioxide (CO_2) and two molecules of ammonia (NH_3).[33] The concentration of NH_3 produced during this enzymatic reaction is subsequently determined using the indophenol blue method.[34] By employing stoichiometric calculations, the concentration of urea can be accurately quanti-

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fied.

$$C(urea) = \frac{n(NH_3, urease) - n(NH_3)}{2 \times V}$$

Where $C(urea)$ is the measured urea concentration, V (mL) is the volume of the electrolyte, $n(NH_3)$ is the moles of ammonia electrosynthesis during the reaction, and n (NH_3, $urease$) is the total moles of ammonia after urea decomposed by urease in the electrolyte. It is worth noting that the indophenol blue method achieved an accurate quantification of ammonia in neutral or alkaline conditions. Under acidic conditions, the indophenol method may yield highly inaccurate results due to the instability of NaClO in acidic solutions.[35] In acidic solutions, when the urea concentration falls within the range of 0.1 to 7.0 μg mL^{-1}, ion chromatography and Nessler's reagent method are recommended to measure the ammonia concentration. However, it is essential to consider the interference factor when quantifying urea using the urease method. Research conducted by Zhang's group revealed that the presence of 100 mM NO_2^- can inhibit the chromogenic reaction of indophenol, leading to an underestimation of the NH_4^+ concentration in the system, thus resulting in a lower calculated urea concentration. Conversely, when the NO_2^- concentration is below 50 mM, the interference on both the urease and indophenol methods can be neglected.[31] When the NH_4^+ concentration is below 20 ppm, the impact on urea quantification is minimal, with a relative error of less than 10%. However, as the NH_4^+ concentration increases over 20 ppm, the relative error in urea quantification can increase up to 30%.[26] Additionally, certain metal ions such as Co^{2+}, Fe^{2+}, and Mn^{2+}, which may leach from catalysts, can inhibit urease activity, leading to an underestimation of urea concentration.[36] On the other hand, Ru^{3+} can react with the color reagent and cause overestimation of urea concentration.[35] Moreover, special attention must be given to the purity of urease reagents to guard against the presence of ammonium ion impurities in urease produced by certain manufacturers, which may overestimation of urea concentration. Given the potential interference factors and their impact on urease methods, it is crucial to be aware of and mitigate these interferences when quantifying urea concentration. By doing so, more accurate, and reliable results can be obtained.

^{1}H NMR spectroscopy and HPLC methods

Both ^{1}H NMR spectroscopy and HPLC methods are valuable for quantifying the concentration of urea. In ^{1}H NMR spectroscopy, it is important to prevent the rapid hydrogen-deuterium exchange between the active $-NH_2$ group of urea and the deuterium reagent. To address this issue, DMSO-d^6 is commonly used as an ideal deuterium reagent.[37,38] The chemical shift of urea is typically observed at approximately 5.59 ppm, and the detection limit of the ^{1}H NMR method is 0.3 ppm. By increasing the accumulation numbers, the LOQ of urea can be further improved to 0.1 ppm, allowing for more sensitive quantification of urea concentration.[26] To achieve a linear correlation coefficient and a lower detection limit, the use of a 700 MHz or 800 MHz NMR spectrometer is necessary. The HPLC method, on the other hand, has a LOQ of 0.005-0.5 ppm. The peak corresponding to urea appears at around 7 minutes, and a high linearity (R^2=0.999) can be obtained in the concentration range of 0.005-0.5 ppm to 500 ppm of urea.[26] Both ^{1}H NMR and HPLC methods have been found to be unaffected by the presence of metal ions, C/N-containing species (such as $HCOO^-$, CH_3OH, CH_3CH_2OH, NH_4^+, NO_2^-, and NO_3^-), and other C-N by-products (like formamide and acetamide), thereby ensuring accurate quantification of the urea concentration. Consequently, both ^{1}H NMR and HPLC methods are considered reliable techniques for quantifying the amount of urea produced during the electrochemical C-N coupling reaction.

To mitigate the impact of interfering substances such as NO_2^-, NH_4^+, and Ru^{3+} on the quantification of urea, we have devised a meticulous and rigorous protocol for photo/electrocatalytic urea synthesis (Figure 1). Subsequently, we present a comprehensive categorization of detection methods derived from the aforementioned investigation. It is important to highlight that employing a multi-quantification approach for urea, conducting control experiments, and incorporating isotopic tracing experiments are highly recommended and deemed essential for ensuring the precision and accuracy of experimental results.

Electrocatalytic C–N coupling via CO_2/N_2 co-reduction

N_2, the main component of earth's atmosphere, possesses a robust triple bond (945 kJ mol^{-1}) between its nitrogen atoms.[39] This triple bond confers high stability to N_2, making it challenging to be utilized by natural processes and human activities, except for certain microorganisms with the nitrogenase and the Haber-Bosch process, which can convert N_2 into more reactive forms like ammonia under extreme conditions.[40] However, the electrochemical C-N coupling process presents a groundbreaking approach to utilize N_2 and CO_2 as feedstocks for urea production. Through electrochemical methods, it becomes feasible to overcome the obstacles associated with breaking the robust triple bond of N_2 and transforming it into more valuable compounds.

Since the first literature reported by Kayan's research group in 2016, they achieved the synthesis of urea through electrochemical co-reduction of CO_2 and N_2.[41] The significant efforts have been devoted to the electrochemical co-reduction of CO_2 and N_2 to urea under ambient conditions. During the electrochemical co-reduction of N_2 and CO_2, the key issues is to form the *N=N and *CO intermediates due to the followed formation of *NCON* species is energetically favorable.[42] However, limited by the hardship in activation of N_2 and complex C-N coupling process, the electrosynthesis of urea suffered from low activity and worse selectivity. Therefore, the attention is suggested to focus on the absorption and activation of N_2 and CO_2 to guarantee the enough intermediates.

The electronic orbit interaction and electronic engineering were considerate as an effective strategy. Zhang's group recently reported two heterostructure catalysts, named Bi-$BiVO_4$ and $BiFeO_3$/$BiVO_4$ respectively.[43,44] They pointed that the built-in electric field of heterostructure achieve the redistribution of local charge to form the electrophilic and nucleophilic regions (Figure 2a). Subsequently, the targeted adsorption and activation of N_2 and CO_2 to yield the *N=N and *CO intermediates, further facilitating the formation of key intermediate *NCON* via exothermic C-N coupling process (Figure 2b). Additionally, a similar σ-orbital carbonylation strategy

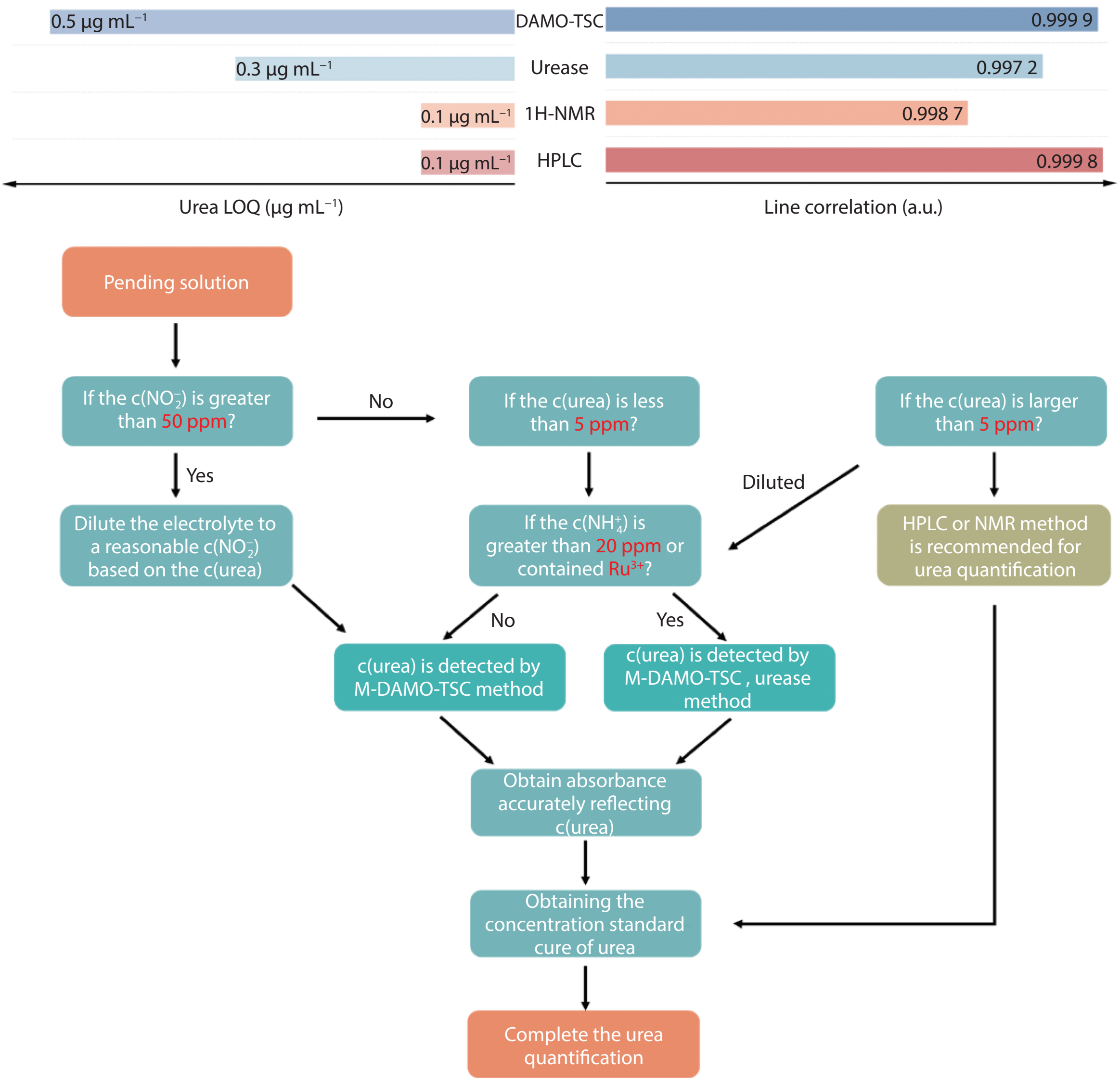

Fig. 1 Comparison of four urea quantitative methods and the proposed photo/electrocatalytic urea synthesis and quantification protocol.

has been reported for a novel conductive MOF Co–PMDA–2-mbIM, induced by host-guest interactions.[45] The local CoO_6 octahedron and 2-mbIM guest molecule provide the electrophilic and nucleophilic regions, respectively, achieve effectively activation of N_2 and CO_2 to produce the target intermediates (Figure 2c, d). A unique frustrated Lewis pairs strategy was demonstrated by the same group, suggested the Lewis basic and acidic sites work together to capture and activate inert CO_2 and N_2 molecules.[46,47] The σ orbital electrons are then transferred to the empty e_g orbitals of the metal sites, facilitating the coupling with the carbine *CO to generate the key intermediate *NCON. Besides, the matched molecular orbitals between *N=N* and *CO can also promote the C-N coupling process catalyzed by PdCu alloyed catalyst, which achieve a high yield rate of urea of 3.36 mmol g^{-1} h^{-1} and a corresponding Faradaic efficiency of 8.92% were achieved in a flow cell.[48] The tuned spin and electronic states, enhance the interaction with key intermediates, overcoming the challenges of the C-N coupling reaction and facilitating the electrosynthesis of urea.

The atomic catalyst with well-defined active sites, high atom utilization efficiency, and adjustable coordination structure have a great potential in urea electrosynthesis. Ghorai's group demonstrated that copper phthalocyanine nanotubes (CuPc NTs) with multiple active sites, specifically pyrrole-N_1 and single Cu sites, can reduce N_2 to *NN and CO_2 to CO, respectively.[49] Subsequently, the released CO molecule can couple with *NN to form *NCON, which achieved a urea yield of 143.47 $\mu g\ h^{-1}\ mg_{cat}{}^{-1}$ and a Faradaic efficiency of 12.99% at −0.6 V versus RHE in 0.1 M $KHCO_3$. However, single active site hardly achieves multi-reactants optimized absorption and activation due to the scaling relationship. Therefore, Wang's group reported the development of a dual atom catalyst Pd_1Cu_1-TiO_2 using a vacancy-anchorage strategy (Figure 3a).[50] Significantly, the Pd_1Cu_1-TiO_2 catalyst exhibited remarkable urea activity of 166.67 $mol_{urea}\ mol_{Pd}{}^{-1}\ h^{-1}$ with a corresponding Faradaic efficiency of 22.54% at -0.5 V versus the reversible hydrogen electrode (RHE), surpassing the per-

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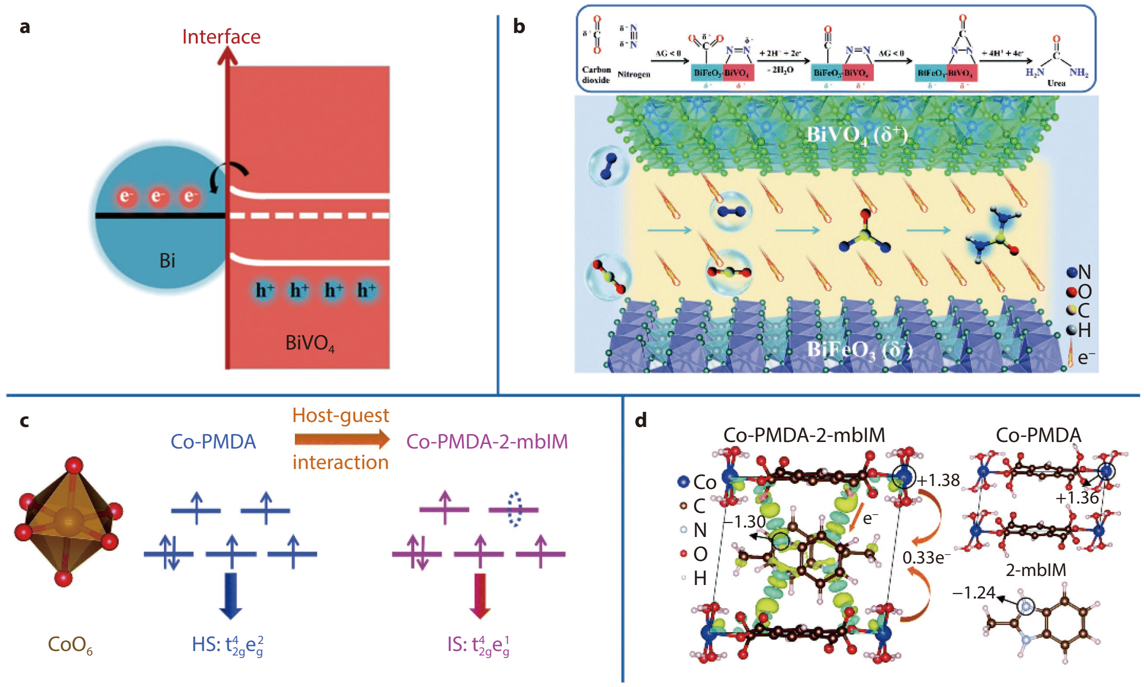

Fig. 2 **a** Schematic illustration of the charge transfer process in Bi-$BiVO_4$.[43] Copyright 2021, Elsevier. **b** The schematic electrocatalytic urea production mechanism based on $BiFeO_3/BiVO_4$ p–n heterostructure synergistic effects.[44] Copyright 2021, Royal Society of Chemistry. **c** A schematic illustration of spin-state regulation and **d** the charge density difference of in Co–PMDA–2-mbIM induced by host–guest interaction.[45] Copyright 2022, Royal Society of Chemistry.

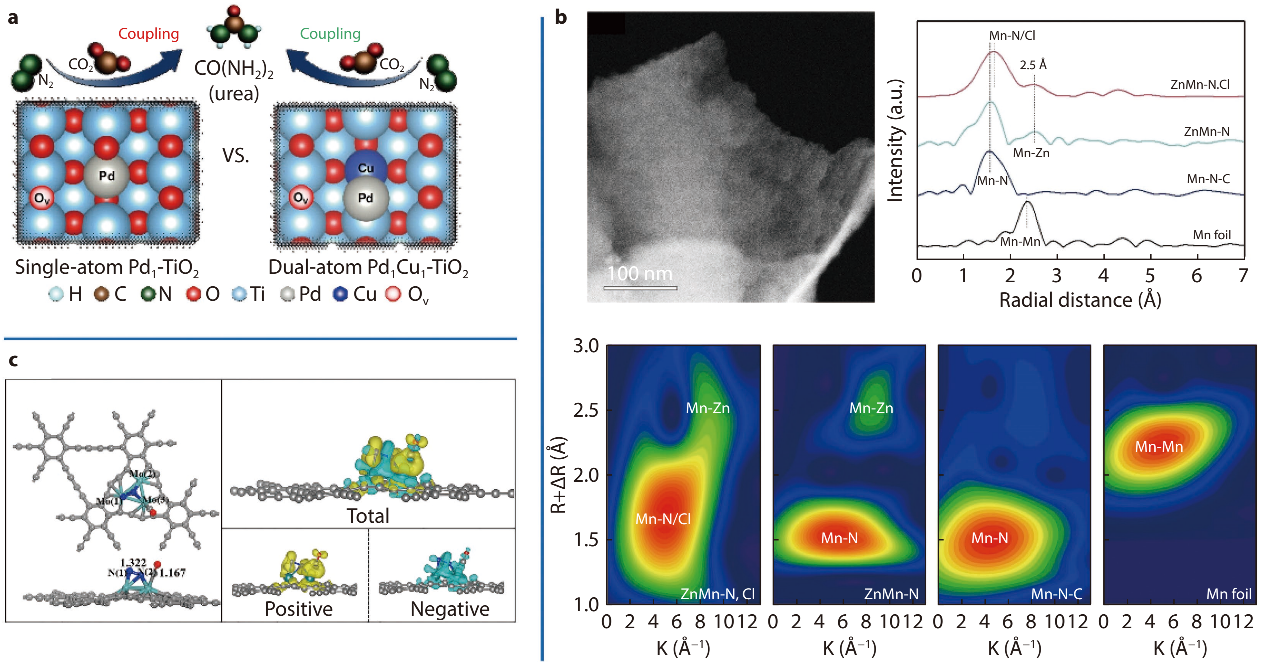

Fig. 3 **a** Schematic illustration of the comparison on electrocatalytic urea synthesis by the single-atom $Pd_1–TiO_2$ and dual-atom $Pd_1Cu_1–TiO_2$ catalyst models.[50] Copyright 2022, Elsevier. **b** Morphology and structure of ZnMn–N,Cl.[51] Copyright 2023, Elsevier. **c** The most stable configuration of N_2 and CO co-adsorption on Mo_3@GDY and the corresponding charge difference diagram.[52] Copyright 2023, Elsevier.

formance of the single atom catalyst Pd_1-TiO_2. The enhancement of urea electrosynthesis can be attributed to the synergistic effect of the Pd_1Cu_1 dual atom and the presence of oxygen vacancies. In addition, non-metal atoms, except for nitrogen atoms, coordinate with atomic-dispersed metal sites to serve as anchoring agents and fine-tune the performance of atomic catalysts, yielding impressive results. A Zn–Mn diatomic catalyst with axial chloride coordination (Figure 3b) and a novel tri-metallic Mo atoms coordinated with carbon atom in graphdiyne (Mo_3@GDY) (Figure 3c) were demonstrated with remarkable performances due to the distinctive coordination environment.[51,52] What interesting example is constructing metal-free clusters by doped B_{12} cluster on nitrogenated graphene substrate catalyst ($B_{12}@C_2N$) to achieve a high catalytic activity for urea synthesis.[53] The construction of multi-active sites via designing and preparing atomic catalysts to simultaneously activate various reactants becomes necessary for further enhanced coupling reaction.

Although most literature demonstrated that the C-N coupling to form *NCON* intermediates play a critical role in synthesis of urea. Recently, Zhao's group reported a MoP-(101) catalyst suggested that the coupling of $*N_2H_2$ with *CO was found to be energetically more favorable in the formation of *NHCONH key intermediates rather than the coupling of $*N_2$ and *CO.[54] While some progress has been documented in achieving C-N coupling for urea electrosynthesis, challenges persist in activating the resilient triple bonds of N_2. Antibonding orbital theory emerges as a potentially effective strategy, involving the introduction of electrons from active sites to the antibonding orbital of N_2. Given the intricacies inherent in the electrocatalytic synthesis of urea, it is essential that we redouble our research endeavors to unravel the underlying reaction mechanism, ultimately striving to enhance the catalytic activity in the electrocatalytic synthesis of urea.

Electrocatalytic C–N coupling via CO_2/NO co-reduction

NO, as an industrial waste gas, has been extensively studied for the electrochemical production of ammonia.[55] Unlike N_2 with a stubborn triple bond and low solubility, the NO with a weak binding energy and easily be acquired, is expected to serve as an alternative nitrogen source for coupling with CO_2 to produce urea. Recently, Zhang's group reported a ZnO nanobelts (ZnO NBs)-based catalyst for electrochemical co-reduction of NO and CO_2 in water to produce urea.[56] The ZnO nanobelts are prepared through the in situ electrochemical reduction of Zn nanosheets (ZnO NSs). The optimized Faradaic efficiency value of 1.12% for urea production at a potential of -0.92 V vs RHE can be obtained. In a flow cell electrolyzer, it is impressive to obtain a urea yield rate of 15.13 $mmol^{-1}$ h^{-1} g^{-1} and a corresponding Faradaic efficiency of 11.26% at a current density of 40 mA cm^{-2}. It was proposed that the urea was synthesized through a ten-step cascade reaction process. Meanwhile, the presence of NO is in favor of the *CO desorption as well as C-N coupling reaction of *CO and $*NH_2$ to form $*CONH_2$ that was considered as the key intermediate for urea electrosynthesis (Figure 4).

Electrocatalytic C–N coupling via CO_2/NO_2^- co-reduction

In 1995, Furuya's group reported the electrochemical co-reduction of CO_2 and NO_2^- catalyzed by Cu-loaded gas-diffusion electrode for urea electrosynthesis.[34] This work firstly figured out that the intermediates *CO and ammonia play a crucial role in urea synthesis via co-reduction CO_2 and NO_2^- species. On the one hand, the enhancement of absorption for CO_2 and NO_2^- can induce the increased accumulated concentration of corresponding intermediates. On the other hand, the optimized free energy of the key intermediates will be beneficial for the C-N coupling process.

The defect engineering was proposed as an efficient strategy to tackle the above issues, resulting from the en-

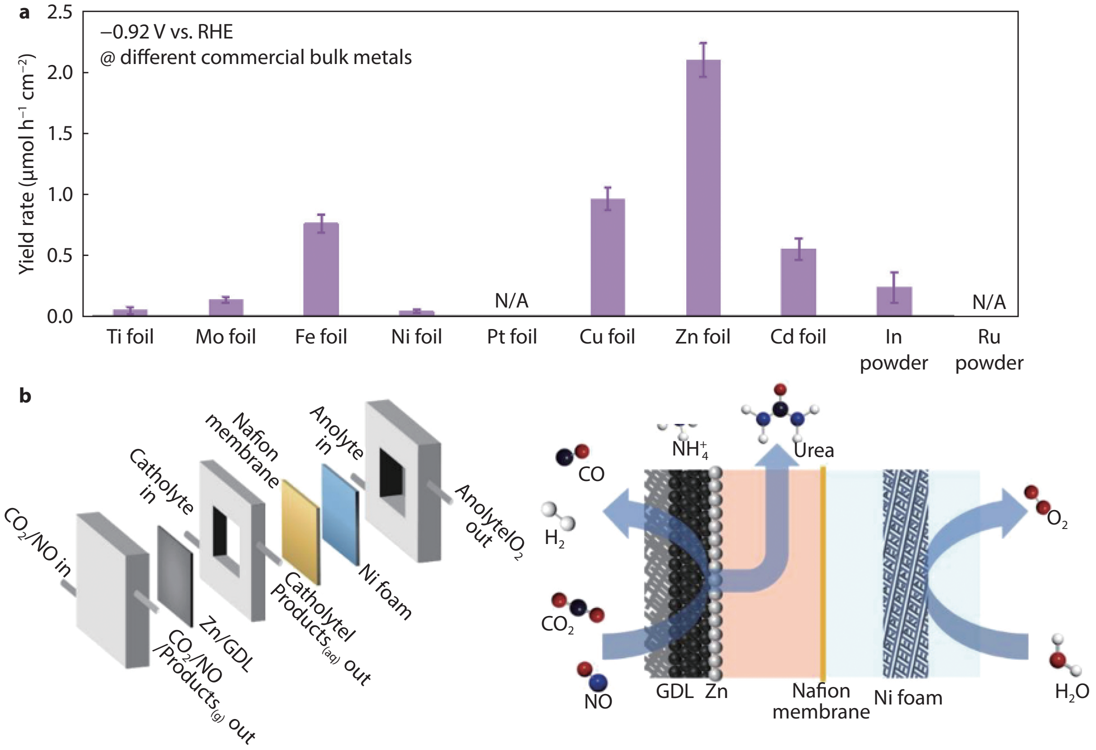

Fig. 4 **a** The performances of electrosynthesis of urea over ZnO NBs and others catalyst. **b** Schematic illustration for the flow cell.[56] Copyright 2022, American Chemical Society.

hancement of the absorption for corresponding reactants. Zhang's group prepared oxygen vacancy-rich ZnO (ZnO-V) porous nanosheets, which the oxygen atom of NO_2^- and CO_2 will fill the oxygen vacancies to generate COOH* and $*NH_2$ species via proton-coupled electron transfer processes.[57] Afterwards, the COOH* acts as the key intermediate species, reacting with $*NH_2$ further boosting the urea electrosynthesis (Figure 5a). To further improve the performances of urea electrosynthesis, the low-valence Cu doped anatase TiO_2 with abundant oxygen vacancies (Cu-TiO_2) was reported.[58] This work demonstrated that low-valence Cu served as catalytic center to reduce CO_2 into CO*, oxygen vacancies and bi-Ti^{3+} defects largely accelerate the adsorption and activation of NO_2^-, indicating the significance of construction of multiple active sites. Besides metal oxide, Wang's group developed ultrathin AuCu alloy nanowires with abundant structural defects and lattice strain achieve a high performances of urea electrosynthesis due to the large number of exposed highly catalytically active sites (Figure 5b).[59]

Besides vacancy engineering, the alloying of materials has emerged for promising electrocatalysis by offering advantages such as diverse element compositions, high atomic diffusivity, superior chemical homogeneity, and synergistic effects. The Te-Pd NCs and Co-NiOx@GDY were reported to boost the urea electrosynthesis (Figure 5c, d).[60,61] Noteworthy, both two work exhibited high activity and selectivity for urea which can be summarized as follows: (1) the multi-component catalyst can effectively boost the activation of CO_2 and NO_2^- species to yield the *CO and $*NH_2$ intermediates followed proceeding C-N coupling towards $*CONH_2$; (2) The coordination state and electronic structure of the bimetallic active sites can be modulated, further promoting the co-activation of CO_2 and NO_2^- sources while inhibiting the competition side reaction. The results highlight the potential of the alloying materials in enhancing the electrocatalytic performance for the co-reduction of CO_2 and NO_2^-.

Electrocatalytic C–N coupling via CO_2/NO_3^- co-reduction

The electrochemical co-reduction of NO_3^- and CO_2 as feedstocks to produce urea presents a promising solution to mitigate environmental pollution, reduce CO_2 emissions, and contributes to the broader objective of establishing a circular carbon economy. Since the first work for the electrocatalytic co-reduction of CO_2 and NO_3^- towards urea synthesis, a tremendous strategy was proposed. The defect engineered strategy including oxygen vacancies, coordination structure regulation for atomic catalyst and hybrid catalyst were reported to tune the electronic structure of the active sites and the adsorption free energy of key intermediates, further boosting the performances of electrosynthesis of urea. Besides, accumulated concentration of key intermediates over active sites was also investigated via a structurally stacked tandem gas diffusion electrode, to enhance the co-reduction of CO_2 and NO_3^- species.

The oxygen vacancies extensively investigated for catalysis have been demonstrated to exhibit relatively high surface energy and to play a crucial role in modifying the electronic structure of active sites and reducing the energy barrier of rate-determining steps as well as accelerating the overall kinetic process. A notable example is that the oxygen vacancies in indium oxyhydroxide (Vo-InOOH) was proposed to facilitate the reduction in energy barrier for the protonation of the $*CO_2NH_2$ intermediate, which is considered as the potential-determining step in the urea electrosynthesis process (Figure 6a, b).[62] One of challenges in electrochemical co-reduction of CO_2 and NO_3^- is the kinetics-favorable hydrogenation process of intermediate species leading to the relatively low yield and selectivity of urea. Wang's group ever prepared an oxygen vacancy-enriched CeO_2 catalyst denoted as Vo-CeO_2-750 was confirmed to exhibit enhanced adsorption of CO_2 and nitrate ions.[63] The C-N coupling process to produce urea was largely accelerated due to the inhibited hydrogenation of

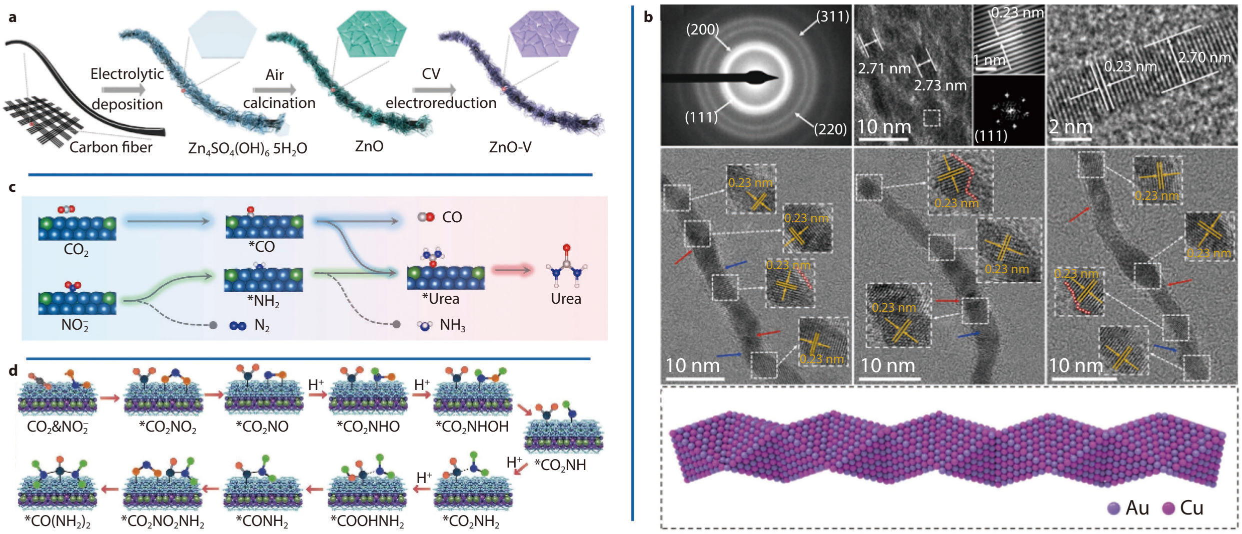

Fig. 5 **a** Schematic illustration of synthesis of ZnO-V porous nanosheets.[57] Copyright 2021, Cell Press. **b** Characterization of the AuCu SANFs.[59] Copyright 2022, Cell Press. **c** Scheme of the urea synthesis from CO_2RR and NO_2RR on Te–Pd NCs.[60] Copyright 2022, American Chemical Society. **d** Reaction mechanism studies for electrocatalytic urea synthesis on Co–NiO_x@GDY.[61] Copyright 2022, Oxford University Press.

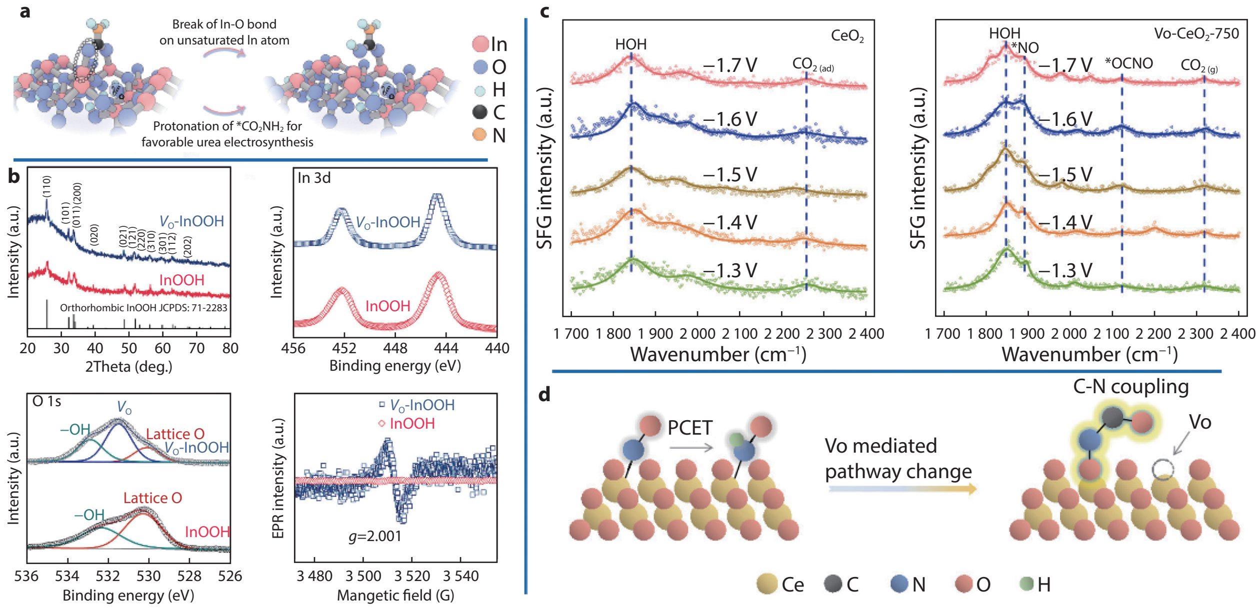

Fig. 6 **a** Illustration for the preparation and urea synthesis processes. **b** XRD patterns, In 3d, O 1s XPS spectra, and EPR spectra of V_O-InOOH and pristine InOOH.[62] Copyright 2022, American Chemical Society. **c** SFG signals of intermediate species on pristine CeO_2 and Vo-CeO_2-750. **d** Schematic diagram of Vo-mediated reaction pathway changes on CeO_2.[63] Copyright 2022, American Chemical Society.

*NO key intermediates towards for evolution of ammonia byproduct (Figure 6c, d). Consequently, the Vo-CeO_2-750 catalyst exhibited an exceptional urea yield of 943.6 mg $h^{-1}g^{-1}$ at -1.6 V vs. RHE in a CO_2-saturated 0.1 M $NaHCO_3$+0.05 M KNO_3 solution. The presence of oxygen vacancies was proposed to reconfigure the electronic structure of the active sites, resulting in enhanced stability of the key intermediates involved in the C-N coupling reaction as well as production of urea.

The activity and selectivity of urea production is greatly related to the sole CO_2RR and NO_3RR reactions, as was demonstrated to be affected by the coordination structure of atomic catalysts. The co-activation of CO_2 and NO_3^- as well as the electrocatalytic C-N coupling of the corresponding key intermediates were considered as two crucial steps for the electrosynthesis of urea. Recently, Amal's group introduced a Cu single atom catalyst with tunable Cu-N_4 and Cu-$N_{4\text{-}x}$ sites by varied pyrolysis temperature, which is more favorable for the CO_2RR and NO_3RR to generate *CO and *NH_2 intermediates, respectively (Figure 7a).[64] While single-atom copper catalysts have shown high performance in C-N coupling reactions, the reconstitution of single atoms into clusters can be challenging to avoid. This makes it even more crucial to identify the real active sites for the electrocatalytic process. Wang's group addressed this issue by reporting a single-atom Cu catalyst supported on CeO_2 (Cu-CeO_2), however, the single atoms were found to reconstitute into clusters (Cu_4) during the electrolysis process.[65] These Cu_4 clusters were the genuine active sites for the adsorption and activation of CO_2 and NO_3^-, leading to the formation of key intermediates (*CO and *NO) and ultimately improving the performance of urea electrolysis (Figure 7b, c). In recent studies, an outstanding Cu-based salphen complex called Cu-SP-OMe, consisting of Cu-N_2O_2 sites, achieved a high urea yields of 3.64 mg h^{-1} mg_{cat}^{-1}.[66] The oxygen coordination atoms in Cu-SP-OMe help in accumulating electrons around the Cu center, thereby promoting the reduction process. Additionally, the -OMe groups in the complex contribute to the stabilization of key intermediates through strong interactions (Figure 7d). Though a few of advancement have been reported in this field, the scaling relation limits cannot be avoided over single active sites, further impeded the activity and selectivity of aimed products for multi-proton couple with electron process.

Herein, diatomic catalysts providing alterative solutions compared to single atomic catalyst, to accelerate the complex multi-step reaction due to its multi-active sites. Besides, the coordinated structure enables to tune the electronic structure and d band center, optimize the adsorption and activation energy of the multi-reactant, further promoted the selectivity and activity of the aimed product. Wang et al. ever prepared a bonded Fe-Ni pair diatomic catalyst (B-FeNi-DASC) achieved a highest urea production rate of 20.2 mmol h^{-1} g^{-1} with a corresponding Faradaic efficiency of 17.8% compared to single atomic Fe-SAC and Ni-SAC catalyst, and isolated dual atomic I-FeNi-DASC catalyst due to the thermodynamically and kinetically feasible C-N coupling process occurring on the bridge sites of Fe-Ni pairs, while simultaneously suppressing the HER side reaction (Figure 8a).[30] The existence of Cu-Ti bimetallic active sites has been documented, and it is found to be favorable for C-N bonding.[67] This is attributed to the proximity of Cu and Ti atoms, which leads to a reduction in the energy barrier for the coupling of *CO and *NH_2 species. Atomically dispersed Cu atoms in Pd lattice with charge-polarized $Pd^{\delta-}$-$Cu^{\delta+}$ dual-sites single-atom alloy provide effective solutions over the issues of stabilized *CO and *NH_2 key intermediates (Figure 8b-d).[68] It is also demonstrated that a dual single-atom Ru and Co on N-doped carbon ($CoRuN_6$) with asymmetric orbital hybridization can help to fix the C/N group respectively, minimize the free energy for intermedi-

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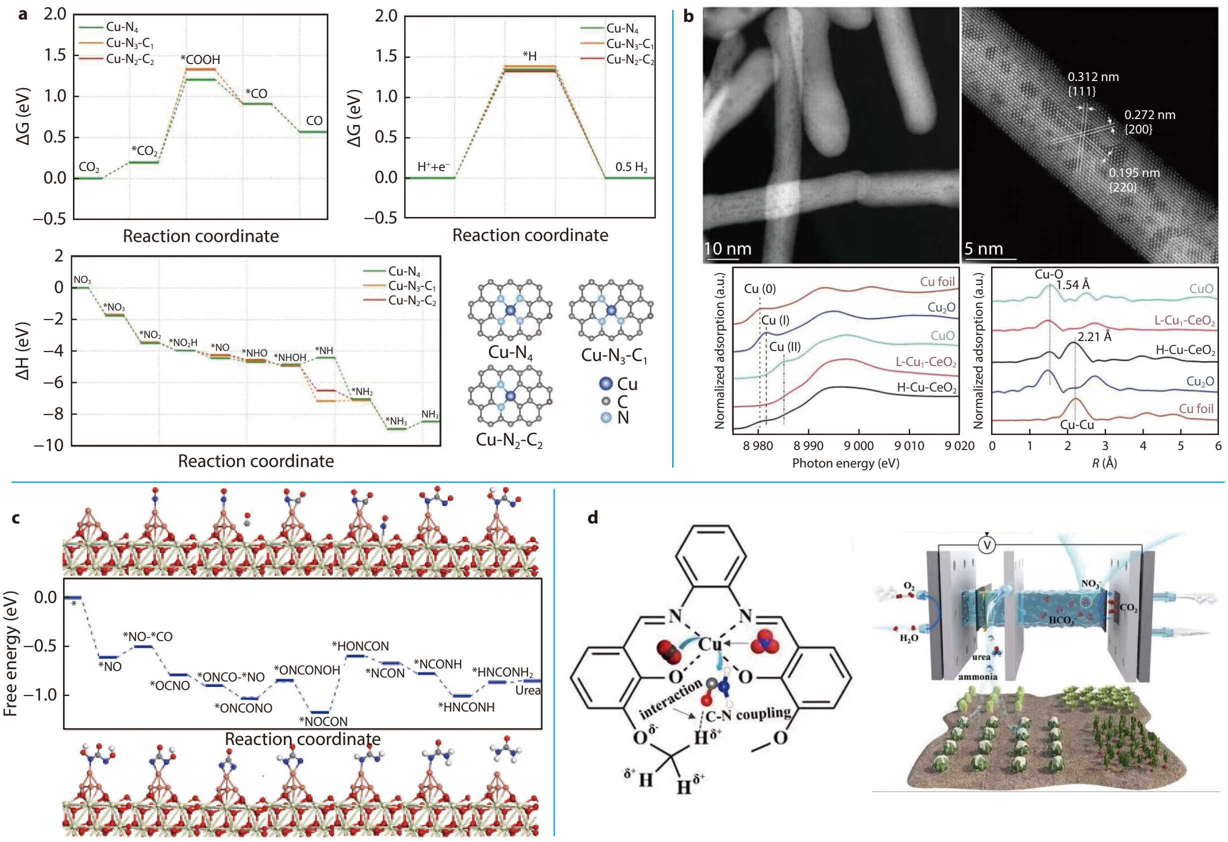

Fig. 7 Reaction pathways for **a** CO_2RR to CO, HER in an acidic medium, and NO_3RR to NH_3 based on the modeled Cu-N-C sites.[64] Copyright 2022, Wiley. **b** Morphology, Cu K-edge XANES spectra, and Cu R-space EXAFS spectra of L-Cu_1–CeO_2, H-Cu–CeO_2 and reference samples. **c** Free-energy profiles and optimized geometric structure schematic of C-N coupling process on Cu_4–CeO_2 sample.[65] Copyright 2023, Wiley. **d** Illustration of the structure of Cu–SP–OMe during the co-reduction process. Copyright 2023, Wiley.

ates, and decreasing coupling barrier due to the spatial regulation of active sites (Figure 8e).[69]

In the complex, multi-step electrochemical co-reduction of CO_2 and NO_3^- for urea synthesis, two critical considerations should be addressed. First, increasing the quantity of exposed active sites is paramount. Second, it is essential to achieve synergistic interactions among various sites to optimize the adsorption intensity and accumulated concentration of key intermediates during the electrocatalytic process. Qin's group reported the synthesis of molybdenum oxide nanoclusters supported on carbon black (MoO_x/C).[70] The presence of a heterostructure between MoO_x nanoclusters and carbon black facilitates the transfer of electrons from the support to the MoO_x nanoclusters. This electron-rich environment in the MoO_x nanoclusters, along with the presence of unsaturated active sites, contributes to the exceptional performance of the catalyst in urea synthesis. The support effect boosts the urea electrosynthesis process via increasing the exposed active sites was also verified by the graphene-In_2O_3 electrocatalysts.[71] The synergistic interactions among various sites have been demonstrated by Yu's group, the (100) facets of $In(OH)_3$ exhibited a significantly higher activity in urea synthesis compared to the (110) facets. The (100) facets conduce to strong $*NO_2$ adsorption and the adjacent In-O-C-O-In configuration can help to stabilize the $*CO_2$ intermediates, which lows the energy barrier of C-N coupling (Figure 9a, b).[72] Regarding the crystal facet effect, another illustrative example involves Cu_2O with (100) facets, where Cu^+ collaborates with Cu^0 to enhance the C-N coupling process through synergistic interactions.[73] The modulation of atomic-scale spacings (ds) in Cu_2O also provide an effective strategy for overcoming the challenge of accelerating the kinetic and thermodynamic aspects of C-N bond formation (Figure 9c).[74] To enhance urea selectivity and mitigate competing side reactions, Sargent's research group has designed a Cu/Zn hybrid catalyst that attains a urea selectivity of 75% through a relay catalysis mechanism.[16] Specifically, the pivotal intermediate $*CO_2NO_2$ is selectively generated on Zn sites, and the subsequent protonation step for the formation of $*COOHNH_2$ benefits from a reduced reaction energy when occurring on nearby Cu sites (Figure 9d). A bimetallic $CuWO_4$ catalyst with two individual sites also suggested to largely improve the performances of urea electrosynthesis via stabilize $*NO_2$ and *CO intermediates and, concurrently, the reduction of the energy barrier for the C-N coupling process.[75]

The heteroatom doped strategy, including nonmetallic atoms and metallic atoms, have been demonstrated as one efficient way to reduce the energy barrier in electrochemical co-reduction CO_2 and NO_3^-. He's group reported a Pd doped the face-centered cubic Au nanocrystal (XC72R-AuPd) realize the electrosynthesis of urea with a low activation barrier due to electronic interaction between Au and Pd. Furthermore,

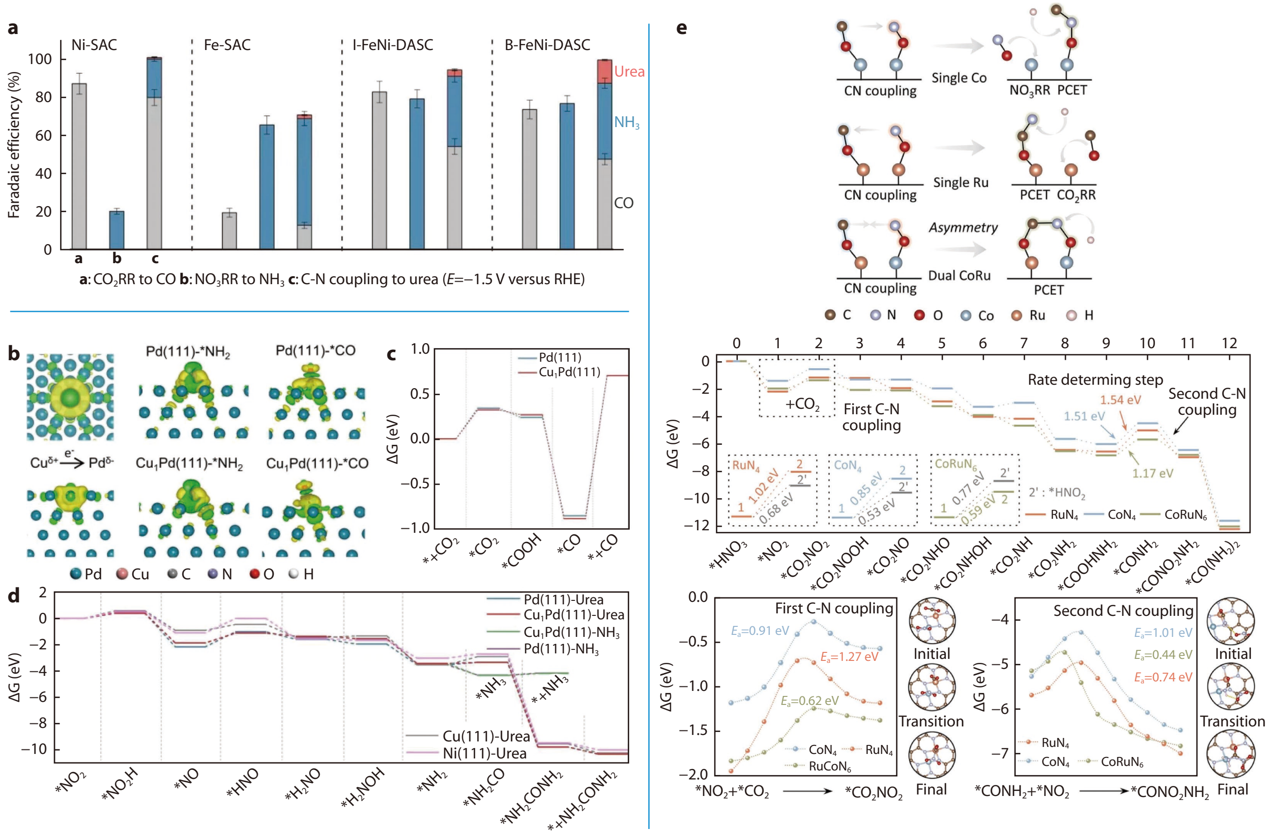

Fig. 8 **a** The product distributions of CO_2RR, NO_3RR and urea synthesis on Ni-SAC, Fe-SAC, I-FeNi-DASC, and B-FeNi-DASC at −1.4 V versus RHE.[30] Copyright 2022, Springer Nature. **b** Differential charge density of $Cu_1Pd(111)$, $Cu_1Pd(111)$-*NH_2, Pd(111)-*NH_2, $Cu_1Pd(111)$-*CO, Pd(111)-*CO. **c** Energy profiles of each elementary step in single CO_2RR catalyzed by $Cu_1Pd(111)$ and Pd(111) planes. **d** Energy profiles of each elementary step in NO_3RR with C−N coupling toward urea synthesis catalyzed by $Cu_1Pd(111)$, Pd(111), Cu(111) and Ni(111) planes.[68] Copyright 2023, Springer Nature. **e** Free-energy diagram of different catalysts for urea production.[69] Copyright 2023, Elsevier.

this research postulated that *NH_2OH and *CO, rather than *NH_2 and *CO, serve as the key intermediates that enable the C-N coupling process.[76] Moreover, when the active metal indium (In) is introduced as a dopant in bismuth (Bi) catalysts, the otherwise inert bismuth can be transformed into active sites, in cooperation with indium, significantly enhance the C-N coupling process, primarily through electronic interactions.[77] Except for metallic element doped, an intriguing observation is the first-ever report of nonmetallic fluorine (F) doping in carbon nanotubes (F-CNT) for urea synthesis over the active sites of C-F_2 moieties.[78]

The above-mentioned strategies, all designed to modulate the absorption intensity of crucial intermediates and lower the energy barrier, prove to be an efficient approach for enhancing the yield rate and selectivity of urea synthesis. It is crucial to emphasize the accumulated concentration of pertinent intermediates in the proximity of active sites. Recently, Wu's group designed a structurally stacked tandem gas diffusion electrode (GDE) to effectively co-reduce CO_2 and NO_3^- for urea synthesis.[79] The stacked gas diffusion electrode (GDE) incorporates a ZnO catalyst layer (CL) segment and a Cu CL segment to selectively activate CO_2 to *CO and NO_3^- to *NH_2, respectively. By adjusting the area ratio of ZnO and Cu, the spatial distribution of *CO and *NH_2 concentrations can be managed (Figure 10a, b). In a flow cell setup, optimal results were achieved with a Cu:ZnO area ratio of 1.0:0.5, yielding a high urea yield of 3.2 μmol h^{-1} cm^{-2} and a faradaic efficiency of 37.4% at a potential of -0.3 V vs. RHE (Figure 10c). Therefore, spatially managing the concentration of critical intermediate species and optimizing the absorption energy over the active sites provide a promising strategy to address the current challenges of poor selectivity and low current in the electrochemical co-reduction of CO_2/NO_3^- for urea synthesis.

Electrosynthesis of other organonitrogen compounds:

In this section, organonitrogen synthesis are classified and described, such as amino acids, oximes, amines, amide, nitrile etc., that have been widely applied in medicine, life science and agriculture. Considering the limited content, the recent advances mainly involved inorganic reagents such as CO_2/CO and N_2/NO/NO_2^-/NO_3^- as feedstocks were summarized.

Amino acids and oxime

Amino acids, as vital constituents of proteins, play a pivotal role in sustaining the functioning of life.[80] While, the current Strecker method for production of amino acids suffered from high toxic cyanogen compounds.[81] Electrosynthesis process provide an alternative strategy which mainly derived from

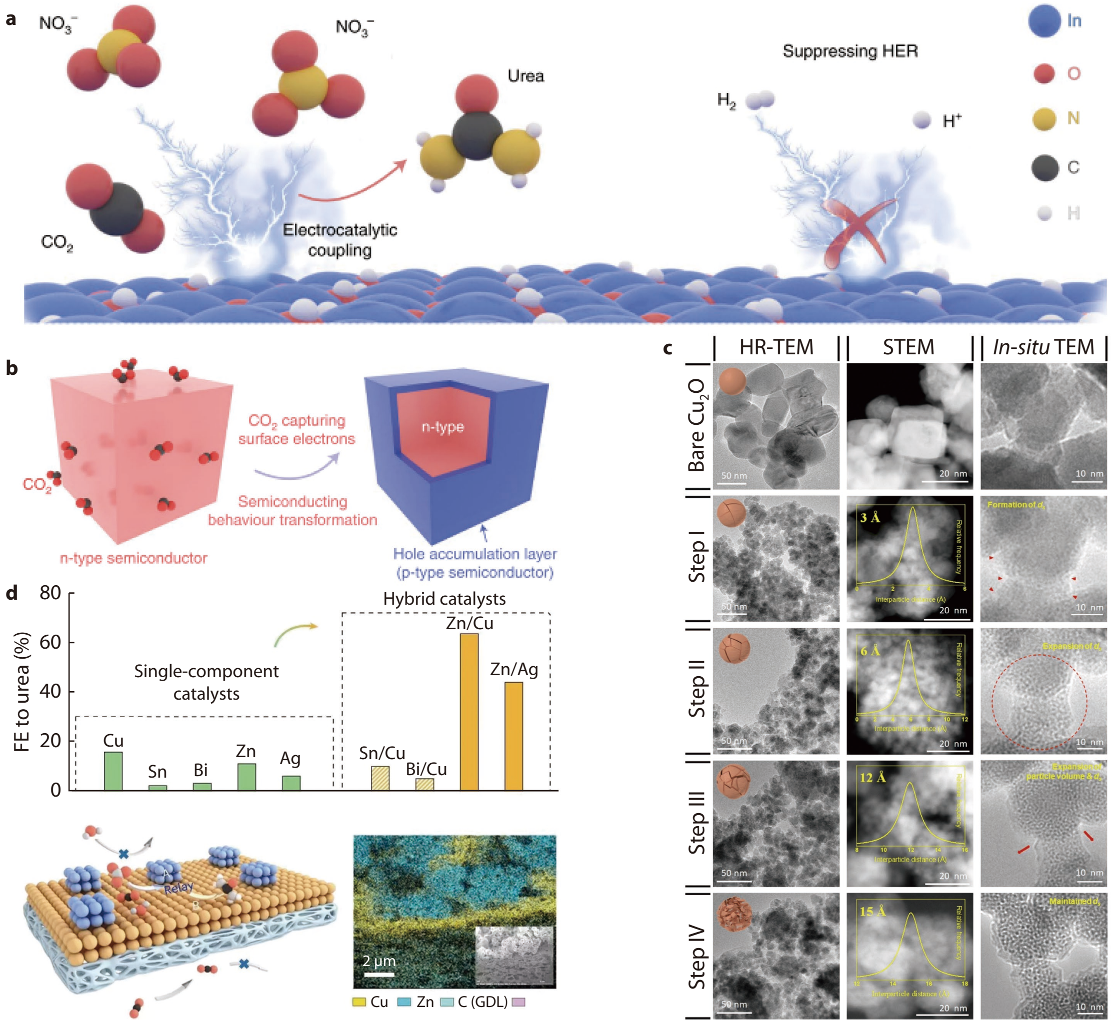

Fig. 9 **a** Illustration for urea synthesis process on the surface of $In(OH)_3$-S. **b** Schematic illustration of n–p transformation process in semiconductor type. The left image is the n-type $In(OH)_3$, while the right image displays the generation of surface p-type layer on $In(OH)_3$ induced by CO_2 capture.[72] Copyright 2021, Springer Nature. **c** HR-TEM, STEM, and in situ TEM analysis of bare and lithiated Cu_2O according to a degree of lithiation.[74] Copyright 2023, Royal Society of Chemistry. **d** Screening of single-component and hybrid catalysts for Zn/Cu catalysts.[16] Copyright 2023, Springer Nature.

electrochemical co-reduction NO_x and keto acids. Among of reported literature, the catalysts for AD Fe/NC, CoFe-SSM, and PdCu NBW achieve the multi-kinds of α-Amino Acids synthesis.[82–84] The critical step is the NH_2OH derived from NO_x attacked the alpha carbon of keto acids to form the key intermediate oxime, followed to produce amino acids via hydrogenation. Zhang's group also developed a two-pot strategy over oxide-derived Ag catalyst, largely boost the yield and selectivity of pyruvic (Figure 11a).[85] This is a multiple-step catalytic cascade process involved electrochemical process, chemical process, and electrochemical process. Besides, more amino acids, such as glycine and serine, also could be produced directly adopted CO_2 and NH_3 as carbon and nitrogen sources. The diverse electrocatalytic synthesis of amino acids holds great significances in the construction of novel ecological system. As exemplified in the mechanism of amino acid synthesis, a pivotal intermediate known as oxime can be generated through the nucleophilic attack on the alpha carbon of keto acids by NH_2OH, which is derived from NO_x. Consequently, the electrosynthesis of cyclohexanone oxime (CHO), a critical precursor for caprolactam used in the synthesis of nylon-6, also can be achieved using NO/NO_2^- and cyclohexanone under ambient conditions.[86–88] Furthermore, this approach exhibits a universal applicability and is well-suited to produce various other oximes.

Amine

Amines, serving as essential building block feedstocks, have found wide-ranging applications in the pharmaceutical and agrochemical industries.[89] Recently, Wang's research group achieved a significant milestone by successfully implementing the electrosynthesis of methylamine using carbon dioxide and nitrate molecules.[90] This accomplishment was made possible through the utilization of a cobalt β-tetraaminophthalocyanine molecular catalyst supported on carbon nanotubes. Like the electrosynthesis of amino acids, this production process primarily involves the spontaneous C-N coupling of two crucial intermediates, NH_2OH and formaldehyde, to generate formaldoxime, which is then subjected to

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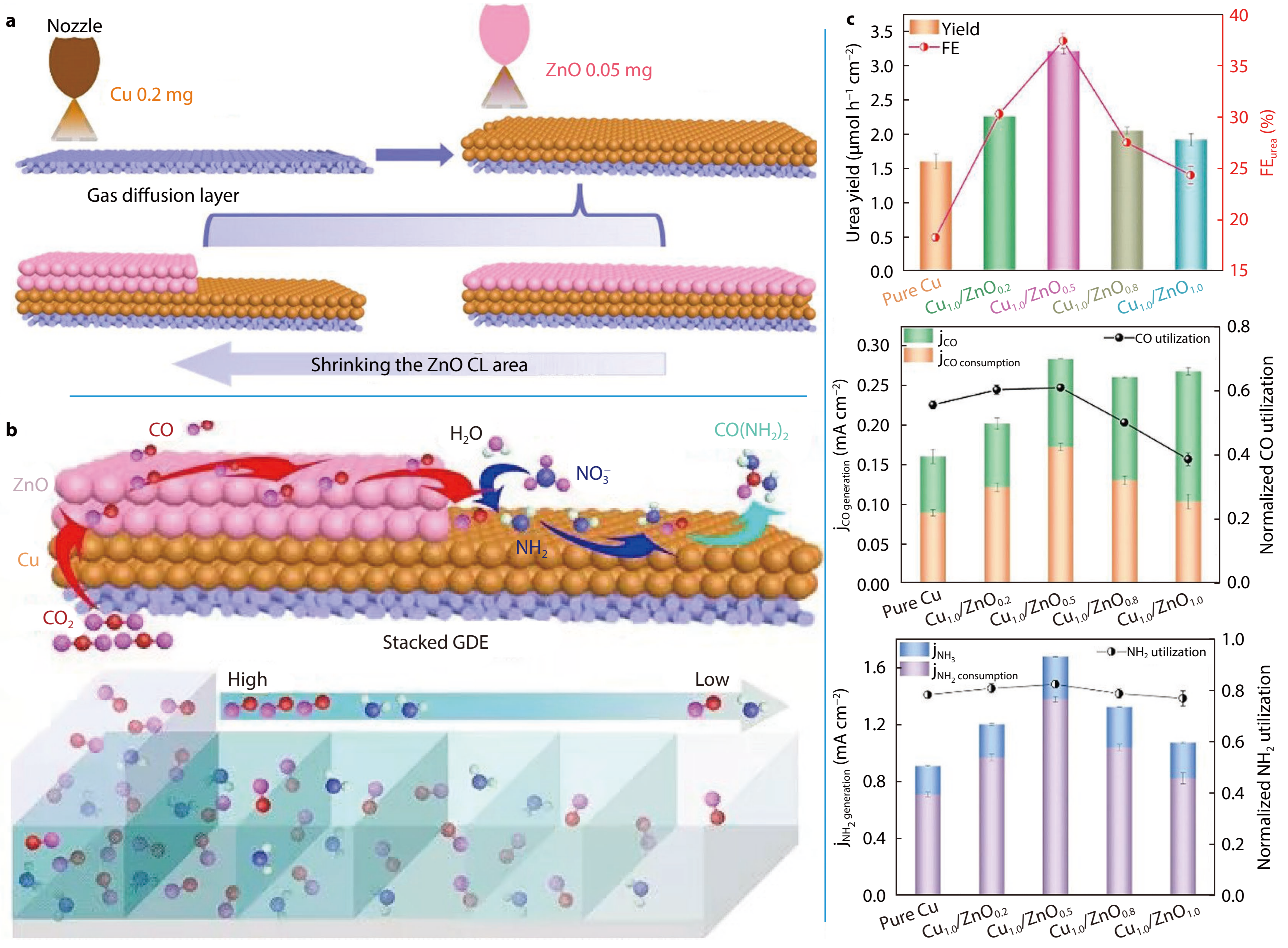

Fig. 10 **a** Schematic of the preparation process of the stacked Cu/ZnO GDEs. **b** Concept of urea synthesis on stacked tandem GDE. **c** Electrochemical performance of the stacked Cu/ZnO GDE.[79] Copyright 2023, American Chemical Society.

hydrogenation and dehydration steps to synthesize methylamine (Figure 11b). Ethylamine has also been produced through a comparable amine-aldehyde coupling reaction mechanism stemming from carbon dioxide and nitrate. Despite the current electrochemical routine's limitations in terms of activity and selectivity, it offers promising prospects for the efficient production of high-value chemicals soon.

Amide

Amides represent a pivotal class of organic compounds used extensively in the production of chemicals, polymers, and pharmaceuticals. Conventional industrial methods for synthesizing amides involve harsh operating conditions and complex equipment and synthetic processes.[91] In a recent breakthrough, Jiao's research group utilized the same feedstocks of carbon monoxide (CO) and ammonia (NH_3) to develop an innovative electrocatalytic approach for the synthesis of acetamide, involving amine nucleophilic attack on a ketene intermediate.[92] This groundbreaking work has paved the way for various systems, such as CO_2/NH_3, $HCOOH/NO_2^-$, CO/NO_2^-, C_2H_4/NO_2^- serving as carbon and nitrogen sources, to enable the electrosynthesis of formamides and acetamide.[93–96] Tan's group firstly developed a Ru-Cu dual active sites catalyst achieving a high-performance electrosynthesis of formamide compared to single active sites catalyst, which is attributed to the spontaneously couple *CO and *NH_2 intermediates (Figure 11c-e).[95] Furthermore, further research efforts are needed to broaden the range of amides amenable to this approach and enhance the activity and selectivity in the C-N coupling process.

Summary and outlook

The electrocatalytic C-N coupling for synthesis of various fine chemicals under ambient conditions, powered by renewable energy, provide an alternative to traditional industrial processes. Despite great progress have been made in this field, some challenges that need to be overcome, including low yields, poor selectivity, low current densities, and a lack of understanding regarding the reaction mechanism. In this review, we first introduce the C-N coupling mechanism for analogous established thermochemical, molecular, and enzymatic catalytic process. Next, the recent literature for electrosynthesis of urea, amine, amides, and amino acids, and involved catalyst design strategy were introduced and summarized, which might provide a new avenue to synthesis diverse high-valuable chemicals via electrochemical C-N coupling process. As the development of sustainable non-fossil fuel-based chemical industries, especially using CO_2/CO and waste NO_x as feedstocks to produce organonitrogen, would effectively

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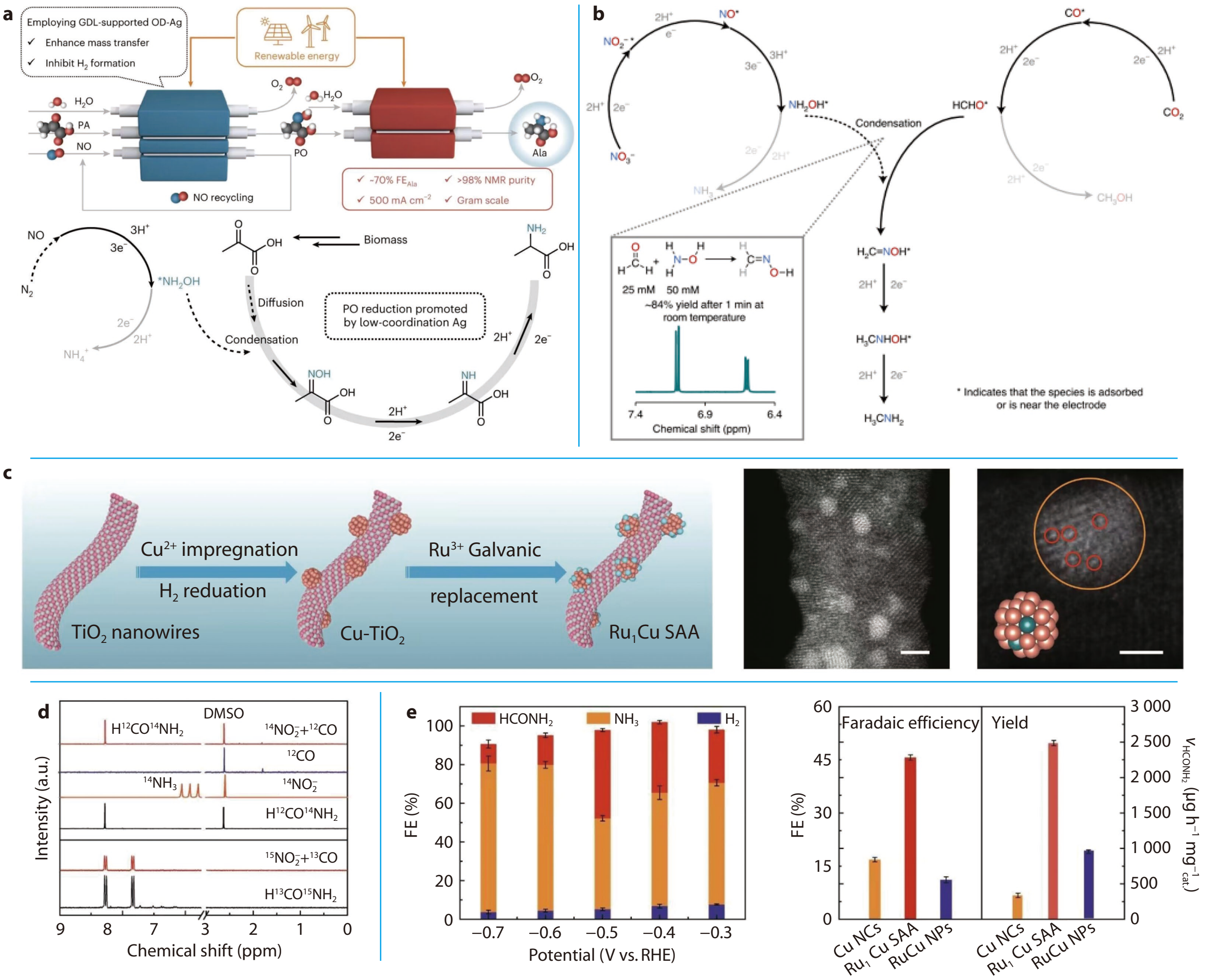

Fig. 11 **a** The proposed two-pot route to enhance the space-time yield of alanine and corresponding alanine generation pathway on the OD-Ag surface.[85] Copyright 2023, Springer Nature. **b** the proposed reaction pathway of the eight-step cascade electrosynthesis of methylamine from CO_2 and NO_3^- catalyzed by CoPc-NH_2/CNt.[90] Copyright 2021, Springer Nature. **c** Schematic illustration of preparation processes and HAADF-STEM image for Ru_1Cu SAA catalysts. **d** ^1H NMR spectra of standard references and the electrolyte obtained after CORR, NO_2^-RR, and $NO_2^- + CO/^{15}NO_2^- + {}^{13}CO$ co-reduction. **e** The electrochemical performances for Cu NCs, Ru_1Cu SAA, and RuCu NPs in a CO-saturated 1 M KOH+ 1 M KNO_2 solution.[95] Copyright 2023, Springer Nature.

mitigate the energy crisis and environment problems. It is important to emphasize that more efforts and research should be focused on addressing these challenges to achieve efficient electrocatalytic synthesis of C-N containing high-valuable chemicals. Extended efforts given below should be further made.

(1) Intermediate adsorption

The activity and selectivity of electrocatalytic C-N coupling processes are contingent upon the free energy associated with the adsorption of intermediates, particularly in reactions involving multiple reactants and intermediates. If the binding strength of the key intermediates is too weak, it may lead to the enhanced occurrence of competing side reactions. Conversely, if the binding is too strong, it can impede the subsequent C-N coupling reaction. Thus, the optimal adsorption affinity of intermediates on active sites is a pivotal factor to low the energy barrier, and can be fine-tuned by optimizing the local environment and electronic interaction of these active sites.

(2) Principles for electrocatalyst design

Up to this point, numerous catalytic strategies have been developed in the field of electrochemical C-N coupling processes for the synthesis of high-value fine chemicals. The intricacy of the electrochemical C-N coupling reaction, which entails multiple proton and electron transfer steps, presents a formidable challenge in achieving both high selectivity and activity. Catalysts with single active sites are unable to efficient catalyze this process with both high activity and selectivity simultaneously. Therefore, it is imperative to conceive and create dual-site or multi-site catalysts to enhance the performance of the electrochemical C-N coupling reaction through the synergistic interactions between distinct active sites. Furthermore, the structural stability of catalysts is also a crucial factor influencing the assessment of catalyst efficacy. Consequently, greater efforts should be dedicated to achieving the adsorption and activation of reactant species, thereby facilitating the C-N coupling process across multiple active sites simultaneously during the electrosynthesis of C-N-containing chemicals.

(3) In-Depth understanding reaction mechanism

Undoubtedly, substantial strides have been taken in comprehending the mechanisms and establishing C-N bonds via electrochemical C-N coupling reactions. Nevertheless, owing to the generation of diverse reactive species and the intricate nature of the reaction pathways, there persists a compelling need for further investigations to fully delineate the coupling reaction mechanisms. Within the electrocatalytic process, a spectrum of intermediates originating from carbon (*CO, *COOH, *CO_2, *HCHO) and nitrogen sources (*NO_2, *NH_2, *NN) are formed, introducing a heightened level of complexity to the C-N coupling process.

Currently, there is a lack of clear and definitive evidence to elucidate the precise pathways of the coupling reactions, primarily attributable to the presence of these intricate reactive intermediates and the dynamic nature of active sites. Hence, on one hand, advanced in-situ/operando characterization techniques should be devised and applied to faithfully replicate the authentic reaction conditions. These methodologies can facilitate the real-time monitoring of the formation and evolution of reactive species from the reactants, as well as the ever-changing surface structure of the catalysts throughout the electrochemical reaction process. On the other hand, advanced density functional theory (DFT) calculations can be harnessed to further illuminate the pathway of the C-N coupling reaction via simulating the entire reaction process and providing valuable insights into energy profiles, reaction intermediates, and transition states. These insights contribute to a comprehensive understanding of the thermodynamics and kinetics of the reaction, while also elucidating the factors that impact the selectivity and efficiency of the C-N coupling process.

(4) Micro-environment designs for C-N coupling reactions

In addition to catalyst, the electrolyte and electrochemical reactors also decide the activity and selectivity of heterogeneous electrochemical processes. It has been demonstrated that the hydrated alkali cations accumulated near the double electrode layer can modulate the electric field, further inhibited the hydrogen evolution sides reaction by adjustment of the concentration of hydronium ions, while at the same time beneficial for the stabilization of key C-contained intermediates.[97] Additionally, hydrophobic engineering can also aid in facilitating the reduction of carbon-containing and nitrogen-containing reactant molecules by increasing the concentration of corresponding intermediates.[98] During the electrochemical C-N coupling process, the large concentration of key intermediates can largely promote the performances of C-N coupling and optimize the selectivity of aimed products. However, it is important to note that the mass transfer limitations arising from the poor solubility of small gas molecules (e.g., CO_2, N_2, NO, etc.) can restrict the overall efficiency of the process. The flow cell is an ideal strategy for accelerating mass transfer, and there is a need to emphasize and prioritize the development of more advanced electrochemical reactors, such as membrane-based flow reactors and MEA electrolyzer. Optimizing the electrolyte and reactors is crucial as it enables the adjustment of the concentration and binding energy of various intermediates adsorbed on the catalysts' surface, enhancing the efficiency of electrochemical C-N coupling reactions.

(5) Expand products range for C-N coupling reactions

The scope of products derived from electrochemical C-N coupling remains restricted, primarily attributed to the constrained variety of carbon and nitrogen sources. Addressing this limitation necessitates a profound understanding of the C-N coupling mechanism, guiding catalyst design with the ultimate goal of enabling versatile control over multi-faceted C-C coupling and C-N coupling steps. In the photocatalytic process, the exceptionally reactive radicals containing carbon and nitrogen undergo coupling, giving rise to a diverse array of organonitrogen compounds with C-N linkages. This process provides a feasible pathway to achieve the electrochemical C-N coupling.[99,100] Furthermore, the utilization of biomass-derived organic carbon sources, characterized by diverse functional groups, has the potential to significantly broaden the spectrum of producible compounds.

In summary, the electrochemical co-reduction of carbon-containing and nitrogen-containing small molecules has shown giant promise in synthesizing valuable chemicals such as urea, amides, amines, and amino acids. Although there are still substantial challenges to overcome in this field, we remain optimistic that a significant breakthrough can be achieved in terms of both the understanding of the mechanisms involved and the development of high-performance electrochemical C-N coupling processes. Such breakthroughs would help overcome current obstacles and pave the way for practical commercial applications soon.

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■ CONFLICT OF INTEREST

The authors declare no conflict of interest.

■ AUTHOR CONTRIBUTIONS

Q. L. Li and Prof F. X. Zhang conceived the framework of the review and wrote the manuscript; Prof F. X. Zhang revised this manuscript and led this project. All authors had approved the final version.

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