**Introduction**

Carbon dioxide (CO₂) conversion technology is emerging as a promising tool to aid in the quest to lower CO₂ emissions.¹,² Current advances have successfully converted CO₂ to small C1 building block chemicals: CO,³ CH₄,⁴ formaldehyde⁵ and formic acid;⁶–⁸ high energy dense liquid fuels: methanol (MeOH),⁹ ethylene (CH₂=CH₂),¹⁰ ethanol,¹¹ petrochemical polymers,¹² and hydrogels.¹³ The abundance and cost efficiency of CO₂ as a resource, makes its conversion economically viable as a competitor to traditional methods of manufacturing (e.g., carbonylation¹⁴ and the methanol to olefin (MTO) process¹⁵–¹⁷). Research efforts to further utilize captured CO₂ as a raw material for the production of higher value compounds and chemical feedstocks have intensified in recent years with the advent of efficient electrolyzer technologies and heterogenization techniques. Electrochemical (EC) and photoelectrochemical (PEC) CO₂ reduction technologies are the leading approaches to achieve CO₂ reduction.¹⁸,¹⁹

Electrocatalysts are instrumental to CO₂RR due to their contributions to overcoming kinetic energy barriers and in mediating Proton Coupled Electron Transfers (PCETs).²⁰–²² Benchmarks for potential commercial implementation stipulate the necessity of high current densities (j > 200 mA cm⁻²), long operation capacities, high selectivities (>90%), and low overpotentials.²³ Although the catalytic capabilities of proposed systems have improved considerably, their current state remains insufficient for industrial/commercial application. Compared to the initial performance of catalysts, their long-term stability needs to be considered. Based on the techno-economic analysis, the stability of electrocatalysts for CO₂RR should be at least 4000 hours.²⁴,²⁵ The stability of the catalytic system depends on multiple factors including catalyst’s structure, catalyst immobilization including chemical and physical including covalent and non-covalent bonding, support material, catalyst’s loading, catalyst surface morphology and the type of metal centre in the case of metallo-porphyrins.²⁶–²⁷

Advances in electrochemical CO₂ reduction reactions (CO₂RRs) offer a realistic pathway to utilization of CO₂ as an abundant and inexpensive source for C1 building blocks.²⁸ Until recently, solid state electrocatalysts had been leading the field in terms of conversion efficiency (current density). Often composed of heavy metals such as Pt, Pd, Au, Ag, Cu, etc., yet costly to implement and maintain.²⁹–³² Although solid state catalysts have proven themselves capable of reducing CO₂ to energy dense compounds like MeOH, ethylene, and ethanol; there is much to be desired for their selectivity for the reduction products they produce.²⁵

On the other hand, molecular catalysts³⁳–³⁵ are favoured for their high selectivity and are capable of converting CO₂ to CO,³⁶ formaldehyde,³⁶ formic acid,³⁷ oxalic acid/oxalate,²⁸ cyclic carbonates,²⁹ etc. with selectivities at near unity. Macrocyclic tetapyrrolic ligands such as porphyrins and phthalocyanines...
CO as the main CO2RR product. Co and Ni in particular, were Pd, belonging to group VIII of the transition elements, generate having outermost s or p electrons, the electron transfer happens with electrons from the metal center. Further reduction can take place, producing CH4. In metals For example, the eavailability of the proton source. Mechanistic pathways of CO2RR

The identity of the metal centre plays a significant role in the activity and selectivity of the catalyst. In the first step of the CO2RR mechanism, the electrophilic C atom is activated by nucleophilic attack from an electron-rich metal centre. The initial binding of CO2 requires the C–O σ* (LUMO) and degenerate C–O π* (LUMO+1) orbitals on the C atom be filled with electrons from the metal center.57,58 To satisfy this condition, an M4+,0 centre with a d8 configuration in a square-pyramidal ligand field is best for binding CO2 via its filled d2 (σ) and dxy,zy (π back-bonding) orbitals. For this reason, Fe, Co and Ni are hypothesized to be the best metals for catalysis due to their d8 electron configuration. Product selectivity is then influenced by the ability of CO to remain adsorbed to the metal for further reduction or desorption, leading to the release of CO.59 It has been proposed that Fe, Co, and Ni contain doubly occupied d2 orbitals that would repel the lone pair of electrons on CO after CO2 reduction, releasing CO as the major product.60 However, if the CO remains bound to the metal via σ bonding, further reduction can take place, producing CH4. In metals having outermost s or p electrons, the electron transfer happens at the more localized, lower energy orbital, which is not strong enough to reduce CO, leading to the production of [CO2] followed by further reduction to formic acid depending on the availability of the proton source.

The prediction from the molecular orbital theory closely resembles to the qualitative results observed in the literature. For example, the effect of the metal centre on CO2RR has been studied in extensively with 17 different metallophthalocyanines (MPCs) using gas diffusion electrodes (GDEs).61 Co, Ni, Fe, and Pd, belonging to group VIII of the transition elements, generate CO as the main CO2RR product. Co and Ni in particular, were most impressive with current efficiencies of 98 and 100% respectively (between −1.0 and −1.75 V (vs. RHE)). Sn, Pb, In, Zn, and Al produce formic acid as the main product, with Zn also being able to generate CO to a comparable extent. Cu, Ga, and Ti are unique in being the only metals that give methane as the main product, with current efficiencies being as large as 30–40%, while methane production for other metals is almost negligible. Lastly, V, Mn, Mg, Pt, and H show poor activity for CO2RR, with competing hydrogen evolution at current efficiencies of 90–100%. Although the selectivity of these metals towards one product is favourable, the activity must also be considered. CoPc and FePc showed higher current densities at lower applied potentials, while NiPc, although having a high selectivity for CO, requires much more energy to drive similar CO current densities. The high activity and selectivity of Co porphyrins towards CO makes the use of Co porphyrins one of the most promising catalysts for CO2RR, and therefore, has been subject to many detailed investigations.62,63 Although, closely following behind are NiPc and FePc, which are also promising catalysts if activity could be increased in the case of NiPc, and selectivity is enhanced in the case of FePc.64 Incorporation of a metal active canter to porphyrin/phthalocyanine-based catalysts promotes a cooperative effect between the catalyst metal site and the metal electrode. For instance, combining CoPc and Fe single-atom sites, showed that the free energy decreased in the activation and desorption steps of CO2RR (Fig. 1a–c).65 In this case, CoPc molecules reduced the adsorption energy of *CO and H*, without...
Weakening the formation activity of *COOH. Therefore, combining CoPc and Fe–NC enhances the CO2RR activity on the Co centre while reducing the adsorption of CO on the Fe site.56

In another study, theoretical calculations indicate that a lower coordination number could change the electronic structure of the active site and increase the success of CO2RR over HER (Fig. 1d–f).67 The free energy of *COOH of coordinated, unsaturated NiN₄, NiN₅, and NiN₅₂ is lower than that of saturated NiN₄. The *H blocking was also relatively weak in the case of NiN₅ and NiN₅₂, and for NiN₅₂, resulting in high product selectivity.

The effect of the ligand can drastically affect the activity of these catalysts. Strategies for improving homogeneous catalysts include introducing functional groups that serve as local proton sources,68,69 hydrogen bond donors,70 or cationic moieties in the second sphere environment,71,72 all of which have resulted in increased CO2RR rates in part due to the stabilization of the formed CO₂ intermediate by the substituents on the porphyrin ligand. A classic strategy of improving performance was pioneered by Savéant’s group on Fe porphyrins through structural modification of the porphyrin ligand by incorporating substituents that can induce through-structure electronic effects.73 Introducing electron-withdrawing groups such as fluoroamine atoms has been shown to decrease overpotential by lowering electron density near the metal active site, making it is easier to inject an electron into the catalyst. However, this may also subsequently decrease catalytic activity by decreasing the nucleophilicity of the metal and its ability to bind to CO₂. On the other hand, the introduction of methoxy substituents increases catalytic activity by increasing the propensity of the metal center to bind to CO₂ via inductive electron-donating effects of the ligand. Careful balance of electron-donating (lowering overpotential) and electron-withdrawing (increasing TOF) is required in ligand design and an optimal push–pull system is needed to achieve the ideal molecular catalyst.74

In the case of heterogeneous catalysts however, the effect of electron withdrawing (i.e. F and CN)75,76 and electron-donating (i.e. octaalkoxyl)77 substituents show little improvement for CO2RR in terms of the desired electronic effect. However, these substituents are crucial in reducing aggregation and reducing π–π stacking interactions that lead to improved catalytic activity. Ligand modification within the context of het-erogenized molecular catalysts presumably affects other factors in the immobilized catalyst system including electron transfer between the catalyst and electrode, the ability for CO₂ to coordinate with the catalyst, the desorption rate of the reduced products, and solvation energies.78 These findings emphasize the need to screen heterogeneous molecular catalysts by the same criteria as homogeneous catalysts alone.

Homogeneous vs. heterogeneous electrocatalysts

Molecular catalysts can be applied in two general categories: as either homogeneous or heterogeneous systems.78 Whereas heterogeneous catalysts exist in a separate physical phase from the reactant (CO₂), homogeneous systems operate in the same phase as the reactant. Homogeneous studies are a convenient way to assess the initial CO₂ reduction ability of novel molecular catalysts. Oftentimes, only those that show promise under these conditions are further investigated with more vigorous heterogeneous studies. Hu et al.79 make a compelling argument for a reassessment of this method of screening, which can sometimes allow promising but underperforming molecules to slip through the cracks. Their report of cobalt tetraphenylporphyrin (CoTPP) immobilized onto carbon nanotubes (CNTs) illustrates how CoTPP, a catalyst whose activity is traditionally eclipsed by iron tetraphenylporphyrin (FeTPP) in homogeneous conditions, performs significantly better when immobilized onto a conductive CNT support in aqueous media (FECO = 83%; j = –0.59 mA cm⁻² at −1.15 V vs. SCE) than an analogous FeTPP-CNT (FECO = 64%; j = –0.9 mA cm⁻²).80 They propose a new, simple deposition method consisting of sonicating the dissolved catalysts and CNTs, drop casting the solution, and drying as a means to quickly screen new molecular catalysts.

Comprehensive studies comparing identical catalysts in homogeneous and heterogeneous environments widely demonstrate an overall enhancement to catalytic performance upon immobilization onto electron conductive supports.76,77 Systematic studies show that a significant enhancement in catalytic reactivity was achieved through immobilization of Fe-TPP-dimers onto CNTs in aqueous solution (TOF = 10 s⁻¹; FEₐ overall = ~90%) compared to their homogeneous analogues in DMF (TOF = 0.11 s⁻¹; FECO = 48% at –1.33 V vs. RHE).81 We have also shown that heterogeneous pyridine–porphyrin complexes exhibit higher catalytic activity and product selectivity (FEₐ overall > 92% and j = –30 mA cm⁻² at –0.6 V vs. RHE) compared to their homogeneous counterparts (FEₐ overall = 76% and j = –1.34 mA cm⁻² at –1.4 V vs. RHE).74

Heterogeneous immobilization of molecular catalysts onto conductive solid supports is advantageous in several ways: (1) unlike in homogeneous systems, immobilized catalysts are locally bound to the electrode, the source of reductive capability, guaranteeing a high degree of catalytic site exposure.82,83 This serves to streamline the pathway of electron transfer from the electrode to the catalytically active site to CO₂; (2) moreover, the solid support is often chosen by virtue of its exceptional electrical conductivity, further ensuring efficient electron transfer processes;⁴⁴,⁸⁵ (3) most organic/inorganic molecules are limited by their solubility in aqueous solvents. Heterogeneous systems enable molecular catalysts to overcome such limitations, freeing them to operate in proton-rich aqueous solutions, which serve a dual purpose in being more green.⁸⁴,⁸⁶ These strategies have proven to be a promising approach to efficiently enhancing catalytic activity. In the previous study of pyridine–porphyrin complexes, we demonstrate that even with a lower catalyst load concentration, the performance of heterogeneous molecules on CNTs is superior to that of its homogeneous analog.74

Converting CO₂ into value-added materials is thought to occur via several mechanistic pathways. After capturing CO₂, an initial proton coupled electron transfer (PCET) process forms intermediates such as *COOH and *OCHO. Among various
carbonaceous products, CO and formic acid are considered pivotal C1 building blocks for C2+ products. The formation of C2+ products is much more challenging due to the number of reaction steps and intermediates required to form the C–C bond. This difficulty is also due to the linear relationship between the binding energies of individual reaction intermediates and their activation energies (kinetic barrier). Given the competition of C–C coupling with H–H and C–H bond formation, strategies that improve CO* dimerization to OC–CO* is key to the production of C2+. General strategies to achieve this include manipulating CO* binding strength through catalytic design, increasing CO* coverage, controlling CO* adsorption energetics, and re-adsorbing electrogenerated CO.

To achieve C–C bond formation, the adsorbed *CO species may interact with each other via the Langmuir–Hinshelwood (LH) step through surface-bound species and a species in solution described in the Eley–Rideal (ER) step. In the case of metallo-porphyrins, the metal active site needs to bind to the *CO intermediates strongly enough to facilitate C–C coupling, but not too much as to significantly increase the energy barriers. Fundamental theoretical studies are valuable when designing catalysts. Li et al. demonstrated the potential of molecule-enhanced surfaces and how the CO2 to CO conversion efficiency of 5,10,15,20-tetraphenyl-21H,23H-porphine iron(III) chloride (FeTPP[Cl]) contributes to enhanced C2 production on a Cu electrode. They were able to utilize immobilized FeTPP[Cl] to create a localized concentration of ·CO, which serves as a key intermediate for the Cu active sites in the production of ethanol. By showing that the binding energy of CO to FeTPP[Cl] was 0.2 eV weaker than that of the Cu (111) substrate, the authors hypothesized that the CO produced by FeTPP[Cl] was readily spilling over onto the Cu active sites.

**Noncovalent electrode immobilization by adsorption**

Noncovalent immobilization relies on the π–π interactions from the conjugated aromatic system that exists on aromatic macrocycles to bind to carbon surfaces. Porphyrins and phthalocyanines being aromatic macrocycles are good candidates for surface immobilization due to their strong π–π interactions (Table 1). These interactions lead to improved electron transport rates due to the closer proximity of the catalyst to the electrode and the potential for improved electron conductivity from the in-plane π–π stacking. Coverage of the electrode surface with molecular catalysts may minimize its contact with water and reduce the opportunity for HERs. This method has been used for different applications such as water oxidation and proton reduction in addition to electrocatalytic reduction of CO2 to CO.

The support material, surface functionality, morphology, and conductivity of the electrode are necessary for CO2RR and have been shown to enhance the catalytic efficiency, catalyst regeneration, and product separation. The support material

**Table 1** Summary of non-covalently immobilized heterogeneous molecular electrocatalysts for electrocatalytic CO2 reduction

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>V vs. RHE</th>
<th>j (mA cm–2)</th>
<th>FE% [CO]</th>
<th>TOF (s–1)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe-TPP</td>
<td>–0.8</td>
<td>7.8</td>
<td>54%</td>
<td>0.02</td>
<td>86</td>
</tr>
<tr>
<td>Fe-TPP-NH₃</td>
<td>–0.8</td>
<td>12.9</td>
<td>79%</td>
<td>0.05</td>
<td>86</td>
</tr>
<tr>
<td>Fe-TPP-ad(NH₂)₂</td>
<td>–0.8</td>
<td>8.0</td>
<td>70%</td>
<td>0.03</td>
<td>86</td>
</tr>
<tr>
<td>Fe-Tetra-Py</td>
<td>–0.7</td>
<td>19.6</td>
<td>37</td>
<td>0.9</td>
<td>74</td>
</tr>
<tr>
<td>Fe-Cis-Py</td>
<td>–0.7</td>
<td>30.4</td>
<td>67</td>
<td>3.49</td>
<td>74</td>
</tr>
<tr>
<td>Fe-Tri-Omc-Py</td>
<td>–0.7</td>
<td>–23</td>
<td>50</td>
<td>1.49</td>
<td>74</td>
</tr>
<tr>
<td>Fe-TPP-dimer</td>
<td>–0.8</td>
<td>16</td>
<td>89</td>
<td>10.2</td>
<td>81</td>
</tr>
<tr>
<td>CoPc/CNT</td>
<td>–0.63</td>
<td>~15</td>
<td>98</td>
<td>4.1</td>
<td>76</td>
</tr>
<tr>
<td>CoP/pc</td>
<td>–0.61</td>
<td>18</td>
<td>90</td>
<td>1.4</td>
<td>100</td>
</tr>
<tr>
<td>COF-367-Co</td>
<td>–0.67</td>
<td>3.3</td>
<td>90</td>
<td>0.53</td>
<td>50</td>
</tr>
<tr>
<td>CoPc-P4VP</td>
<td>–0.73</td>
<td>2.0</td>
<td>89</td>
<td>4.8</td>
<td>101</td>
</tr>
<tr>
<td>CoPc2</td>
<td>–0.67</td>
<td>18.1</td>
<td>93</td>
<td>6.8</td>
<td>95</td>
</tr>
<tr>
<td>Co-TPP</td>
<td>–0.8</td>
<td>0.9</td>
<td>70</td>
<td>2.75</td>
<td>79</td>
</tr>
<tr>
<td>Fe-CATpyr</td>
<td>–0.59</td>
<td>0.24</td>
<td>93</td>
<td>0.04</td>
<td>102</td>
</tr>
<tr>
<td>CAFCO₂H</td>
<td>–1.35</td>
<td>0.4</td>
<td>80</td>
<td>0.05</td>
<td>103</td>
</tr>
<tr>
<td>CoFPC</td>
<td>–0.9</td>
<td>6.0</td>
<td>88</td>
<td>2.05</td>
<td>75</td>
</tr>
<tr>
<td>CoTAP</td>
<td>–0.8</td>
<td>2.5</td>
<td>86</td>
<td>2</td>
<td>104</td>
</tr>
<tr>
<td>Co/TPP</td>
<td>–0.9</td>
<td>0.8</td>
<td>52</td>
<td>4.5</td>
<td>105</td>
</tr>
<tr>
<td>FePGH</td>
<td>–0.4</td>
<td>2.8</td>
<td>96</td>
<td>0.8</td>
<td>106</td>
</tr>
<tr>
<td>NiPc-CTF</td>
<td>–0.9</td>
<td>42</td>
<td>97</td>
<td>0.47</td>
<td>107</td>
</tr>
<tr>
<td>Co-NiMe2PC/NRGO</td>
<td>–0.8</td>
<td>8.7</td>
<td>90</td>
<td>8</td>
<td>108</td>
</tr>
<tr>
<td>FePc/Gr75</td>
<td>–0.6</td>
<td>1.7</td>
<td>90</td>
<td>—</td>
<td>109</td>
</tr>
<tr>
<td>CoPc/ZnIn2S4</td>
<td>–0.83</td>
<td>8.1</td>
<td>92.6</td>
<td>—</td>
<td>110</td>
</tr>
<tr>
<td>PCN-222(Fc)/C</td>
<td>–0.6</td>
<td>1.2</td>
<td>91</td>
<td>1.2</td>
<td>111</td>
</tr>
<tr>
<td>Ni-TPP-NitBu</td>
<td>–0.5</td>
<td>22</td>
<td>94</td>
<td>7.2</td>
<td>47</td>
</tr>
<tr>
<td>Co-qpyCOOH/CNT</td>
<td>–0.65</td>
<td>6.7</td>
<td>100</td>
<td>0.28</td>
<td>112</td>
</tr>
<tr>
<td>CoTPPy/CNT</td>
<td>–0.6</td>
<td>7.5</td>
<td>95</td>
<td>2.1</td>
<td>54</td>
</tr>
</tbody>
</table>
tion of CO2 reaction intermediate in CO production. Although the forma-

tion of the catalyst throughout the solid support and minimize

and its interaction with the molecular catalyst directly affect the elec-

tron transfer, transport of species, the strength of catalyst

bonding to the surface, and durability of catalyst; it also may

alter the CO2RR mechanism.114 Highly conductive support

ensures suitable electron transfer and reduces the ohmic

resistance of the electrode, making high current densities

possible.76–79 Carbon-based materials such as CNTs, carbon

black (CB), carbon paper (CP), graphene derivatives, etc. are of

particular interest for CO2RR due to their high stability and

conductive surface area (Fig. 2).76,79,94,97,98,115–117 In another

study, it has been reported that the CoPc catalysts immobilized

on CNTs reveal an exceptional CO activity compared to CoPc

immobilized onto other carbon-based materials such as

reduced graphene oxide, carbon fiber paper, and CB.76

Several techniques may be used to achieve noncovalent

hybridization, such as dip coating and drop-casting. These

methods involve dissolving the catalyst and immersing the

carbon-based support material in a suitable solvent such as

DMF, followed by deposition of the mixture onto the desired

surface. Suspension methods ensure a homogeneous disper-
sion of the catalyst throughout the solid support and minimize

the chance of unfavourable molecular aggregation, which can

inhibit electron delivery. Shen et al.3 propose a detailed mecha-
nistic scheme for CO2 electroreduction to CO and CH4 with

CoTPP immobilized onto pyrolytic graphite (PG). Their work

shows a schematic representation of the CoPc/CNT hybrid. (c)

Representative chronocoulomperograms of CO2 electroreduction cata-

lyzed by the CoPc/CNT (2.5%) hybrid for 1 h at various potentials in

0.1 M KHCO3 aqueous solution; (d) FE of reduction products at

different potentials for CoPc–CN/CNT (solid line) and CoPc/CNT

dotted line.76 Copyright 2017, Nature Publishing Group.

they identified conflicting reaction pathways for the reaction

products, where CO production is catalysed at pH = 3, and CH4

production is catalysed at pH = 1. They achieved 60% FE\textsubscript{CO} at

pH = 3, pressure = 10 atm, at −0.6 V vs. RHE and traces of CH4

(−2.4% FE\textsubscript{CH4}) at higher overpotentials (−0.8 V vs. RHE).

The surface morphology and graphitic degree of different

materials should be considered when choosing a solid support.

Wang et al.76 compared the catalytic activity of CoPc catalysts

immobilized directly onto several carbon materials including

CNTs, carbon fiber paper, reduced graphene oxide, and CB.

Compared to CNTs, these other materials were found to have

less than a third of the current density, ~10% lower FEs, and

inferior catalytic stability. The morphology of the immobilized

CoPc/CNT can be visualized with transmission electron

microscopy (TEM) (Fig. 3a and b). Aoi et al.116 found that a

significant decline in FE\textsubscript{CO} selectivity of a cobalt-porphyrin

chlorin complex occurred when a graphene oxide matrix was

used compared to when the same catalysts were deposited onto

multi-wall CNTs (MWCNTs) in similar conditions. This decline

in selectivity was attributed to the higher graphitic degree of

CNTs, which resulted in increased π–π interactions between

the molecular catalyst and the carbon support.79 In their study,

Hu et al. noted a higher level of catalyst detachment occurring

with a CB scaffold during electrolysis, whereas a comparable

CNT support was more stable.

In another recent report, an enhancement in electro-
chemical CO2RR of free base phthalocyanines was reported

using N-doped carbon materials (N-Cmat).118 It was demon-

strated that reduction of CO2 to CO occurred with the pyridinic

N’s as opposed to the pyrrolic N’s. Introduction of Co nano-

particles, Co@Pc/C, led to CO production with a FE\textsubscript{CO} of

84% and current density of 28 mA cm\textsuperscript{−2} at −0.9 V (Fig. 4).

Other studies of immobilized Co\textsuperscript{II,III}-2,3-naphthalocyanine

(NapCo) complexes onto doped graphene in aqueous solution

find that the electronic transfer processes between the catalyst

Fig. 2 Non-covalent immobilization of porphyrin/phthalocyanine

CO2RR catalysts onto carbon-based electrodes representative of the
catalysts reported in (a) an iron triphenylporphyrin bearing 6 pendant
−OH groups on the ortho positions of the phenyl rings immobilized on

CNTs with a pyrene group (copyright 2016, Royal Society of Chem-

istry);102 (b) iron tetraphenylporphyrin immobilized in a flow cell
(copyright 2020 Elsevier);86 (c) iron porphyrin–pyridine derivatives

immobilized on CNTs (copyright 2020 American Chemical Society);74

(d) cobalt chlorin adsorbed on MWCNTs on a glassy carbon electrode

(copyright Royal Society of Chemistry);76 and (e) cobalt phthalocy-
nine immobilized on CNTs (copyright 2019, Nature Publishing

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has also seen success. The hydrophobic microenvironment of the polymer significantly enhances CO2 gas diffusion and mass transport, increasing the local concentration of CO2 on the electrode for CO2RR. Nafton is another example of a tetrafluoroethylene based polymer that possesses additional ionic properties due to its sulfonic acid groups which facilitates proton transfer for CO2 reduction. It was shown to work synergistically with carbon-based materials such as CNTs, demonstrating a ~10 fold current enhancement for the reduction of CO2 to CO at ~1.4 V vs. Ag/AgCl (pH 7). However, CO2 permeability through the Nafton membrane remains limited, resulting in lower FE and current density when used for CO2 reduction to formate.

Early studies of covalent modification of an electrode surface with metalloporphyrins was reported by Aramata et al. in which Co-5,10,15,20-tetrakis(4-carboxylphenyl)porphyrin (CoTCPP) was fixed to a glassy carbon electrode functionalized with 4-aminoypyridine groups via coordination of the Co centre with pyridine. The modified electrode demonstrated a FE of 50% at ~1.2 V vs. SCE in a CO2-saturated standard phosphate buffer solution (pH 6.8). Even after prolonged potentiostatic electrolysis under above conditions, the electrode remained stable, with no decrease in current density for more than 4 h. The authors attribute this improvement in catalytic activity to the increased electron density on the central Co(i) ion after axial coordination to the electron-donating pyridine moiety, thereby stabilizing the binding of CO2 on the opposite coordination site.

A later study utilizes a similar strategy to immobilize Co phthalocyanine (CoPc) onto polymeric films composed of pyridines (poly-4-vinylpyridine or P4VP) via a coordination bond. The CoPc–P4VP films display a FE of ~90%, with a TOF of 4.8 s\(^{-1}\) at ~0.75 vs. RHE, which is drastically improved over the CoPc alone, adsorbed onto an edge-plane graphite (EPG) electrode. The latter only displays a 36% FE along with a TOF of 0.6 s\(^{-1}\). In addition to the increase in \(d_{2}\) orbital energy from the axial coordination, the authors hypothesize the improvement in catalytic activity to be from the encapsulation of the porphyrin catalyst inside the polymer film. This leads to higher CO2 solubility in the otherwise hydrophobic membrane due to basic pyridine sites and the second sphere hydrogen bond/proton network provided by the ionizable pyridine groups.

**Covalent modification of electrode**

Covalent immobilization establishes a direct bond between the molecular catalyst and the electrode surface (Table 2). This is beneficial in a number of ways. For one, the bond connecting the electrode to the catalyst layer can lead to heightened electron conductivity, and by extension more efficient use of energy (lower potentials). Secondly, covalent immobilization is a more robust alternative to non-covalent approaches which can show signs of catalyst displacement after several hours of operation. Here, the ligand groups of the porphyrin must be functionalized in a way that both allows for covalent binding to a surface, without destabilizing the molecule, while also remaining active for CO2RR. Such an approach provides the opportunity for long-term stability and predictable
catalyst orientations, but leads to a high degree of constraints, generally adding complexity to the synthetic approach required.

Covalent attachment of an electrocatalyst to a solid support has been shown to improve catalytic performance as demonstrated by Y.-F. Han et al.131 in which protoporphyrin IX cobalt chloride (CoPPCl) was covalently linked to hydroxyl-functionalized carbon nanotubes (CNT–OH). The drafted catalyst was synthesized by refluxing CoPPCl with CNT–OH (3.06 wt% hydroxyls) in ethanol with triethylamine, generating a covalent bond between the hydroxyl O atom and the Co center, and resulting in the functionalized material CoPP@CNT. The CoPP@CNT composite and Nafion were suspended in ethanol and drop cast onto carbon paper reaching a catalyst loading of 60 µg cm⁻². The catalytic performance was then evaluated in a low-volume two-compartment cell with a CO₂-saturated 0.5 M NaHCO₃ electrolyte. The FEₐ of the CoPP@CNT composite ranges from 90% at −0.65 V to 80% at −0.5 V vs. RHE, with TOF value varying from 0.34 s⁻¹ to 2.1 s⁻¹ respectively.

Although the CoPP@CNT composite showed negligible current decay over time, electrodes that were prepared by non-covalent attachment (physically mixed samples) of CoPPCl/CNT–OH with various CoPPCl loadings (CoPPCl/CNT–OH weight ratios of 4.4 × 10⁻⁴ to 5.6 × 10⁻¹) at −0.55 vs. RHE showed a 20% decrease in the current density after a 1 hour electrolysis. Not only does covalent grafting improve catalyst stability, but the current density is also enhanced; physically mixed CoPPCl/CNT–OH showed a 50% lower current density at −0.55 vs. RHE (1 mA cm⁻²) compared to the covalently grafted CoPP@CNT value (2.1 mA cm⁻²). The authors attribute this decrease in current density to catalyst aggregation which is a consequence of non-covalent grafting. The formation of aggregates blocks available active sites on the catalyst and hinder efficient electron transfer, especially at higher catalyst loadings, resulting in lower current densities. Through covalent grafting, the number of immobilized catalysts on the electrode can be optimized, while maintaining a high level of dispersion such that all grafted Co porphyrins are catalytically active.

Molecules with amine/amide-derived functionalized groups (e.g. amines, pyridine linkers) are well positioned for covalent anchoring to a surface through their monodentate axial ligands.14,15 Recent approaches have pioneered new techniques whereby a similar effect can be accomplished with organic molecules interfaced with solid supports.15,31,131 Marianov et al.153 have successfully demonstrated direct attachment of porphyrin derivatives (CoTPP-cov) through a aniline-mediated linkage onto glassy carbon (Fig. 6a). In these conditions a higher current density (4.7 mA cm⁻²) was observed compared to their unlinked counterparts (1.4 mA cm⁻²) (Fig. 6b). A positive correlation between the current density and catalyst loading concentration and active surface area was also shown (Fig. 6b and c).

Lessons from homogeneous electrocatalysts have been incorporated into the design of a number of heterogeneous systems. For example, electron donating groups are known to increase the partial negative charge on the metal centre via inductive effect resulting in higher CO₂-to-metal bonding energy and enhanced CO₂RR. Covalent immobilization of an iron tetraphenylporphyrin with six pendant –OH groups in the ortho positions and one carboxylic acid group, resulted in a high FE of 92%.132 Jiang et al.133 covalently grafted cobalt tetrakis-(4-amino-phenyl)porphyrin (CoTAP) bearing 4 electron-donating amino groups onto a carboxylic acid functionalized CNT via an amide linkage. This strategy resulted in an unprecedented ~100% FEₐ at overpotentials of 550 mV and a TOF value of 6.0 s⁻¹, while the non-covalent grafted electrode demonstrated a more moderate FEₐ of 85% and TOF of 2.3 s⁻¹. In comparison to

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### Table 2  Summary of covalently immobilized heterogeneous molecular electrocatalysts for electrocatalytic CO₂ reduction

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>V vs. RHE</th>
<th>j (mA cm⁻²)</th>
<th>FE% (CO)</th>
<th>TOF (s⁻¹)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoTPP</td>
<td>−0.9</td>
<td>4</td>
<td>100</td>
<td>6</td>
<td>104</td>
</tr>
<tr>
<td>CATCo₃H</td>
<td>−0.8</td>
<td>0.6</td>
<td>86</td>
<td>0.05</td>
<td>130</td>
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<tr>
<td>CoPPCl</td>
<td>−0.8</td>
<td>25</td>
<td>98</td>
<td>1.9</td>
<td>131</td>
</tr>
<tr>
<td>Co-TPP</td>
<td>−0.8</td>
<td>1.5</td>
<td>67</td>
<td>8.3</td>
<td>105</td>
</tr>
<tr>
<td>COF-366-Co-CNT</td>
<td>−0.68</td>
<td>6.8</td>
<td>92</td>
<td>1.2</td>
<td>132</td>
</tr>
<tr>
<td>MWCNT-Por-COF-Co</td>
<td>−1.0</td>
<td>18.7</td>
<td>99.3</td>
<td>70.6</td>
<td>129</td>
</tr>
</tbody>
</table>

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**Fig. 6**  (a) Preparation of covalently immobilized Co tetraphenylporphyrin (CoTPP-cov); (b) cyclic voltammetry (CVs) of CoTPP-cov in N₂- and CO₂-purged aqueous solution. CVs of bare carbon cloth are shown for clarity; (c) CV traces of CoTPP-nocov with a variable amount of noncovalently immobilized CoTPP in CO₂-saturated solution. Conditions: electrolyte: 0.5 M KHCO₃ in all cases, potential scan rate is 100 mV s⁻¹. Copyright 2019 Elsevier B.V.
their previous work with covalent and non-covalent grafted cobalt tetrphenylporphyrin (CoTPP), a much lower FECO was observed in both electrodes; 67% (TOFCO 8.3 s⁻¹) for covalent and 52% (TOFCO 4.5 s⁻¹) for non-covalent. The authors rationalize this improvement of catalytic activity for several reasons; the presence of electron donating amino groups improves the intrinsic catalytic activity of each individual catalyst, furthermore the amide bond acts as a molecular wire that enhances electron transfer from the CNT to the catalytically active Co centre. Direct covalent connection of the CoTAP to the surface of CNT improves overall reaction rate due to faster electron migration and the diffusion of CO₂ towards the active centres is no longer hindered by the layers of CoTAP aggregates.

**Electrode immobilization by electropolymerization**

Electrode surface immobilization via electropolymerization involves a monomer unit consisting of the molecular catalyst and a reactive moiety that undergoes polymerization upon oxidation, which then propagates onto the electrode surface. The oxidation of the monomer can be initiated by chemical means, however electrochemical oxidation grants control of film thickness, the possibility for in situ characterization during polymer growth, the lack of complicated purification steps, and most importantly is devoid of toxic oxidants, making this immobilization technique essentially ‘green’.

The polymerization of the film is generally achieved by voltammetrically cycling the monomer in solution at an appropriate potential range and at a controlled sweep rate. Care must be taken to determine the optimal potential for deposition of these films as many have found that they can undergo oxidative degradation at more positive potentials, having negative consequences for the catalytic properties of the film. This technique is demonstrated in one study where the authors use a thiophene ((T)-3,4-ethylenedioxythiophene or EDOT) moiety attached to CoTPP via a flexible 1,3-aminothiopropylene spacer, which was electropolymerized into polythiophene on indium-tin-oxide (ITO)-coated glass and carbon paper substrates. At −0.66 V vs. RHE, the Co-porphyrin-based polymer demonstrated a FECO of 66%, as well as a TOF and TON of 1.6 s⁻¹ and 5.7 × 10⁵ respectively, after 1 hour. The polymer film is highly stable and demonstrated a relatively constant current density of 0.936 mA cm⁻² and FECO of 36% over the course of a 6 hour controlled potential electrolysis (CPE).

Metal-organic frameworks (MOFs)¹³⁶,¹³⁷ and covalent organic frameworks (COFs)¹³⁸ introduce more structure and conformation to the aforementioned covalent strategies. Due to the breadth of this field, the topic of (MOFs) and (COFs) is not covered in this review.

**Conclusions and future prospects**

As described in this review, electrocatalytic reduction of CO₂ into fuels and higher value chemicals has become increasingly viable with the advent of recent methodical and technological advances. In order for CO₂ electroreduction to be industrially viable, electrocatalysts need to perform with both high activity and high selectivity. The use of metalloporphyrins as molecular catalysts has achieved unprecedented results for the reduction of CO₂ due to their favourable structural and electronic properties. Namely, their structural tuneability enables one to benefit from a wide range of immobilization techniques unavailable to other species. Furthermore, their highly conjugated system allows for enhanced electron conductivity and the ability to tune the electronic structure of the catalytic metal centre. These advantages are further accentuated though immobilization onto heterogeneous electrodes. A number of porphyrin catalysts and their electrocatalytic propensity for CO₂ electroreduction in heterogeneous systems have been reported herein.

The catalytic activity of these catalysts is strongly dependent on their structural properties and the immobilization technique chosen. Although the goal behind these immobilization techniques is to reduce catalyst aggregation and improve electron transfer from the electrode to the catalyst, the structural complexity of porphyrin molecules coupled with the particular constraints of synthesizing immobilization-compatible molecules hinders rapid development. Advances in structural design allow successful molecules to form stable interactions with the electrode to prevent dissociation, resulting in longer operation capacities.

Despite the variety of optimized heterogeneous molecular catalysts reported so far, there are still limitations which need to be addressed. For commercial electrochemical CO₂ conversion, it is crucial to achieve a high selectivity of reduction products while ensuring long-term stability of the molecular catalysts. Promising strides in understanding multi-step reaction mechanisms that use molecular catalysts to localize reaction intermediates for reducing CO₂ to complex C₂ products is underway.

**Conflicts of interest**

There are no conflicts to declare.

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