1 Introduction

CO₂ photoreduction is one of the potential technologies for carbon utilisation. However, major optimization in photocatalyst design is required for its applicability. Possible approaches in heterogeneous photocatalysis to improve photocatalytic activity include photocatalyst dispersion on highly porous substrates and the use of coupling two semiconductors as photocatalysts. For these reasons, composite mixtures of ZnO and TiO₂ were prepared on an ordered mesoporous SBA-15 silica support for CO₂ photoreduction. SBA-15 was chosen as it has several favourable characteristics including: a large surface area which may enhance photocatalyst dispersion and the availability of photons; SBA-15 is also chemically and mechanically stable and SBA-15 has shown effectiveness as a CO₂ photoreducation support. TiO₂ has been shown to be an effective photocatalyst for CO₂ photoreduction with numerous examples found in the literature. ZnO has also shown promise as a photocatalyst for CO₂ photoreduction. ZnO offers improved CO₂ adsorption and low charge carrier recombination. Both TiO₂ and ZnO share low cost, non-toxicity and relatively environmentally friendly properties.

TiO₂ is not efficient for CO₂ photoreduction due to: poor charge carrier mobility leading to a fast recombination rate and hindered CO₂ adsorption in the presence of H₂O due to the limited presence of surface basic functionalities. On the contrary, ZnO exhibits a longer charge carrier lifetime and suitable surface basicity which can improve CO₂ adsorption. Moreover, the coupling of TiO₂ and ZnO was reported to form a heterojunction that could reduce charge carrier recombination leading to enhanced CO₂ photoreduction activity. Composite mixtures of anatase TiO₂ and wurtzite-type ZnO, due to the TiO₂/ZnO heterojunction formed, showed improved CO₂ photoreduction activity. Other examples of composite mixtures of TiO₂ and ZnO leading to improved photocatalytic activity, due to less charge recombination, include the degradation of phenols and salicylic acid. Due to their synergistic effects on electronic and acid/base properties, the use of TiO₂ and ZnO as photocatalyst mixture is promising for CO₂ photoreduction. However, no examples have described the impact of different mixing fractions of TiO₂ and ZnO on CO₂ photoreduction performance.

CO₂ photoreduction faces the challenge of low efficiency but also the deactivation of the photocatalyst. Deactivation of the photocatalyst has been reported, especially when production data is collected in continuous flow setups, for CO₂ photoreduction by a growing number of authors. Possible
explanations for deactivation include: photocatalyst poisoning due to irreversible adsorption of reaction intermediates; sintering and agglomeration of the photocatalyst metal active sites and loss of active reaction sites that include oxygen vacancies, surface hydroxyls and Ti\(^{3+}\) sites.\textsuperscript{22} To develop CO\(_2\) photoreduction, low efficiency and deactivation of the photocatalyst need to be addressed. In a closely related field of photocatalytic oxidation, radical scavenging of the reactive oxygen species as hydroxyl radicals have been found to lead to deactivation.\textsuperscript{33} Some inorganic anions are known to interact with radical processes, by yielding less reactive and more stable intermediates and thus hampering the overall photocatalytic reaction.\textsuperscript{24}

High throughout technologies and automation are critical to finding suitable photocatalysts.\textsuperscript{25} Central to these technologies is the use of systematic experimental designs, Design of Experiments (DOE), for decision making. There are numerous examples in the literature describing the use of DOE for engineering and process optimisation.\textsuperscript{29,36,37} Mixture designs can efficiently evaluate the impact of component fractions in a mixture.\textsuperscript{28} In this work, the impact of TiO\(_2\) and ZnO fractions used for the formulation of a mixed metal oxide (MO) photocatalyst mixture on a SBA-15 support, was evaluated for CO\(_2\) photoreduction using a novel combination of a systematic mixture design and photocatalysis theory.

In this work in-house synthesis of the photocatalysts was used due to the potential and scope, using different synthetic methodologies, for improvements to increase surface area, crystallinity,\textsuperscript{39} photocatalyst coverage and optical properties.\textsuperscript{29}

### 2 Experimental

#### 2.1 Photocatalyst preparation

SBA-15 was synthesized according the procedure reported in literature.\textsuperscript{40} Briefly, template EO20-PO70-EO20 (P123, Aldrich) was dissolved in aqueous HCl solution and tetraethoxysilicate (TEOS) was introduced as silica precursors. Powder was aged at 90 °C, dried and then calcined at 550 °C for 6 h under air flow. TiO\(_2\) and ZnO were synthesised by precipitation of inorganic salts. In the case of TiO\(_2\), a titanate sulphate solution and a NaOH solution were added dropwise to deionised H\(_2\)O under vigorous stirring, keeping pH neutral. Then the Ti(OH)\(_4\) suspension was aged at 60 °C for 20 h and then washed with distilled H\(_2\)O to remove the sulphate ions and dried at 110 °C for 18 h and finally calcined at 400 °C for 4 h in air flow.\textsuperscript{41} ZnO was prepared following the same procedure reported for TiO\(_2\), but starting from a ZnSO\(_4\) solution as precursor and keeping the pH slightly alkaline (pH 9) during the precipitation. The prepared TiO\(_2\) and ZnO were added onto SBA-15 by incipient wetness impregnation using isopropanol as a liquid medium. Samples were then dried at 110 °C for 18 h.

#### 2.2 UV-vis absorption

The light absorption and electronic band were characterized using a UV-vis spectrometer (PerkinElmer lambda 950) equipped with a 150 mm integration sphere (PerkinElmer). The band gap was determined using the Kubelka–Munk function (1) and intersection of the Tauc segment and hv-axis of the Tauc plot.\textsuperscript{42}

\[
F(R_{\infty}) = \frac{(1 - R_{\infty}^2)}{2R_{\infty}} \quad (1)
\]

where \(F(R_{\infty})\) is the remission function and \(R_{\infty}\) is the reflectance of the sample with infinite thickness.

#### 2.3 XRD characterisation

For the analysis of mixed MOs on SBA-15, a Bruker D8 Advance powder diffractometer, operating with Ge-monochromated Cu K\(_\alpha\) radiation (wavelength = 1.5406 Å) and a LynxEye linear detector. Data were collected over the angular range 5–85° in 2\(\theta\). For the analysis of pure ZnO and TiO\(_2\), X-ray Diffraction (XRD) patterns were collected on a Bruker D8 Advance powder diffractometer with a sealed X-ray tube (copper anode, 40 kV and 40 mA) and a Si(Li) solid state detector (Sol-X) set to discriminate the Cu K\(_\alpha\) radiation. Apertures of divergence, receiving, and detector slits were 2.0 mm, 2.0 mm, and 0.2 mm, respectively. Data scans were performed in the 2\(\theta\) range 5–75° with 0.02° step size and counting times of 3 s per step. Quantitative phase analysis determination performed using the Rietveld method as implemented in the TOPAS v4.3 program (Bruker AXS) using the fundamental parameters approach for line-profile fitting.

#### 2.4 N\(_2\) physisorption

Specific surface areas (SSA) of the samples were evaluated by N\(_2\) physisorption. 200 mg of the sample was placed under vacuum at 200 °C for 2 h. The analyses were then carried out recording the adsorption–desorption isotherm at –196 °C with a Micromeritics ASAP 2000 analyzer. SSAs were finally determined by the BET equation.\textsuperscript{43}

#### 2.5 CO\(_2\) adsorption

Samples were degassed under a constant purge of N\(_2\) at 200 °C for 10 h. CO\(_2\) adsorption capacities were estimated by the maximum value found from the CO\(_2\) adsorption isotherm measured at 273 K over fifteen equidistant points from 0 to 0.95 \(P/P_0\) (Gemini VII 2390).

#### 2.6 CO\(_2\) photoreduction tests

A slurry of the prepared mixed MO photocatalyst was prepared by adding \(\approx\)100 mg of the mixed MO photocatalyst to 1 ml DI H\(_2\)O in a 5 ml vial. The vial was sealed and agitated in a ultrasonic bath for two minutes. The slurry was then deposited dropwise onto a glass fiber disc (47 mm diameter). The coated glass fiber disc was dried at 120 °C for 2 h. The coated glass fiber disc was placed in the middle of a stainless steel photoreactor (\(r = 25\) mm, \(h = 1\) mm, \(r = 1.96\) mm\(^3\)) and sealed. Residual air in the system was evacuated via three repetitive steps of placing the system under vacuum to –1 bar and the vacuum released with CO\(_2\) (99.995%) to +1 bar. The flow rate of CO\(_2\) was set to 0.35 ml min\(^{-1}\) and passed through the temperature controlled (±0.1 °C) aluminium body saturator for at least 12 h to allow the
system to equilibrate. Relative humidity (±1.8% RH) was measured using an inline Sensirion SHT75 humidity sensor potted (MG Chemicals 832HD) into a Swagelok 1/4" T-piece. The temperature of the photocatalyst surface (40 °C ± 2.0 °C) was controlled using a hotplate and the surface temperature measured using a Radley’s pyrometer. To prevent condensation at higher saturation temperatures, the lines from the saturator up until the inlet of the H2O trap were heated and temperature controlled (±0.1 °C) with a heating rope and thermocouple (Fig. 1).

An OmniCure S2000 fitted with a 365 nm filter was used as the light source and the irradiance (295.71 gcat m2 h−1) was checked before each experiment using an OmniCure R2000 radiometer (±5%). An inline GC (Agilent, Model 7890B series) with a Hayesep Q column (1.5 m), (1/16 inch od, 1 mm id), MolSieve 13× (1.2 m), (1/16 inch od, 1 mm id), thermal conductivity detector (TCD), nickel catalysed methanizer and flame ionization detector (FID) was used to analyze the output of the photoreactor every four minutes. CO and CH4 production were measured using a Radley’s pyrometer. To prevent condensation at higher saturation temperatures, the lines from the outlet of the saturator up until the inlet of the H2O trap were heated and temperature controlled (±0.1 °C) with a heating rope and thermocouple (Fig. 1).

2.7 Ionic chromatography method for testing sulphates
Quantitative analysis of sulphates was performed through a procedure previously reported for sulphate-doped zirconia.44 200 mg of the sample was treated with 250 mL of 0.1 M NaOH solution to extract the sulphates. The suspension was filtered and analyzed. An LC20 ionic chromatographer equipped with a 25 μL injection loop, a AS14 separation column, a AG14 guard column, an acid resin suppressor and a ED40 conductivity detector was used. A buffer solution of 10 mM Na2CO3 and 3.5 mM NaHCO3 in Milli-Q H2O, at room temperature was used as eluent. A calibration curve for quantitative analysis was obtained using standard Na2SO4 solution between 1 and 8 ppm.

2.8 SEM/EDX analysis
Scanning electron microscopy and X-ray energy dispersive spectroscopy analysis of the mixed MOs and SBA support were performed using a FEI Scios SEM equipped with an EDAX Octane Plus EDS detector.

2.9 Design of experiments
A two component three degree simplex lattice design was employed with experimental settings and results shown in Table 1. MATLAB was used to estimate: the fitted coefficient values; determine the p-values and plot the models and data.

The experimental design results were used to fit the polynomial function shown by (2).

\[ Y = \beta_1X_1 + \beta_2X_2 + \beta_3X_1X_2 \]  

where \( Y \) is the cumulative production of CO or CH4; \( X_1 \) and \( X_2 \) are the fractions of TiO2 and ZnO respectively; \( \beta_1 \) and \( \beta_2 \) are the coefficients estimated for the impact of the fractions of TiO2 and ZnO used respectively and \( \beta_3 \) is the coefficient estimated for the interaction term between the fraction of TiO2 and ZnO.

Using the matrix of \( X_1 \) and \( X_2 \) fractions of TiO2 and ZnO values shown in Table 1 and either the maximum CO2 adsorption, cumulative production of CO or CH4 production as a response shown by \( Y \) in (2), the coefficients \( \beta_1, \beta_2 \) and \( \beta_3 \) from (2), were estimated by linear regression using a QR decomposition algorithm (fitlm function) in MATLAB (Table 3). The p-values for each coefficient were determined using the MATLAB fitlm function call. Using 95% confidence, p-values less than 0.05 indicated that the coefficient value was not equal to zero and its associated parameter \((X_1, X_2 \text{ or } X_3)\) had a statistically significant impact on either maximum CO2 adsorption, CO or CH4 cumulative production.

Table 1. Two component three degree simplex lattice design points used for experimental settings \((X_1 \text{ and } X_2)\) as mass fractions of TiO2 and ZnO respectively. Amounts of TiO2 and ZnO mixed with 800.0 mg SBA-15.

| Exp. name | \( X_1 \) fraction | \( X_2 \) fraction | Amount TiO2 (mg) | Amount ZnO (mg) |
|-----------|------------------|------------------|----------------|----------------|
| MO1       | 1.00             | 0.00             | 200.2          | 0.0            |
| MO2       | 0.67             | 0.33             | 133.9          | 67.4           |
| MO3       | 0.33             | 0.67             | 66.5           | 133.2          |
| MO4       | 0.00             | 1.00             | 0.0            | 200.4          |
| MO5       | 0.50             | 0.50             | 100.4          | 102.7          |
| MO6       | 0.75             | 0.25             | 149.3          | 53.5           |
| MO7       | 0.25             | 0.75             | 50.7           | 150.7          |

3 Results and discussion

3.1 Characterization and properties of mixed metal oxides
The samples prepared with a high fraction of TiO2 (MO1, MO2, MO5 and MO6) showed the characteristic broad adsorption peak of anatase TiO2 (Fig. 2a). As the fraction of ZnO increased (MO3, MO4 and MO7) the Tauc plot peak shapes became sharper and characteristic of the adsorption peaks of ZnO (Fig. 2a). Increasing the fraction of TiO2 increased the band gap linearly from the ZnO region (3.16 eV) towards the anatase region (3.24 eV) (Fig. 3). Increasing the fraction of ZnO increased the...
The intensity of the characteristic zincite peaks (JCPDS card no. 36-1451) at 2θ = 31.9, 34.4 and 36.2 (Fig. 3).

As reported in Fig. 4a, adsorption isotherms of all the mixed MO samples exhibited the typical shape of SBA-15, suggesting that its ordered mesoporous structure was retained. Nevertheless, when comparing the SSAs with the TiO2 fraction (Fig. 4b), a sinusoidal trend was observed, suggesting that SSA has no or little effect on photoreduction efficiency and selectivity in these mixed MO systems.

3.2 Mixture design and the impact of TiO2 and ZnO fractions

3.2.1 Impact TiO2 and ZnO fractions on CO2 adsorption. Fig. 5 shows the impact of increasing the fraction of TiO2 used in the mixture on maximum CO2 adsorption. CO2 adsorption increased significantly when a small fraction of ZnO was present with little change with increasing the fraction of ZnO thereafter (Fig. 5).

Both the fraction of ZnO and TiO2 positively impacted (β1 = 19.31, β2 = 22.65) maximum CO2 adsorption with statistical significance (p-value = 2.61 × 10-4, p-value = 1.39 × 10-4), respectively (Table 2). The impact of the ZnO fraction had a larger coefficient value (β2 = 22.65) versus TiO2 (β1 = 19.31) and this could be explained by the increase in surface basicity. It was expected that an increase in CO2 adsorption would increase CO2 photoreduction photocatalytic activity. However, photocatalytic processes are complicated and often multiple properties of the photocatalyst need to be considered.

3.2.2 Impact TiO2 and ZnO fractions on CO2 photoreduction. Fig. 6a and b shows the impact of increasing the fraction of TiO2 used in the mixture on CO and CH4 production, respectively. Increasing the fraction of TiO2 increased CO cumulative
Parameter coefficient | Value estimated | $p$-Value
--- | --- | ---
$\beta_1$ | 19.31 | $2.61 \times 10^{-8}$
$\beta_2$ | 22.65 | $1.39 \times 10^{-8}$
$\beta_3$ | 9.28 | $2.32 \times 10^{-7}$

These results were not encouraging from an activity point of view but they offered an opportunity for further scientific enquiry. Both TiO$_2$ and ZnO were synthesized using a precipitation method that employed sulphate salts TiOSO$_4$ and ZnSO$_4$, respectively. Ion chromatography (IC) analyses were performed on pristine TiO$_2$ and ZnO samples, showing 0.4% and 12.0% wt sulphates, respectively. The large amount of sulphates observed in the ZnO samples, was also confirmed by XRD analysis (Fig. 7), showing that this material is actually composed of 43% Zn$_3$O(SO$_4$)$_2$, corresponding to 20.7% wt amount of sulphates, and 57% ZnO. The difference in the amount of sulphates recorded by IC and XRD is likely due to the inability of the IC analysis extraction procedure to recover all the sulphates. Sulphur and zinc mapped very closely to one another by SEM/EDX analysis (Fig. 8). Visually, sulphur content increased with increasing fraction of ZnO (Fig. 8). The EDX analysis also yielded a linear increase in sulphur with increasing the fraction of ZnO used (Fig. 9). Together, these were additional pieces of evidence highlighting the incorporation of sulphates by the ZnO used.

Lo et al. reported acidic sulphate modified titania as an efficient photocatalyst for CO$_2$ photoreduction. Nevertheless, sulphate anions was observed to have a detrimental effect on photooxidation by acting as both radical scavenger and competing with reagents for adsorption to active photocatalyst sites. We can discount the latter hypothesis since as discussed in Section 3.2.1, ZnO was observed to improved CO$_2$ adsorption. The radical (or hole) scavenging hypothesis was thus considered. Several mechanisms, all involving radical intermediates, have been proposed for CO$_2$ photoreduction. Sulphates or species arising from radical scavenging yielding SO$_4^{2-}$ species significant ($p$-value = $2.30 \times 10^{-2}$) and negative impact ($\beta_1 = -2.64$) on CH$_4$ cumulative production (Table 3). This would indicate that the inclusion of ZnO significantly hampered the production of CH$_4$.

An interaction effect was found between the fractions of TiO$_2$ and ZnO used in the photocatalyst mixture with a statistically significant ($p$-value $= 2.93 \times 10^{-4}$) and negative impact ($\beta_1 = 9.71$) CO cumulative production with statistical significance ($p$-value $= 1.35 \times 10^{-3}$) (Table 3). This was also the case for CH$_4$ cumulative production ($\beta_1 = 1.43$, $p$-value $= 1.35 \times 10^{-3}$) (Table 3).

Fig. 7 XRD comparison of TiO$_2$ and ZnO. A = anatase (TiO$_2$ phase), Z = zincite (ZnO phase) and S = Zn$_3$O(SO$_4$)$_2$.

![Image](image_url)
might interfere with the CO₂ photoreduction reaction pathway. Moreover, the oxidizing holes generated on both TiO₂ (+2.91 V vs. NHE) and ZnO (+2.89 V vs. NHE) valence band, can be potentially scavenged by sulphates \( E^\circ = +2.43 \text{ V vs. NHE} \), thus acting as charge carrier trap and competing with water oxidation (Fig. 10). The sulphates acting as radical and/or hole scavengers are very likely to undergo chemical transformations towards reduced sulphur species such as H₂S, SO₂ and S. To confirm this hypothesis, future work would include attempting to identify these species formed during the CO₂ photoreduction reaction.

4 Conclusion

A systematic experimental mixture design as used to investigate the impact of the fractions of TiO₂ and ZnO as mixed MOs on an ordered SBA-15 mesoporous support for CO₂ photoreduction activity. The combination of a systematic experimental mixture design using numerical tools and the analysis of the prepared TiO₂/ZnO photocatalyst properties offered an opportunity to provide evidence for the trapping of radical CO₂ photoreduction intermediates and/or charge carriers by sulphate groups. This approach has shown use for rapid screening and the development of mixed MOs for CO₂ photoreduction.

Increasing the fraction of ZnO increased the adsorption of CO₂ with statistical confirmation using the mixture design. Increasing the fraction of TiO₂ improved the production of CO with a linear trend observed. Increasing the fraction of TiO₂ also improved the production of CH₄ with an exponential trend observed. This was confirmed by numerical analysis where the fraction of TiO₂ was found to be statistically significant for both CO and CH₄ cumulative production. The exponential trend for CH₄ cumulative production could be explained by the statistical significance of a negative interaction between the fraction of TiO₂ and ZnO used. Increasing the fraction of ZnO yielded significantly less CH₄ production and had a slightly less dramatic, albeit still negative, impact on CO production.

The impact of radical scavengers on deactivation has not been explored for CO₂ photoreduction. The mixed MO mixtures was initially intended to improve the efficiency of CO₂ photoreduction. However, this study showed how the inclusion of sulphates from the synthesis method very likely led to deactivation and lower production of CH₄ and CO. In addition, this study serves as a framework for the efficient and systematic study of other novel photocatalyst synthetic techniques and subsequent formulation of novel mixtures for CO₂ photoreduction.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The authors thank the financial support provided by the Engineering and Physical Sciences Research Council (EP/K021796/1), the Research Centre for Carbon Solutions (RCCS) and the James Watt Scholarship Programme at Heriot-Watt University.
We are also grateful for the support provided by the Buchan Chair in Sustainable Energy Engineering.

Notes and references

1 O. Ola and M. Maroto-Valer, J. Photochem. Photobiol., C, 2015, 24, 16–42.
2 A. Olivo, D. Zanardo, E. Ghedini, F. Menegazzo and M. Signoretto, ChemEngineering, 2018, 2, 42.
3 Y. Belmaoujahid, M. Bonne, Y. Scudeller, D. Schleich, Y. Grohens and B. Lebeau, Microporous Mesoporous Mater., 2015, 201, 124–133.
4 D. Zhao, Q. Huo, J. Feng, B. F. Chemelka and G. D. Stucky, J. Am. Chem. Soc., 1998, 120, 6024–6036.
5 C. Zhao, L. Liu, Q. Zhang, J. Wang and Y. Li, Catal. Sci. Technol., 2012, 2, 2558–2568.
6 R. Chen, X. Cheng, X. Zhu, Q. Liao, L. An, D. Ye, X. He and Z. Wang, Chem. Eng. J., 2017, 316, 911–918.
7 C.-C. Yang, J. Vermimnen, V. Meynen, P. Cool and G. M. J. Catal., 2011, 284, 1–8.
8 K. Li, B. Peng and T. Peng, ACS Catal., 2016, 6, 7485–7527.
9 X. Chang, T. Wang and J. Gong, Energy Environ. Sci., 2016, 9, 2177–2196.
10 X. Liu, L. Ye, S. Liu, Y. Li and X. Ji, Sci. Rep., 2016, 6, 38474.
11 W.-N. Wang, F. Wu, Y. Myung, D. M. Niedzwiedzki, H. S. Im, J. Park, P. Banerjee and P. Biswas, ACS Appl. Mater. Interfaces, 2015, 7, 5685–5692.
12 C. Xin, M. Hu, K. Wang and X. Wang, Langmuir, 2017, 33, 6667–6676.
13 Y. Li, W. Xie, X. Hu, G. Shen, Z. Zhou, Y. Xiang, X. Zhao and P. Fang, Langmuir, 2010, 26, 591–597.
14 X. Zhang, J. Qin, Y. Xue, P. Yu, B. Zhang, L. Wang and R. Liu, Sci. Rep., 2014, 4, 4596.
15 S. Krischok, O. Höft and V. Kempter, Surf. Sci., 2002, 507–510, 69–73.
16 M. Quintana, T. Edvinsson, A. Hagfeldt and G. Boschloo, J. Phys. Chem. C, 2007, 111, 1035–1041.
17 H. Li, D. Gao, P. Gao, F. Wang, N. Zhao, F. Xiao, W. Wei and Y. Sun, Catal. Sci. Technol., 2013, 3, 2801–2809.
18 G. Xi, S. Ouyang and J. Ye, Chem.–Eur. J., 2019, 17, 9057–9061.
19 K. Wu, X. Dong, J. Zhu, P. Wu, C. Liu, Y. Wang, J. Wu, J. Hou, Z. Liu and X. Guo, J. Mater. Sci., 2018, 53, 11595–11606.
20 V. Sukharev and R. Kershaw, J. Photochem. Photobiol., A, 1996, 98, 165–169.
21 N. Serpone, M. Maruthamuthu, P. Pichat, E. Pelizzetti and H. Hidaka, J. Photochem. Photobiol., A, 1995, 85, 247–255.
22 F. Fresno, I. J. Villar-Garcia, L. Collado, E. Alfonso-Gonzalez, P. Reñones, M. Barawi and V. A. de la Peña O’Shea, J. Phys. Chem. Lett., 2018, 9, 7192–7204.
23 L. Liu, C. Zhao, D. Pitts, H. Zhao and Y. Li, Catal. Sci. Technol., 2014, 4, 1539–1546.
24 W. N. Wang, W. J. An, B. Ramalingam, S. Mukherjee, D. M. Niedzwiedzki, S. Gangopadhyay and P. Biswas, J. Am. Chem. Soc., 2012, 134, 11276–11281.
25 S. Pouydel and S. Laursen, J. Phys. Chem. C, 2018, 122, 8045–8057.
26 P. Reñones, A. Moya, F. Fresno, L. Collado, J. J. Vilatela and V. A. de la Peña O’Shea, J. CO2 Util., 2016, 15, 24–31.
27 L. Liu, C. Zhao, J. T. Miller and Y. Li, J. Phys. Chem. C, 2017, 121, 490–499.
28 Y. Li, W.-N. Wang, Z. Zhan, M.-H. Woo, C.-Y. Wu and P. Biswas, Appl. Catal., B, 2010, 100, 386–392.
29 W. A. Thompson, C. Perier and M. M. Maroto-Valer, Appl. Catal., B, 2018, 238, 136–146.
30 F. Fresno, P. Reñones, E. Alfonso, C. Guillén, J. F. Trigo, J. Herrero, L. Collado and V. A. de la Peña O’Shea, Appl. Catal., B, 2018, 224, 912–918.
31 L. Liu, F. Gao, H. Zhao and Y. Li, Appl. Catal., B, 2013, 134–135, 349–358.
32 H. Zhao, L. Liu, J. M. Andino and Y. Li, J. Mater. Chem. A, 2013, 1, 8209–8216.
33 L. Gomathi Devi, S. Girish Kumar, K. Mohan Reddy and C. Munkirshnappa, J. Hazard. Mater., 2009, 164, 459–467.
34 M. Chiha, O. Hamdouai, S. Baup and N. Gondrexon, Ultrason. Sonochem., 2011, 18, 943–950.
35 F. Häse, L. M. Roch and A. Aspuru-Guzik, Trends Chem., 2019, 1, 282–291.
36 J. Antony, Design of Experiments for Engineers and Scientists, Elsevier Science, 2014.
37 L. Iázarbe, M. J. Álvarez, E. Viles and M. Tanco, Qual. Reliab. Eng. Int., 2019, 24, 417–428.
38 C. C. Solvason, N. G. Chemmangattuvallapill, F. T. Eljack and M. R. Eden, Ind. Eng. Chem. Res., 2009, 48, 2245–2256.
39 A. Olivo, E. Ghedini, M. Signoretto, M. Compagnoni and I. Rossetti, Energies, 2017, 10, 1394.
40 E. Ghedini, M. Signoretto, F. Pinna and G. Cruciani, Catal. Lett., 2008, 125, 359–370.
41 A. Olivo, V. Trevisan, E. Ghedini, F. Pinna, C. Bianchi, A. Naldoni, G. Cruciani and M. Signoretto, J. CO2 Util., 2015, 12, 86–94.
42 A. Escobedo-Morales, I. I. Ruiz-López, M. Ruiz-Peralta, L. Tepech-Carrillo, M. Sánchez-Cantú and J. E. Moreno-Orea, Heliyon, 2019, 5, e01505.
43 S. Brunauer, P. H. Emmett and E. Teller, J. Am. Chem. Soc., 1938, 60, 309–319.
44 C. Sarzanini, G. Saccheri, F. Pinna, M. Signoretto, G. Cerrato and C. Morretta, J. Mater. Chem., 1995, 5, 353–360.
45 W. Liu and Y. Zhang, J. Mater. Chem. A, 2014, 2, 10244–10249.
46 M. M. Demir, R. Muñoz-Espi, I. Lieberwirth and G. Wegner, J. Mater. Chem., 2006, 16, 2940–2947.
47 A. Moezzi, M. B. Courtie and A. M. McDonagh, Dalton Trans., 2013, 42, 14432–14437.
48 C.-C. C. Lo, C.-H. H. Hung, C.-S. S. Yuan and Y.-L. L. Hung, Chin. J. Catal., 2007, 28, 528–534.
49 W. Zhang, T. An, M. Cui, G. Sheng and J. Fu, J. Chem. Technol. Biotechnol., 2004, 80, 223–229.
50 P.-S. Yap and T.-T. Lim, Appl. Catal., B, 2011, 101, 709–717.
51 S. N. Habisreutinger, L. Schmidt-Mende and J. K. Stolarczyk, Angew. Chem., Int. Ed., 2013, 52, 7372–7408.
52 R. E. Huie, C. L. Clifton and P. Neta, Int. J. Radiat. Appl. Instrum., Part C, 1991, 38, 477–481.