

Preliminary performance screening of cubic CeO₂ supported bimetallic catalysts for CO₂ hydrogenation

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Abstract

Four CeO₂ containing bimetallic formulations CuNi/CeO₂, AuRu/CeO₂, FeCu/CeO₂, and AgNi/CeO₂ were evaluated as a preliminary activity/selectivity screening set for the reverse water-gas shift (RWGS) and methanation pathways. The formulations were tested using the same fixed-bed reaction protocol from 40 to 350°C, but they do not constitute a strict single-variable catalyst series: the metal pairs and nominal precursor ratios differ, and AuRu/CeO₂ was synthesized by a different route. SEM–EDS verified the presence and microscale distribution of the target elements, N₂ physisorption described the mesoporous CeO₂ support, and XRD showed that cubic fluorite CeO₂ remained the dominant crystalline phase. CuNi/CeO₂ gave the highest CO₂ conversion (50.94% at 350°C), FeCu/CeO₂ gave the highest CO formation rate (624 μmol g⁻¹ h⁻¹), AuRu/CeO₂ gave the highest CH₄ formation rate (545 μmol g⁻¹ h⁻¹), and AgNi/CeO₂ retained the highest CH₄ selectivity at 350°C (76.6%). These results identify formulation-level performance trends only; they do not establish intrinsic effects of metal identity, metal ratio, preparation route, active-site structure, or reaction mechanism.

1. Introduction

Catalytic CO₂ hydrogenation is an important route for converting CO₂ into CO through the reverse water-gas shift (RWGS) reaction or into CH₄ through methanation. Recent reviews and mechanistic analyses describe the CO₂ hydrogenation network and methanation pathway in detail (Ye et al. 2019; Liang et al. 2024). Product distribution depends on reaction conditions and on how catalyst composition affects CO₂ activation, H₂ activation, CO_x intermediate binding, CO desorption, and further hydrogenation, as also shown in selectivity-control studies by Yao et al. (2021) and Sheng et al. (2026). For catalyst-screening studies, testing several formulations under one reactor window can provide useful performance guidance even when the available characterization is not sufficient for molecular level mechanistic assignment.

Ceria is relevant for CO₂ hydrogenation because CeO₂ can participate in CO₂ activation through reducible Ce⁴⁺/Ce³⁺ surface sites, oxygen-vacancy chemistry, and metal-support contact (Li et al. 2023; Liang et al. 2024). Cubic CeO₂ also offers a defined support morphology for comparing supported metal formulations. However, SEM-EDS, XRD, and support-only BET data cannot determine exposed facets, oxygen-vacancy concentration, oxidation states, metal dispersion, or active-site structures. The present manuscript therefore uses CeO₂ as a common support platform and avoids claims that require advanced surface or operando characterization.

Previous studies show that composition regulation can shift CO₂ hydrogenation selectivity between CO and more hydrogenated products (Yao et al. 2021), while CeO₂-supported transition metals also show that metal identity can change activity and product distribution (Li et al. 2023). For Ni/CeO₂, the support and accessible Ni sites influence methanation behavior (Zheng et al. 2022; Chen et al. 2024a), while support morphology also changes Ni/CeO₂ performance (Gupta et al. 2024; Musig et al. 2024). Ru-

containing CeO₂ catalysts and Ru-Ni tandem systems highlight the role of H₂ activation in methane formation (Zhang et al. 2023; Li et al. 2024). Broader comparisons of Ni-based catalysts on oxide supports further support the importance of support-dependent metal availability (Kuhaudomlap et al. 2024; Chen et al. 2024b). On this basis, CuNi/CeO₂, AuRu/CeO₂, FeCu/CeO₂, and AgNi/CeO₂ were selected as a practical screening set rather than as a strict single-variable series.

The four formulations were selected to span experimentally available metal functions relevant to CO₂ hydrogenation rather than to isolate a single compositional variable. Ni- and Ru-containing formulations were included because these metals commonly promote H₂ activation and methanation, whereas Cu- and Fe-containing formulations were included to examine CO-forming/RWGS-oriented behavior; Ag and Au were included as coinage-metal components that can modify adsorption and product distribution. This functional rationale is consistent with the reported sensitivity of CO₂ hydrogenation to metal identity and composition (Yao et al. 2021; Li et al. 2023; Zhang et al. 2023; Liang et al. 2024). Nevertheless, because both metal pairing and nominal ratio vary, the data are interpreted only as formulation screening and not as a controlled test of bimetallic synergy.

This study compares the four catalysts under the same reaction window and reports CO₂ conversion, CO formation, CH₄ formation, and CO/CH₄ selectivity trends. The comparison is intentionally described as screening-level because the catalysts differ in nominal metal ratio, and AuRu/CeO₂ was prepared by a different route from the impregnated samples. The discussion therefore focuses on directly measured performance trends and explicitly separates those trends from unverified structure-performance and mechanistic interpretations.

2. Results and discussion

2.1 Morphology, composition, and textural properties of cubic CeO₂

The CeO₂ support was characterized before metal introduction to establish the baseline material used for the comparative catalyst set. SEM images show cube-like particles with visible edges and flat faces (Fig. 1a,b), with some aggregation after drying and thermal treatment but without complete morphological collapse. EDS mapping shows Ce and O distributed throughout the mapped region, and the spectrum shows Ce/O signals within the detection limit. These results support formation of a morphologically defined ceria support, while facet identity, oxygen-vacancy concentration, and Ce³⁺/Ce⁴⁺ ratio require techniques beyond SEM-EDS.

This support characterization provides the baseline for comparing the metal-loaded samples. The cube-like CeO₂ morphology is relevant to CO₂ hydrogenation studies, but the present data do not prove a specific exposed facet, vacancy-mediated pathway, or metal-support interfacial structure. Accordingly, the catalytic discussion treats the support as a shared material platform and focuses on measured

differences in activity and product distribution. The surface and pore properties of the CeO₂ support were investigated by N₂ adsorption-desorption analysis (Fig. 2a,b). The isotherm shows low nitrogen uptake at low relative pressure followed by stronger uptake at high relative pressure, consistent with mesopores and interparticle voids rather than dominant microporosity. The BET surface area is 51.0 m² g⁻¹, and the single-point surface area is 49.1 m² g⁻¹. The BET fit gave a monolayer adsorption capacity of 11.7 mL g⁻¹, a BET constant of 57.5, and a correlation coefficient of 0.9998 over P/P₀ = 0.057–0.299.

The pore-size information in Fig. 2b further confirms the mesoporous character of the support. The total pore volume is 0.213 cm³ g⁻¹, and the average pore diameter calculated by the BET 4V/A method is 16.7 nm. BJH desorption analysis gives an average pore diameter of 12.3 nm and a most probable desorption pore diameter of 19.9 nm. These values are reported with appropriate significant digits and are used only to describe the CeO₂ support; they are not used to claim textural differences among the bimetallic catalysts.

Table 1
Textural properties of the cubic CeO₂ support.

Parameter	Value	Meaning/measurement
BET surface area	51.0 m ² g ⁻¹	Multipoint BET surface area of the support
Single-point surface area	49.1 m ² g ⁻¹	Surface area estimated by the single-point method
Total pore volume	0.213 cm ³ g ⁻¹	Estimated pore volume of the support
Average pore diameter	16.7 nm	BET 4V/A average pore diameter
BJH desorption average pore diameter	12.3 nm	Mesopore-size estimate
BJH most probable pore diameter	19.9 nm	Main desorption pore contribution
Note: BET = Brunauer-Emmett-Teller; BJH = Barrett-Joyner-Halenda. Values are for the cubic CeO ₂ support only. BET measurements for the metal-loaded catalysts were not available, so catalyst activity is not interpreted in terms of post-loading textural changes.		

2.2 Elemental distribution of bimetallic catalysts on cubic CeO₂

SEM-EDS mapping was used to verify that the target elements were introduced into each catalyst and distributed over the CeO₂-based particles. The maps provide microscale compositional evidence, but they do not prove bulk metal loading, oxidation state, alloy formation, or exposed active-site density. These limits are considered in the interpretation below.

2.2.1 Elemental distribution of AgNi/CeO₂

The SEM-EDS mapping result of AgNi/CeO₂ is shown in Fig. 3. The SEM image indicates that the catalyst retains the aggregated CeO₂-based morphology after impregnation. Ce and O maps define the support matrix, while Ag and Ni signals show that both target metals are detected in the selected region. Regional EDS values of 53.13 wt% Ce, 20.50 wt% O, 14.14 wt% Ni, and 11.22 wt% Ag indicate local presence of Ni and Ag, with Ni showing the higher apparent abundance. These values are treated as local semi-quantitative estimates rather than bulk composition.

2.2.2 Elemental distribution of AuRu/CeO₂

The SEM-EDS elemental mapping results of AuRu/CeO₂ are presented in Fig. 4. The SEM image shows aggregated CeO₂-based particles after noble-metal incorporation. Ce and O are distributed across the selected region, indicating that ceria remains the main support matrix. Au and Ru maps are also detected over the same region, showing that both noble-metal components are present at the mapping scale.

The EDS spectrum contains Ce, O, Au, and Ru signals, supporting the presence of the intended elements. Because EDS values are semi-quantitative and depend on the selected area, they are used here only to indicate elemental presence and approximate spatial distribution, not to determine true bulk loading, oxidation state, or alloy composition.

The SEM-EDS results show that Au and Ru are associated with the ceria-based particles after the coprecipitation/hydrothermal preparation. This supports the sample label AuRu/CeO₂, while the presence or absence of alloyed Au-Ru domains cannot be concluded from SEM-EDS alone.

2.2.3 Elemental distribution of CuNi/CeO₂

The CuNi/CeO₂ mapping result is shown in Fig. 5. The SEM image shows aggregated particles similar to the bare CeO₂ support, while Cu and Ni maps appear across the Ce/O-containing region. This shows that both metals are detected on CeO₂-based particles and are spatially associated with the support at the mapping scale.

The quantitative EDS result gives 55.58 wt% Ce, 17.97 wt% O, 14.24 wt% Cu, and 12.20 wt% Ni in the analyzed region. Cu and Ni are both detected at appreciable levels in this selected region. EDS mapping cannot confirm whether Cu and Ni form an alloy or exist as separate oxide/metal species, but it does show that both elements are present within the same catalyst region and in contact with CeO₂-based particles.

2.2.4 Elemental distribution of FeCu/CeO₂

The SEM-EDS mapping result of FeCu/CeO₂ is shown in Fig. 6. The catalyst consists of aggregated CeO₂-based particles, and the Ce and O maps show that the support remains the main matrix. Fe and Cu signals are both detected in the mapped region, indicating local presence of both metals on the CeO₂-based material.

2.3 XRD analysis of bimetallic catalysts

The XRD patterns of the CeO₂-supported bimetallic formulations are shown in Fig. 7. All four patterns contain the main reflections of cubic fluorite CeO₂ at approximately 28.6, 33.1, 47.5, 56.3, 59.1, 69.4, 76.7, 79.1, and 88.4°, corresponding to the (111), (200), (220), (311), (222), (400), (331), (420), and (422) planes. The retained CeO₂ reflections show that fluorite ceria is the dominant crystalline phase after metal introduction.

The XRD patterns shown in Fig. 7 represent the calcined catalysts before the H₂ pretreatment used for catalytic testing. Oxide-containing phases are therefore expected in these ex situ patterns. The additional weak features in CuNi/CeO₂ are described as unassigned Cu/Ni-containing crystalline domains because peak overlap and the available data do not permit an unambiguous distinction among Cu-, Ni-, or mixed-oxide phases. For AuRu/CeO₂, AgNi/CeO₂, and FeCu/CeO₂, no intense independent metal-containing reflections are resolved. This may reflect small crystallites, low crystallinity, low diffracting-phase abundance, or overlap with CeO₂ reflections; it is not taken as proof of high dispersion. XRD therefore establishes retention of the dominant CeO₂ phase but does not determine oxidation state, metal dispersion, particle-size distribution, alloy formation, or metal-metal structure.

2.4 Comparative CO₂ hydrogenation performance

The catalytic behavior of the four CeO₂-supported bimetallic catalysts was evaluated from 40 to 350°C (Fig. 8). The catalysts showed distinct product distributions under the same reactor conditions, indicating different activity/selectivity trends within the tested formulation set. FeCu/CeO₂ gave the highest CO formation rate, increasing from 92 μmol g⁻¹ h⁻¹ at 40°C to 624 μmol g⁻¹ h⁻¹ at 350°C. CuNi/CeO₂ also produced CO at high temperature, reaching 384 μmol g⁻¹ h⁻¹ at 350°C, and gave the highest CO₂ conversion of the series (50.94%). AuRu/CeO₂ produced the highest CH₄ formation rate, reaching 545 μmol g⁻¹ h⁻¹ at 350°C, while AgNi/CeO₂ showed the lowest high-temperature CO formation and retained comparatively high methane selectivity.

The selectivity trends show that conversion and pathway preference are not explained by a single measured descriptor in this dataset. FeCu/CeO₂ remains strongly CO-selective, AgNi/CeO₂ shows the strongest methanation preference, AuRu/CeO₂ combines high CH₄ formation with a high-temperature shift toward CO, and CuNi/CeO₂ provides the highest overall conversion with mixed selectivity. Because metal ratio, preparation route, and post-synthesis treatment are not identical across the full set, these

observations are reported as comparative performance trends rather than as proof that metal identity alone controls selectivity.

Direct benchmarking against literature catalysts is not included as a ranking table because reported CO₂ hydrogenation performance depends strongly on feed composition, space velocity, pretreatment, catalyst loading, metal dispersion, support morphology, reactor configuration, and time-on-stream protocol. The present results are therefore interpreted only within the internally consistent testing window used for the four catalysts in this study.

2.5 Performance trend interpretation and study limitations

The observed selectivity differences are consistent with different catalytic functions introduced by the four bimetallic formulations, but the present characterization does not allow definitive active-site assignments. CeO₂ may assist CO₂ adsorption and activation through reducible surface oxygen and vacancy-related sites, while supported metals can influence H₂ dissociation, CO_x intermediate binding, CO desorption, and further hydrogenation to CH₄. Within the tested set, FeCu/CeO₂ shows a CO-forming trend, AgNi/CeO₂ retains strong CH₄ selectivity, AuRu/CeO₂ gives the highest CH₄ formation rate, and CuNi/CeO₂ gives the highest conversion.

These observations should be regarded as performance correlations rather than confirmed structure-performance relationships. Quantitative metal loading, surface composition, metal oxidation state, metal particle size, reducibility, CO₂ adsorption strength, and adsorbed reaction intermediates were not measured. ICP-OES/ICP-MS, XPS, H₂-TPR, CO₂-TPD, Raman spectroscopy, TEM/STEM, isotopic experiments, and in situ/operando DRIFTS would be required to establish a molecular-level mechanism. The present contribution is therefore limited to comparative activity/selectivity screening under one reaction protocol.

3. Experimental

3.1 Materials

All reagents were analytical grade and used without further purification. Ce(NO₃)₃·6H₂O and NaOH were used to synthesize the CeO₂ support. CuCl₂·2H₂O, NiCl₂·6H₂O, FeCl₂·4H₂O, AgNO₃, RuCl₃·nH₂O, and HAuCl₄·4H₂O were used as metal precursors. Deionized water (18.2 MΩ cm), ethanol, and isopropanol were used for catalyst preparation and washing. High-purity H₂, CO₂, N₂, and He were used for pretreatment, reaction testing, and gas chromatography analysis.

3.2 Synthesis of cubic CeO₂ support

Cubic CeO₂ was synthesized hydrothermally. Ce(NO₃)₃·6H₂O (3.472 g) was dissolved in 20 mL deionized water, and NaOH (38.4 g) was dissolved in 140 mL deionized water. The NaOH solution was added dropwise to the cerium nitrate solution under stirring for 30 min. The resulting slurry was transferred to a

Teflon-lined autoclave, filled to about one-third of its volume, and heated at 180°C for 24 h. After cooling, the precipitate was separated, washed with deionized water and ethanol, dried, ground, and used as the cubic CeO₂ support.

3.3 Preparation of bimetallic catalysts

3.3.1 Wet impregnation of CuNi/CeO₂, FeCu/CeO₂, and AgNi/CeO₂

CuNi/CeO₂, FeCu/CeO₂, and AgNi/CeO₂ were prepared by wet impregnation. For each formulation, cubic CeO₂ (3 mmol basis) was dispersed in an aqueous solution containing the corresponding precursor amounts: 4 mmol Cu precursor and 6 mmol Ni precursor for CuNi/CeO₂; 2 mmol Fe precursor and 2 mmol Cu precursor for FeCu/CeO₂; and 2 mmol Ag precursor and 2 mmol Ni precursor for AgNi/CeO₂. The suspension was sonicated for 60 min, stirred at 70°C until the solvent was removed, dried overnight at 60°C, ground, and calcined at 450°C for 4 h under Ar. These are nominal synthesis amounts rather than measured bulk loadings because ICP-based composition data were not available.

3.3.2 Preparation of AuRu/CeO₂

AuRu/CeO₂ was prepared by a one-pot coprecipitation/hydrothermal route to incorporate Au and Ru during ceria formation. CeCl₃·7H₂O (3.8 mmol), RuCl₃·nH₂O (0.2 mmol), and HAuCl₄·4H₂O (0.5 g) were dissolved in 10 mL deionized water and gradually added to NaOH solution (7 M, 70 mL) under vigorous stirring. After aging for 30 min, the mixture was heated at 140°C for 48 h in a Teflon-lined autoclave. The precipitate was separated by centrifugation, washed with deionized water and isopropanol, dried under vacuum at room temperature, ground, and calcined in air at 400°C for 4 h. The local reagent record identifies the Au precursor as chloroauric acid tetrahydrate; the hydration state of the Ru precursor was not independently quantified. Because the recorded Au and Ru quantities are not documented on one consistently verified molar basis, a precise Au:Ru ratio and final bulk metal loading are not claimed. This formulation also used a different Ce precursor, synthesis route, temperature, duration, and calcination atmosphere; it is therefore treated as a separate screened formulation, not as a controlled analogue of the impregnated catalysts.

3.4 Catalyst characterization

Sample morphology was examined by SEM using a FEI 200F field-emission environmental scanning electron microscope operated at 5 kV. Elemental composition and distribution were analyzed by EDS mapping. Powder XRD patterns of the calcined samples were recorded at room temperature using a Rigaku TTR-III diffractometer with Cu K_α radiation ($\lambda = 1.5406 \text{ \AA}$) over $2\theta = 5\text{--}90^\circ$. Textural properties were determined by N₂ adsorption-desorption analysis for the CeO₂ support, and specific surface areas were calculated by the BET method. EDS compositions are treated as semi-quantitative values from selected regions rather than as bulk metal loadings. BET measurements of the metal-loaded

formulations and quantitative measurements of bulk loading, oxidation state, exposed sites, particle size, reducibility, oxygen-vacancy concentration, and spent-catalyst changes were not available.

3.5 Catalytic evaluation of CO₂ hydrogenation

CO₂ hydrogenation was evaluated in a stainless-steel fixed-bed reactor with an 8 mm internal diameter. For each test, 0.30 g catalyst was mixed with 0.20 g inert silica sand. Before reaction, the catalyst was reduced in flowing H₂ at 350°C for 2 h using an H₂ flow of 50 mL min⁻¹. The reaction was conducted at 3.0 MPa using CO₂, H₂, and N₂ as an internal standard. The individual feed flow rates were CO₂ = 10 mL min⁻¹, H₂ = 30 mL min⁻¹, and N₂ = 10 mL min⁻¹, corresponding to H₂/CO₂ = 3:1 and a total flow rate of 50 mL min⁻¹ (10,000 mL g_{cat}⁻¹ h⁻¹). Performance was measured from 40 to 350°C after stabilization for 35 min at each temperature. Products were analyzed using a Shimadzu GC-2014 equipped with TCD and FID detectors. Product formation rates were normalized to catalyst mass; turnover frequencies were not calculated because exposed-metal-site densities were not measured.

$$\text{CO}_2 \text{ conversion, } X_{\text{CO}_2} (\%) = [(F_{\text{CO}_2,\text{in}} - F_{\text{CO}_2,\text{out}}) / F_{\text{CO}_2,\text{in}}] \times 100 \quad (1)$$

$$\text{Product selectivity, } S_i (\%) = [F_i / (F_{\text{CO}} + F_{\text{CH}_4})] \times 100, \text{ where } i = \text{CO or CH}_4 \quad (2)$$

$$\text{Product formation rate, } r_i (\mu\text{mol g}^{-1} \text{ h}^{-1}) = F_i / m_{\text{cat}} \quad (3)$$

Here, F denotes the molar flow rate determined from the calibrated GC response and the N₂ internal standard, and m_{cat} is the catalyst mass. These equations assume that CO and CH₄ are the quantified carbon-containing products. A complete carbon balance was not independently established.

4. Conclusions

This study compared four CeO₂-supported bimetallic catalyst formulations to evaluate CO₂ conversion, CO formation, CH₄ formation, and CO/CH₄ selectivity trends during CO₂ hydrogenation. Under identical testing conditions, CuNi/CeO₂ gave the highest CO₂ conversion, reaching 50.94% at 350°C, while AuRu/CeO₂ gave the highest CH₄ formation rate. FeCu/CeO₂ showed the strongest CO-forming trend, whereas AgNi/CeO₂ retained high CH₄ selectivity after methanation onset.

SEM-EDS, N₂ physisorption, and XRD supported the preparation of the CeO₂-supported catalyst set, described the mesoporous texture of the CeO₂ support, and showed that cubic fluorite CeO₂ remained the dominant crystalline phase after metal introduction. However, the available characterization is insufficient to prove alloy formation, exposed active sites, oxidation states, oxygen-vacancy concentration, or intrinsic structure-performance relationships.

The interpretation remains limited by the absence of quantitative metal-loading analysis, exposed-site measurements, replicate error analysis, long-term stability tests, a complete carbon balance, BET

measurements for the metal-loaded formulations, spent-catalyst characterization, and operando spectroscopy. The dataset therefore provides a preliminary comparison obtained under one catalytic testing protocol, not a controlled comparison of intrinsic bimetallic effects. Its value is to identify formulations for subsequent synthesis under matched composition and preparation conditions followed by deeper characterization.

Abbreviations

Term	Abbreviation
Carbon dioxide	CO ₂
Carbon monoxide	CO
Cerium oxide	CeO ₂
Methane	CH ₄
Hydrogen	H ₂
Copper	Cu
Nickel	Ni
Iron	Fe
Silver	Ag
Gold	Au
Ruthenium	Ru
Scanning electron microscopy	SEM
Energy-dispersive X-ray spectroscopy	EDS
X-ray diffraction	XRD
Brunauer-Emmett-Teller	BET
Barrett-Joyner-Halenda	BJH
Reverse water-gas shift	RWGS
Gas hourly space velocity	GHSV

Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contribution

M.U.A. contributed to conceptualization, methodology, investigation, formal analysis, visualization, and preparation of the original manuscript draft. S.A. contributed to methodology, investigation, data curation, and manuscript review and editing. A.A. contributed to methodology, validation, formal analysis, and manuscript review and editing. Q.L. contributed to conceptualization, supervision, funding acquisition, project administration, and manuscript review and editing. All authors read and approved the final manuscript.

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Figures

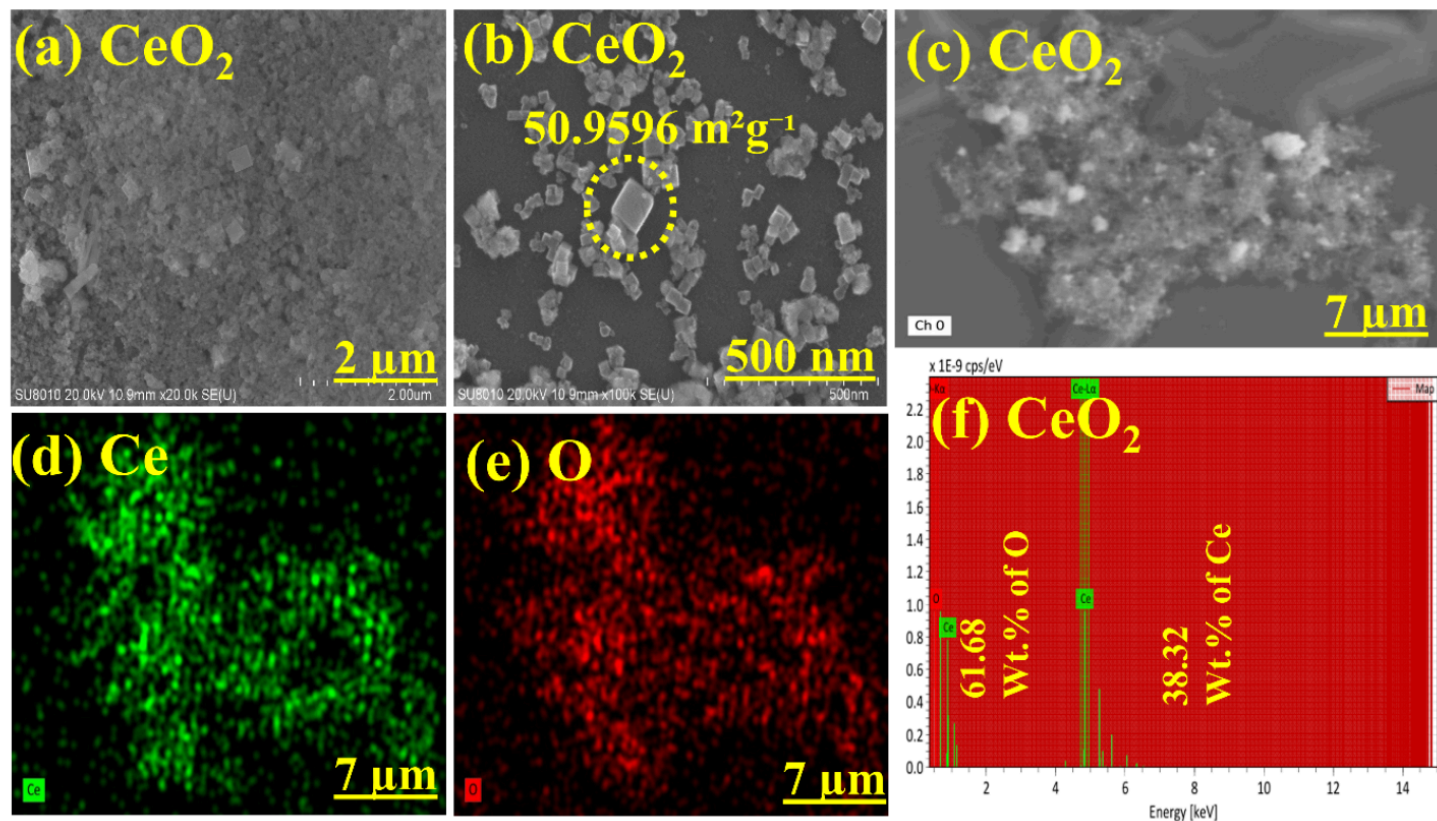


Figure 1

Morphology and elemental composition of cubic CeO_2 support: SEM images at different magnifications (a,b), EDS spectrum, and elemental mapping results (c-f)

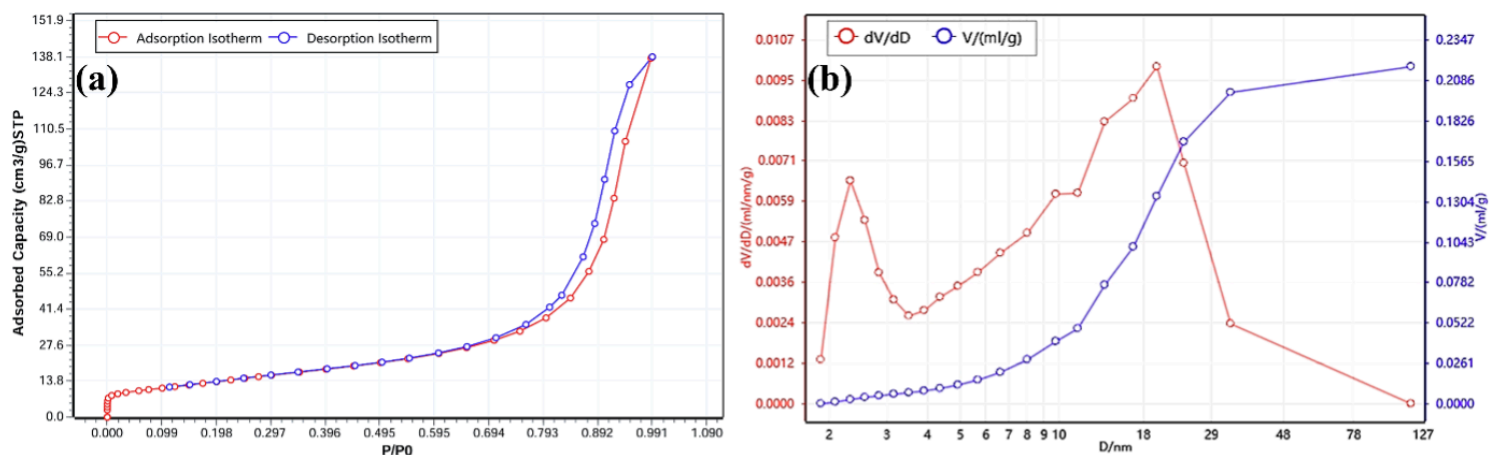


Figure 2

N_2 adsorption-desorption isotherm (a) and pore-size distribution analysis (b) of cubic CeO_2

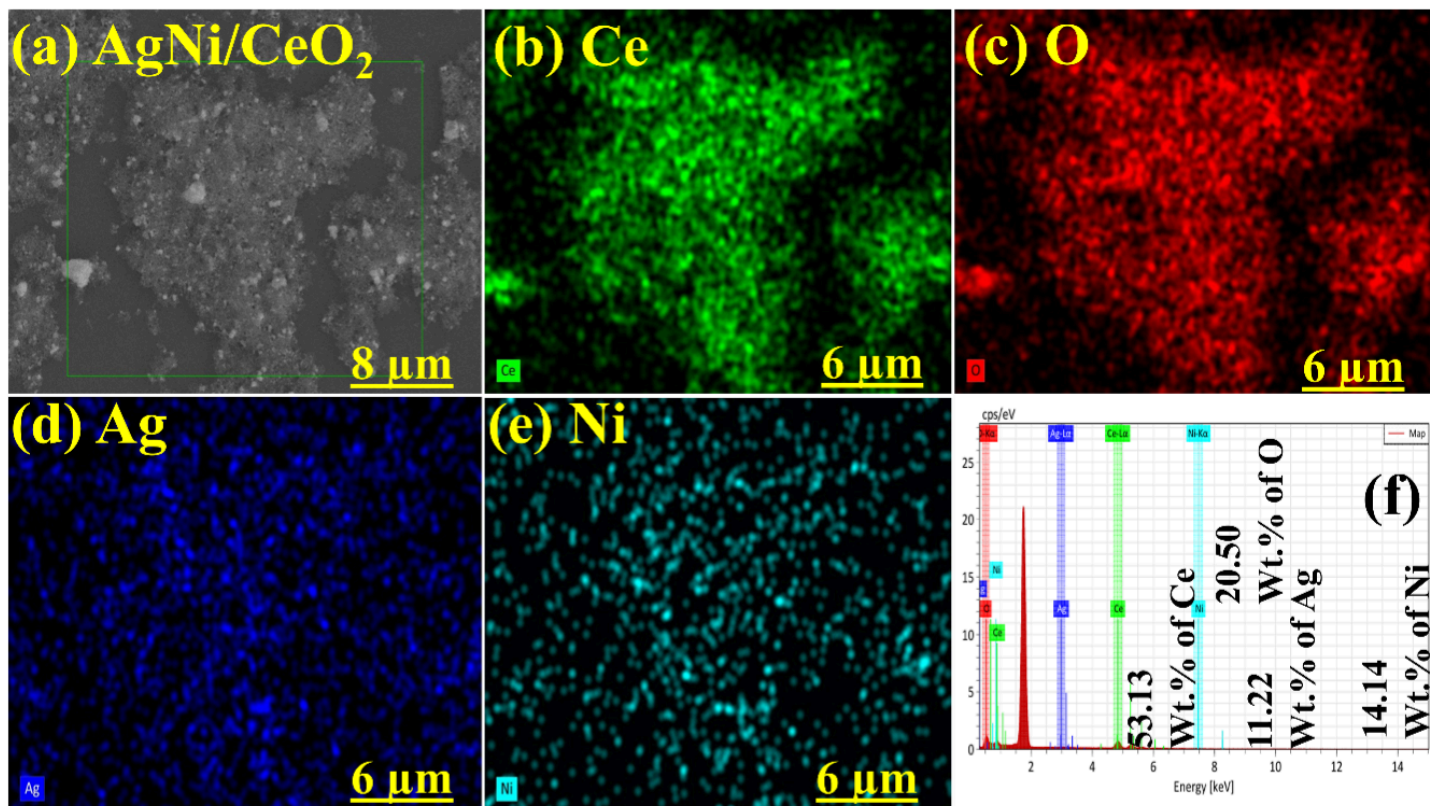


Figure 3

SEM image and EDS elemental mapping of AgNi/CeO₂: (a) SEM image of the selected mapping region, (b) Ce map, (c) O map, (d) Ag map, (e) Ni map, and (f) corresponding EDS spectrum

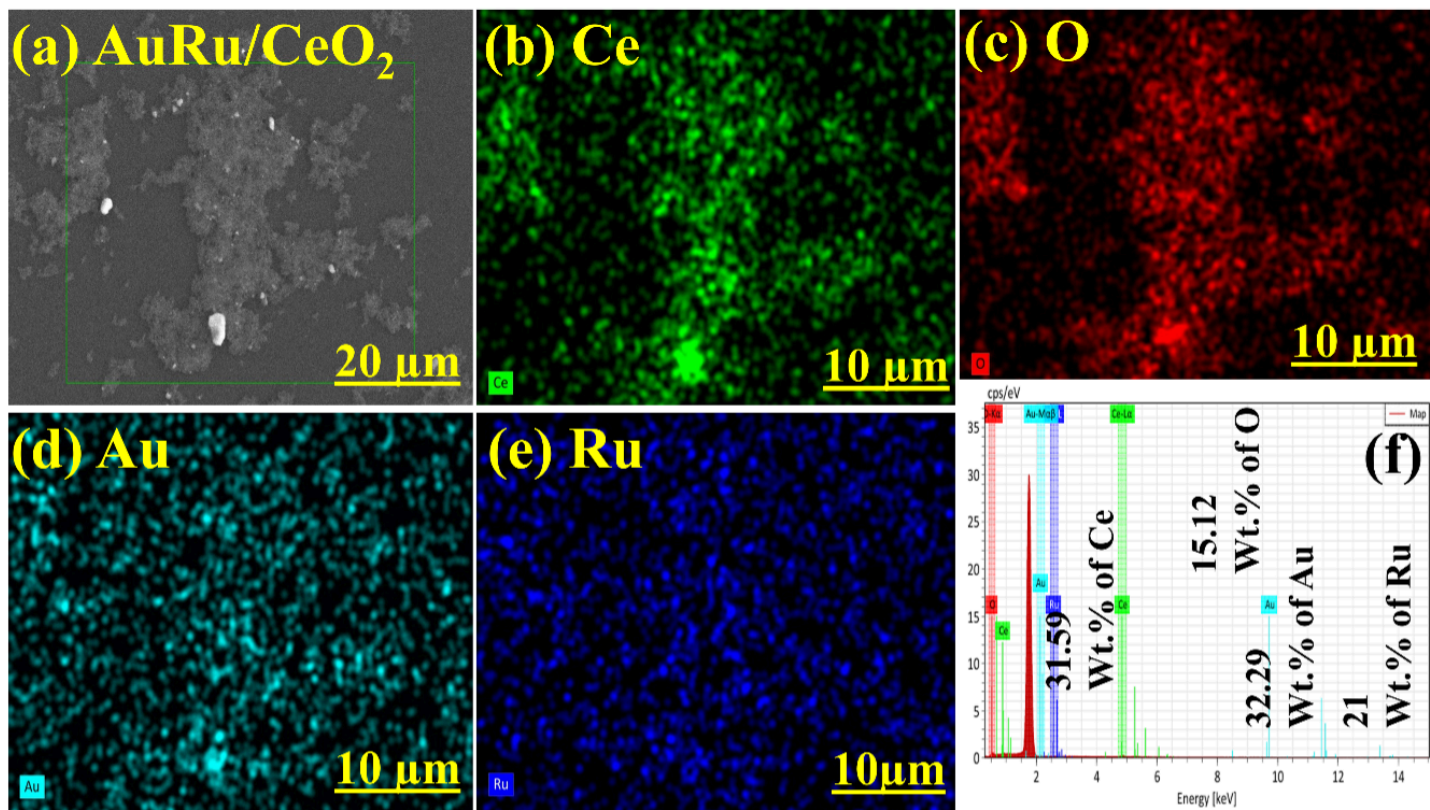


Figure 4

SEM image and EDS elemental mapping of AuRu/CeO₂: (a) SEM image of the selected mapping region, (b) Ce map, (c) O map, (d) Au map, (e) Ru map, and (f) corresponding EDS spectrum

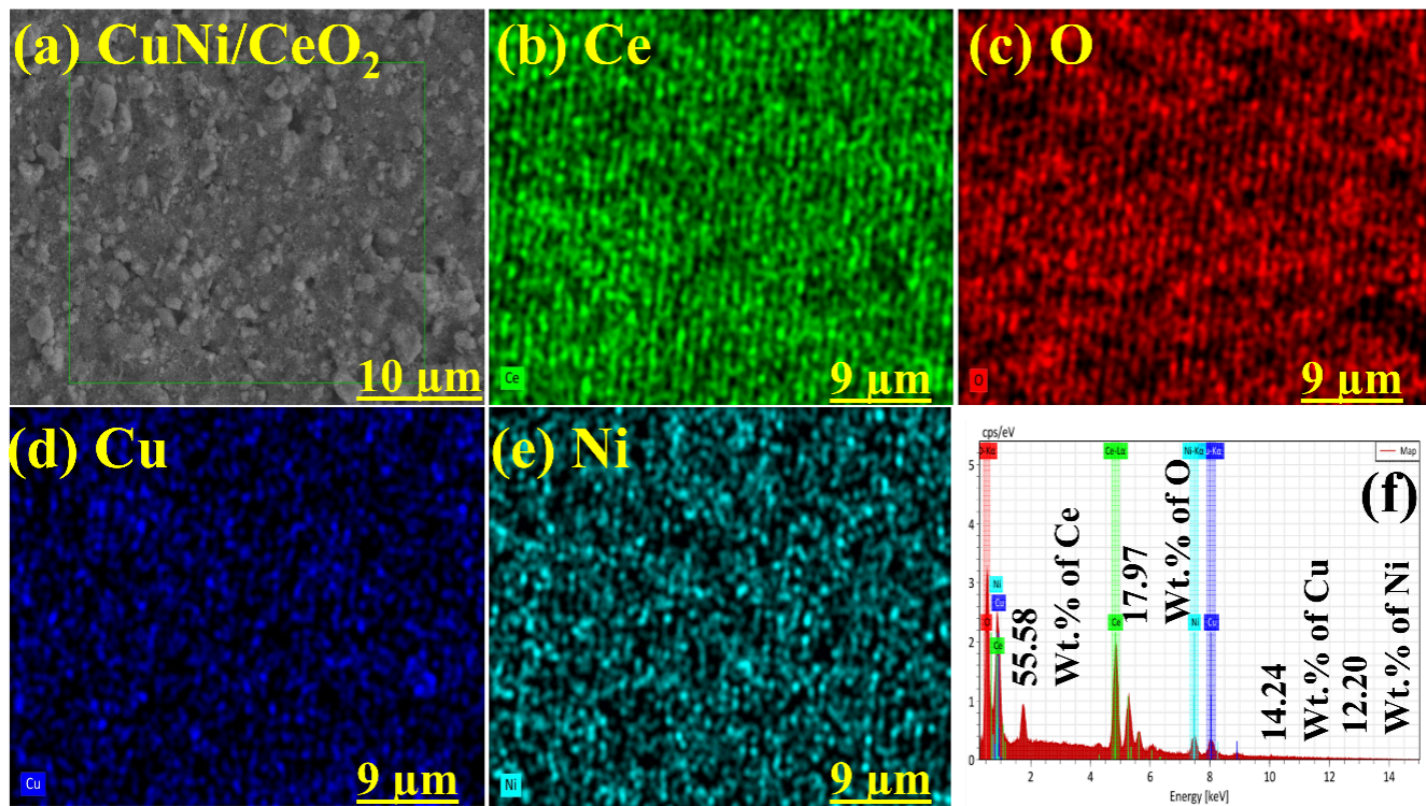


Figure 5

SEM image and EDS elemental mapping of CuNi/CeO₂: (a) SEM image of the selected mapping region, (b) Ce map, (c) O map, (d) Ni map, (e) Cu map, and (f) corresponding EDS spectrum

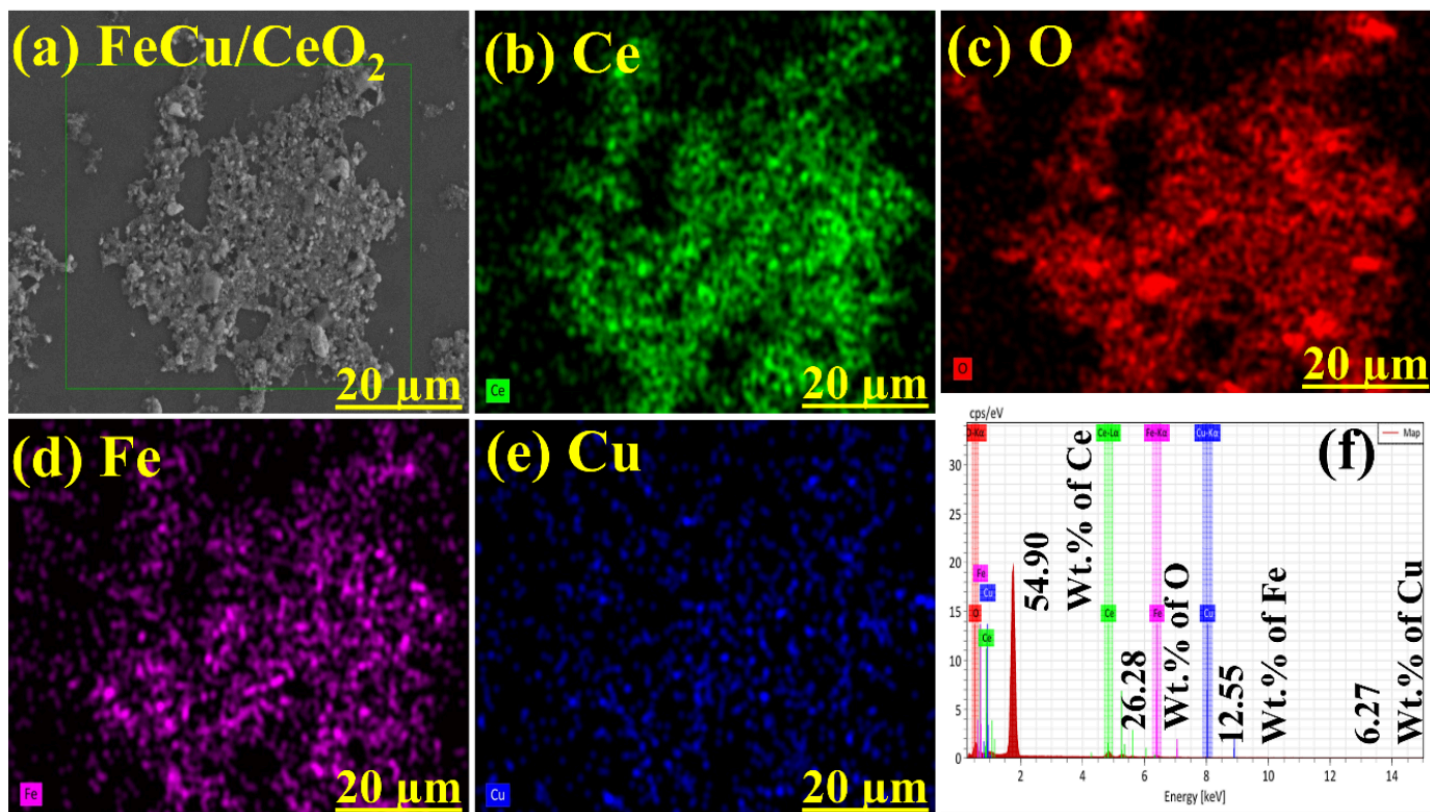


Figure 6

SEM image and EDS elemental mapping of FeCu/CeO₂: (a) SEM image of the selected mapping region, (b) Ce map, (c) O map, (d) Fe map, (e) Cu map, and (f) corresponding EDS spectrum

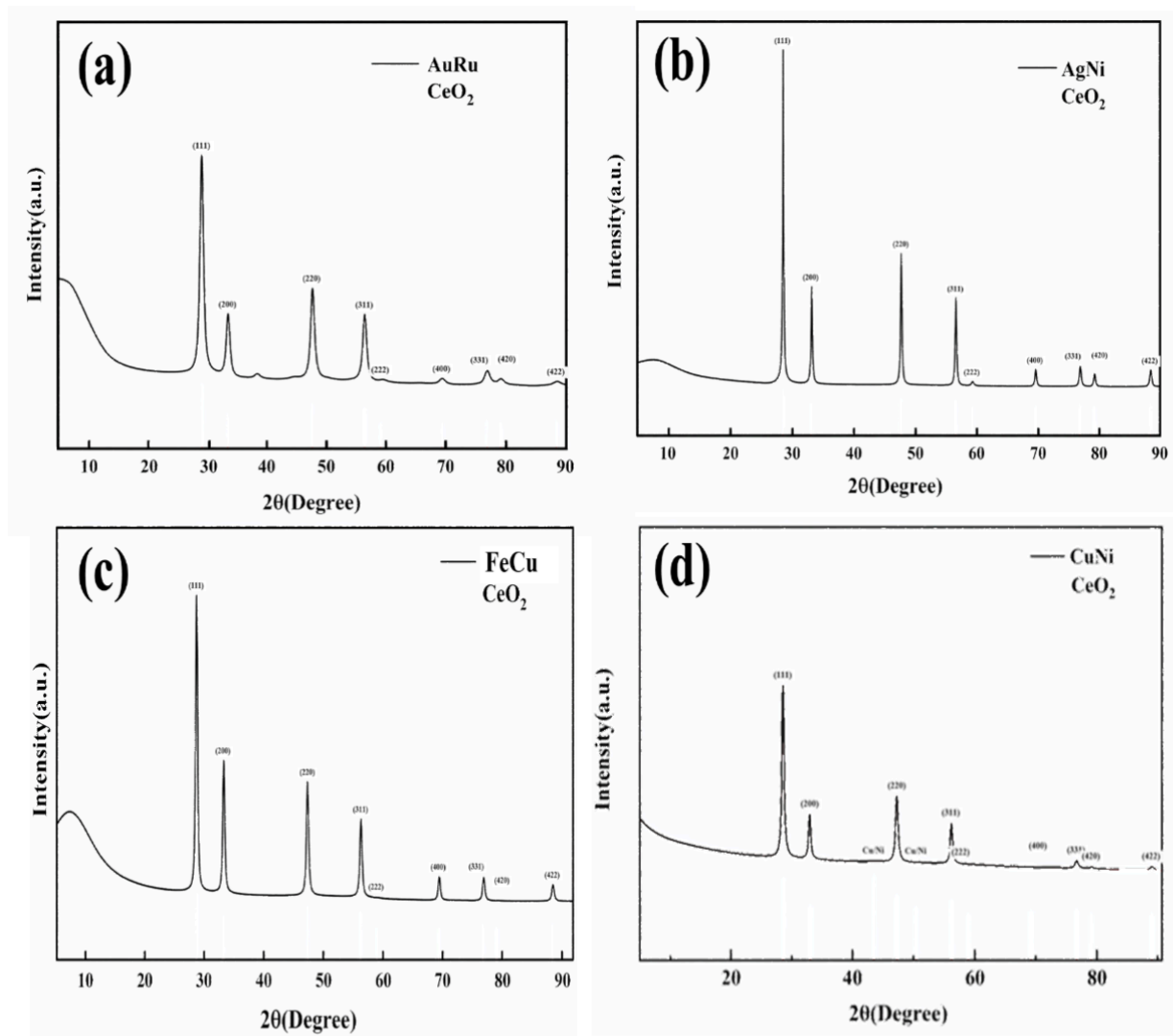


Figure 7

XRD patterns of the calcined CeO_2 -supported bimetallic formulations: (a) AuRu/CeO_2 , (b) AgNi/CeO_2 , (c) FeCu/CeO_2 , and (d) CuNi/CeO_2 . The black curves are the measured patterns. Reference-stick overlays have been removed because phase-specific source metadata for those overlays were not available. The dominant labeled reflections are consistent with cubic fluorite CeO_2 . The weak additional features in panel (d) are discussed cautiously in the text and are not taken as proof of a Cu-Ni alloy or a specific oxidation state

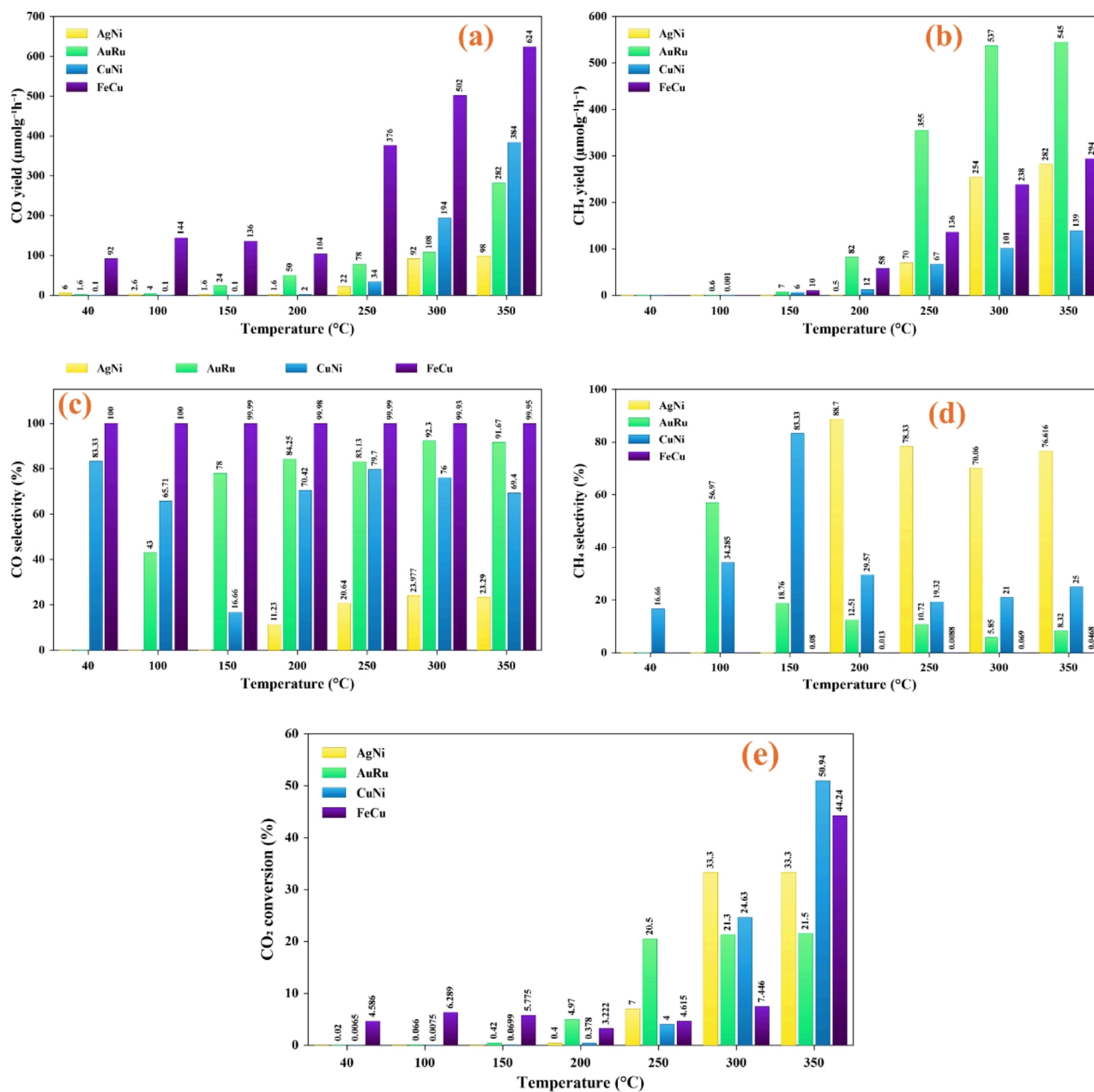


Figure 8

Catalytic performance of CeO_2 -supported bimetallic catalysts: (a) CO formation rate, (b) CH_4 formation rate, (c) CO selectivity, (d) CH_4 selectivity, and (e) CO_2 conversion as a function of reaction temperature