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RARE-EARTH METAL-DOPED CATALYSTS FOR VOLATILE ORGANIC COMPOUND OXIDATION: MECHANISMS, STRUCTURE–ACTIVITY RELATIONSHIPS, AND FUTURE DIRECTIONS

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ABSTRACT

Volatile organic compounds (VOCs) are important atmospheric and indoor pollutants because they participate in photochemical ozone and secondary aerosol formation and include compounds with substantial toxicity. Catalytic oxidation is attractive because VOCs can be converted, ideally, to CO₂ and H₂O at temperatures substantially below those required for thermal incineration. Rare-earth (RE) elements are particularly useful catalyst modifiers because their ionic size, coordination chemistry, redox behavior, oxygen-storage characteristics, and ability to generate lattice defects can be tuned across the lanthanide series. This review critically examines original experimental studies on RE-doped and RE-modified catalysts for thermal, photothermal, photocatalytic, and plasma-assisted VOC degradation, with emphasis on La, Ce, Pr, Nd, Sm, Eu, Gd, Ho, and Y. The evidence shows that RE incorporation can increase oxygen-vacancy concentration, alter the Mn³⁺/Mn²⁺ or Ce³⁺/Ce⁴⁺ redox balance, improve lattice-oxygen mobility, modify adsorption strength, stabilize active phases, and enhance resistance to water or chlorine. Representative data include T₉₀ values of 162 °C for Nd-modified Co₃O₄ during toluene oxidation, 204 °C for CuHoCeO_x at high gas hourly space velocity, 202 °C for complete toluene conversion over 1% Sm/CeO₂, 255 °C for 4 mol% La-doped CuMnO_x, and 120 °C for complete formaldehyde oxidation over 4% Eu/CeO₂ nanosheets. However, direct ranking of catalysts is inappropriate unless VOC concentration, space velocity, catalyst loading, oxygen concentration, humidity, reactor configuration, and conversion definition are matched. The review therefore emphasizes structure–property–performance relationships rather than nominal light-off temperatures alone. Remaining challenges include standardization of performance reporting, validation with realistic VOC mixtures, long-term stability under humidity and sulfur/chlorine contaminants, scalable monolith design, and quantitative descriptors linking RE ionic characteristics with oxygen-vacancy formation and reaction kinetics.

Keywords: Rare-earth metals; VOC oxidation; Oxygen vacancies; Catalytic combustion; T₅₀/T₉₀; Toluene

1 INTRODUCTION

VOCs comprise a chemically diverse group of gaseous organic pollutants emitted by petrochemical processing, coatings, printing, solvent use, fuel handling, transport, and household products. Aromatic VOCs such as benzene, toluene, ethylbenzene, and xylenes are particularly relevant because of their persistence and toxicity, whereas oxygenated VOCs such as formaldehyde, acetone, and ethyl acetate often show different adsorption and oxidation pathways. Chlorinated VOCs, including chlorobenzene and dichloroethane, present an additional challenge because chlorine-containing intermediates can poison active sites and generate undesirable chlorinated by-products. Catalytic oxidation is widely investigated because it can achieve deep oxidation at lower temperatures than direct thermal incineration [1,2]. The central scientific problem is not simply to maximize VOC conversion at one temperature, but to construct a catalyst that simultaneously provides strong VOC adsorption, facile C–H/C–C bond activation, rapid oxygen activation and replenishment, high selectivity to CO₂, resistance to water and poisons, and structural stability. Reviews of VOC oxidation have established that noble metals provide high low-temperature activity but are costly, whereas transition-metal oxides are more abundant but often require improved redox properties and surface defect chemistry. Rare-earth elements offer a versatile route for this modification because they can alter lattice strain, oxygen non-stoichiometry, acid–base properties, electronic structure, and metal–support interactions [1,2].

This review focuses specifically on the role of rare-earth metal incorporation or modification in VOC-degrading catalysts. The objective is to connect the identity and mode of RE incorporation with catalytic descriptors and experimentally observed performance. Rather than reproducing previously published tables, the performance data below are independently compiled from primary studies and normalized only where the original papers provide sufficient information. This distinction is important because T_{50}/T_{90} values are highly condition-dependent.

2 SCOPE AND LITERATURE-SEARCH METHODOLOGY

A structured literature search was designed around four concepts: (i) rare-earth elements and compounds, including La, Ce, Pr, Nd, Sm, Eu, Gd, Ho, and Y; (ii) catalyst modification terms such as doping, substitution, solid solution, supported oxide, and defect engineering; (iii) VOC targets including toluene, benzene, chlorobenzene, formaldehyde, ethyl acetate, and mixed VOCs; and (iv) catalytic processes including oxidation, combustion, photothermal oxidation, photocatalysis, and plasma-catalysis. Publisher records, PubMed/PMC records, RSC records, and open-access journal platforms were used to verify bibliographic information and extract reported catalytic metrics. Priority was given to original experimental articles with identifiable catalyst composition and reaction conditions. Reviews were used for mechanistic context and to locate additional primary studies.

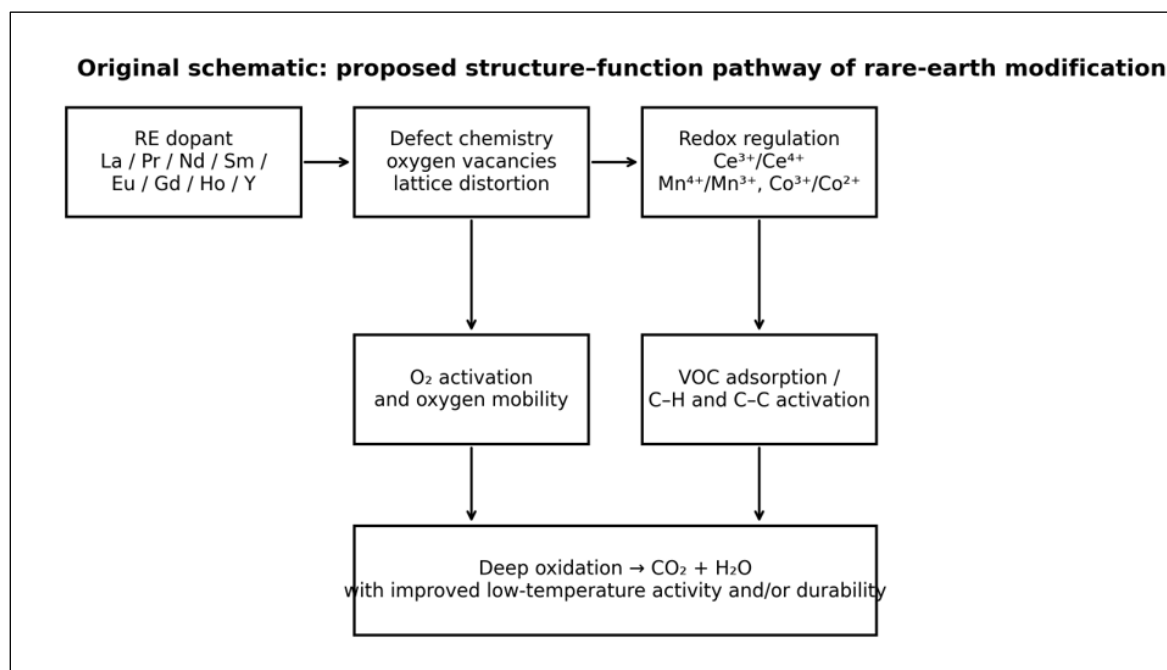


Figure 1: Original schematic of the principal structure–function pathway by which rare-earth modification can influence VOC oxidation. The figure is newly created for this review and does not reproduce a published graphical element.

3 WHY RARE-EARTH DOPING CHANGES VOC OXIDATION

3.1 Oxygen-vacancy formation and oxygen mobility

The most consistently reported effect of RE incorporation is modification of oxygen-vacancy chemistry. In fluorite CeO_2 , substitution of Ce^{4+} by a lower-valent cation such as La^{3+} , Sm^{3+} , Eu^{3+} , or Gd^{3+} can be charge-compensated by oxygen vacancies. The defect population is not determined by formal valence alone: ionic radius, local coordination, dopant aggregation, synthesis history, and reduction state all influence whether vacancies are isolated, clustered, or associated with dopant–oxygen complexes [2,5,7,8,20]. Oxygen vacancies can facilitate O_2 adsorption and dissociation and can increase the mobility of lattice oxygen. During VOC oxidation, this enables a redox cycle in which lattice oxygen participates in organic oxidation and gaseous O_2 replenishes the reduced catalyst. The CuHoCeOx study achieved complete toluene mineralization at 200 °C at GHSV 50,000 h^{-1} and attributed the performance to vacancy-rich, oxygen-mobile CuHoCeOx ; Raman, DFT, and in situ DRIFTS evidence supported a Mars–van Krevelen-type pathway [5].

3.2 Modification of variable-valence redox couples

Rare-earth dopants can redistribute charge between the RE ion and transition-metal/ceria framework. In CeO_2 , changes in the $\text{Ce}^{3+}/\text{Ce}^{4+}$ ratio are directly connected with oxygen non-stoichiometry. In Co- and Mn-containing oxides, RE addition can alter $\text{Co}^{3+}/\text{Co}^{2+}$ and $\text{Mn}^{4+}/\text{Mn}^{3+}$ ratios, changing the availability of redox-active oxygen. Nd-modified Co_3O_4 exhibited T_{50} and T_{90} values of 160 and 162 °C for toluene, respectively, and the enhanced activity was associated with abundant Co^{3+} and lattice oxygen and the ability to utilize lattice oxygen at lower temperatures [9].

3.3 Adsorption and interfacial electronic effects

RE doping can also change the adsorption and activation of VOC molecules. In Pt/CeO_2 , systematic comparison of La, Pr, Nd, Sm, and Gd showed a strong lanthanide-dependent effect. Gd incorporation generated more oxygen vacancies and promoted electron transfer from the support to Pt, producing more electron-rich and under-coordinated Pt sites that favored toluene adsorption and dissociation [8]. This finding illustrates that RE doping can influence a noble-metal catalyst through an indirect electronic mechanism rather than acting as the primary oxidation site.

3.4 Structural stabilization and morphology

RE ions can suppress crystallite growth, stabilize metastable phases, alter facet exposure, and regulate porosity. These effects are especially relevant to perovskites and mixed oxides. For example, $\text{La}_{0.8}\text{Ce}_{0.2}\text{MnO}_3$ supported on cordierite showed that catalyst loading and support morphology changed surface area, oxygen vacancies, and reducibility; the optimized 15 wt% material gave $T_{50} = 167$ °C and $T_{90} = 273$ °C for toluene under the reported conditions [16]. The result illustrates why catalyst architecture and reactor geometry must be evaluated together.

4 RARE-EARTH-DOPED CERIA AND CERIA-CONTAINING SYSTEMS

Ceria is arguably the most important rare-earth oxide platform for VOC oxidation because of its $\text{Ce}^{3+}/\text{Ce}^{4+}$ redox pair and oxygen-storage capacity. Substitution with other RE ions provides a controlled route to tune defect chemistry. A particularly informative comparative study examined Pt/CeO_2 catalysts containing La, Pr, Nd, Sm, or Gd. The authors found that Gd provided the strongest promotion among the tested lanthanides, linking activity to dopant ionic radius, valence state, oxygen-vacancy population, and Pt electronic structure [8]. The study is important because it compares several dopants within one catalyst family and therefore minimizes some sources of inter-study variability. Sm-doped CeO_2 provides another useful case. A 1 wt% Sm/CeO_2 catalyst prepared from a Sm/Ce metal-organic framework precursor achieved 50% and 100% toluene conversion at 194 and 202 °C, respectively, at WHSV 60,000 $\text{mL g}^{-1} \text{h}^{-1}$. Sm incorporation increased oxygen-vacancy concentration, low-temperature reducibility, and oxygen mobility, and the catalyst retained high performance under high-moisture conditions [7]. The CuMCEox family further demonstrates that the best RE dopant is system-dependent. CuHoCeOx gave complete toluene mineralization at 200 °C at 50,000 h^{-1} , while Y, Eu, and Sm also improved the parent CuCeOx system. The study identified Ho as particularly effective because its coordination altered Ce–O bonding and increased oxygen-storage capacity [5]. These results caution against treating all RE ions as interchangeable vacancy promoters.

5 RE MODIFICATION OF TRANSITION-METAL OXIDES

5.1 Co-based catalysts

Co_3O_4 is an attractive non-noble catalyst for aromatic VOC oxidation because of its multiple cobalt valence states and active surface oxygen. Nd modification dramatically improved the low-temperature oxidation of toluene, with $T_{90} = 162$ °C. The improvement was attributed to increased $\text{Co}^{3+}/\text{Co}^{2+}$, more oxygen vacancies, and greater low-temperature

participation of lattice oxygen [9]. La modification of CoMn_2O_4 provides complementary evidence. In situ solvothermal La doping increased the toluene oxidation rate of $\text{Co}_1\text{Mn}_{1.9}\text{La}_{0.1}$ by 20.74 times relative to undoped Co_1Mn_2 at 200 °C, while oxygen-vacancy content increased approximately 1.4-fold [18]. The work demonstrates that RE incorporation can tune both lattice oxygen mobility and gas-phase oxygen activation.

5.2 Cu–Mn oxides

La-doped CuMnOx catalysts illustrate a non-monotonic doping effect. At 30,000 h^{-1} and 1000 ppm toluene, 4 mol% La gave $T_{50} = 217$ °C and $T_{90} = 255$ °C, compared with 245 and 274 °C for the undoped CuMn catalyst. Increasing La to 6 mol% worsened activity, with T_{90} increasing to 280 °C [10]. Therefore, excessive RE loading can block active sites, alter phase composition, or produce less favorable defect structures. For ethyl acetate, La-modified Cu–Mn oxide coated on honeycomb ceramic achieved complete conversion at 239 °C at 12,500 h^{-1} and 1000 ppm and retained 100% removal after 1440 min [11]. The monolithic architecture is important because it reduces pressure drop and is closer to practical reactor designs than loose powders.

5.3 MnO₂-based catalysts

In situ grafting of Gd, Sm, Ce, or La oxides onto defective MnO_2 surfaces enhanced chlorobenzene oxidation. $\text{MnO}_2@\text{GdOx}$ was the strongest system, with $\text{Mn}^{4+}/\text{Mn}^{3+} = 1.10$ and $\text{O}_{\text{ads}}/\text{O}_{\text{latt}} = 0.45$, together with improved lattice-oxygen mobility. The catalyst also operated in mixed-VOC experiments involving toluene, benzene, acetone, and chlorobenzene and showed stability during an 18 h test [13]. This is particularly relevant because industrial VOC streams are rarely single-component.

6 PEROVSKITE AND MIXED-OXIDE SYSTEMS

RE elements are intrinsic structural components of many perovskites rather than mere dopants. La-based perovskites allow substitution at A and B sites and can create oxygen non-stoichiometry while maintaining thermal stability. Ce substitution in LaCoO_3 generated $\text{Co}^{2+}/\text{Co}^{3+}$ and $\text{Ce}^{3+}/\text{Ce}^{4+}$ couples and increased oxygen vacancies; Ce-doped LaCoO_3 catalysts showed stable chlorobenzene combustion for 45 h under the reported conditions [14]. $\text{La}_{0.8}\text{Ce}_{0.2}\text{MnO}_3$ is another recurring composition. When supported on cordierite, 15 wt% loading produced $T_{50} = 167$ °C and $T_{90} = 273$ °C for toluene [16]. Three-dimensionally ordered macroporous $\text{La}_{0.8}\text{Ce}_{0.2}\text{MnO}_3$ /cordierite has also been investigated, with the study emphasizing morphology and calcination-controlled oxygen vacancies [17]. Such results demonstrate that the beneficial effect of RE modification cannot be separated from morphology and support architecture.

7 FORMALDEHYDE AND OXYGENATED VOCs

Oxygenated VOCs can follow reaction pathways distinct from aromatic hydrocarbons. Eu-doped CeO_2 nanosheets provide a notable example for formaldehyde. The 4% Eu/ CeO_2 material achieved complete thermal oxidation at 120 °C and maintained stability for 100 h. The reported advantages included surface defects, high surface area and pore volume, improved redox ability, and altered electronic/optical properties [15]. More recently, La-doped CeO_2 has been investigated as a bifunctional thermo-/photocatalyst for indoor formaldehyde removal. La incorporation promoted oxygen-vacancy formation, HCHO adsorption, water dissociation, and reactive oxygen generation; under indoor light, photocatalytic and thermocatalytic functions acted synergistically [19]. This direction is important for indoor air purification, where pollutant concentrations are lower, but humidity and illumination are variable. Ethyl acetate oxidation over Cu/Ce–Ln systems further shows that RE identity can control activity. For bare supports, the reported order was $\text{CeO}_2 \approx \text{Ce}_{0.5}\text{Pr}_{0.5}\text{O}_{1.75} > \text{Ce}_{0.5}\text{Sm}_{0.5}\text{O}_{1.75} > \text{Ce}_{0.5}\text{Gd}_{0.5}\text{O}_{1.75} > \text{Ce}_{0.5}\text{Nd}_{0.5}\text{O}_{1.75} > \text{Ce}_{0.5}\text{La}_{0.5}\text{O}_{1.75}$. Cu addition improved performance without changing the activity order, and the best catalysts achieved complete ethyl acetate conversion below approximately 290 °C [6].

8 CHLORINATED VOCs AND RESISTANCE TO POISONING

Chlorinated VOCs are more demanding because chlorine can occupy oxygen vacancies, alter metal oxidation states, and promote chlorinated by-product formation. RE doping can improve chlorine tolerance by strengthening oxygen mobility and maintaining a dynamic redox cycle. In RE-doped CoCeOx catalysts, La, Pr, Nd, and Y all promoted chlorobenzene oxidation relative to the undoped system, with CoCeYOx reaching 90% conversion at 256 °C and showing reduced dichlorobenzene formation [12]. Ce-doped LaCoO_3 provides another route: coupling $\text{Ce}^{3+}/\text{Ce}^{4+}$ and $\text{Co}^{2+}/\text{Co}^{3+}$ redox pairs increases oxygen-vacancy concentration and enables complete chlorobenzene combustion without detectable final intermediates in the reported experiments [14]. However, catalyst performance against chlorinated VOCs must always be judged together with selectivity to CO_2 , HCl/Cl_2 , and suppression of polychlorinated by-products.

9 MECHANISTIC FRAMEWORK

Three mechanistic descriptions dominate VOC oxidation: Mars–van Krevelen, Langmuir–Hinshelwood, and Eley–Rideal [1,2]. RE-modified metal oxides frequently operate through a mixed or temperature-dependent mechanism. In the Mars–van Krevelen picture, VOC molecules react with lattice oxygen, leaving oxygen vacancies; gas-phase O_2 subsequently replenishes the vacancies. RE doping can accelerate both steps by lowering vacancy formation energy and increasing oxygen mobility [5,20]. In Langmuir–Hinshelwood pathways, both VOC and oxygen-derived species adsorb before reacting. In Eley–Rideal pathways, an adsorbed species reacts directly with a gas-phase reactant. For aromatic VOCs, a typical pathway begins with adsorption, followed by benzylic C–H activation and formation of benzyl alcohol/benzaldehyde/benzoate-type intermediates, then ring opening and mineralization to CO_2 . The exact sequence depends on catalyst oxidation state, oxygen species, humidity, and adsorption strength. RE doping may change the relative abundance of these intermediates rather than creating a completely new mechanism.

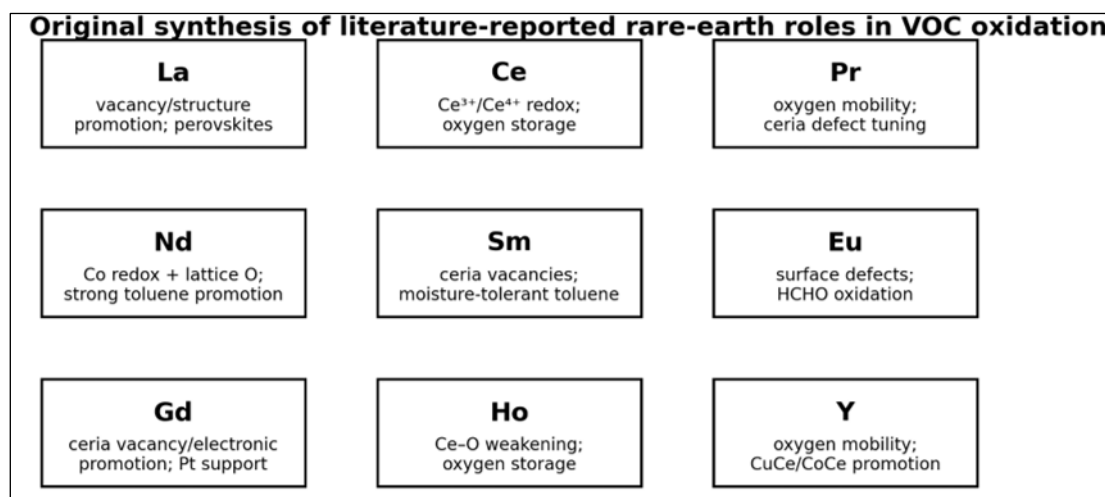


Figure 2: Original synthesis of experimentally reported roles of selected rare-earth modifiers in VOC oxidation. Roles are summarized from primary studies [5–19].

9.1 Structure–activity relationships

The literature supports five recurring descriptors: (1) oxygen-vacancy concentration and accessibility; (2) oxygen mobility/reducibility; (3) surface active oxygen composition; (4) redox-state distribution of the transition-metal component; and (5) adsorption/activation energetics of the VOC [2,5,8,13,18,20]. However, these descriptors interact. Increasing vacancy concentration is not automatically beneficial: excessively strong adsorption can inhibit product desorption, while excessive dopant loading can dilute active transition-metal sites or form segregated REOx domains. The best performance generally occurs at an intermediate dopant concentration where defect density, redox kinetics, surface area, and active-site accessibility are balanced [10].

9.2 Critical comparison of reported performance

Reported T_{50} and T_{90} values are useful screening metrics but are not directly comparable across studies. A catalyst tested at 900 ppm and $50,000\text{ h}^{-1}$ cannot be ranked directly against one tested at 1000 ppm and $12,000\text{ h}^{-1}$. Reactor type, catalyst mass, dilution, oxygen concentration, humidity, and whether conversion or CO_2 yield is reported can shift light-off curves substantially [2]. Therefore, this review uses T_{50}/T_{90} only as reported indicators and avoids constructing a universal ranking. The most informative comparisons are within a study. Examples include La-doped CuMnOx, where 4 mol% La outperformed both 0 and 6 mol% La [10], and the Pt/CeO₂ series, where changing only the lanthanide dopant changed activity substantially [8]. Such controlled comparisons provide stronger evidence for a genuine RE effect than comparisons among unrelated catalyst families.

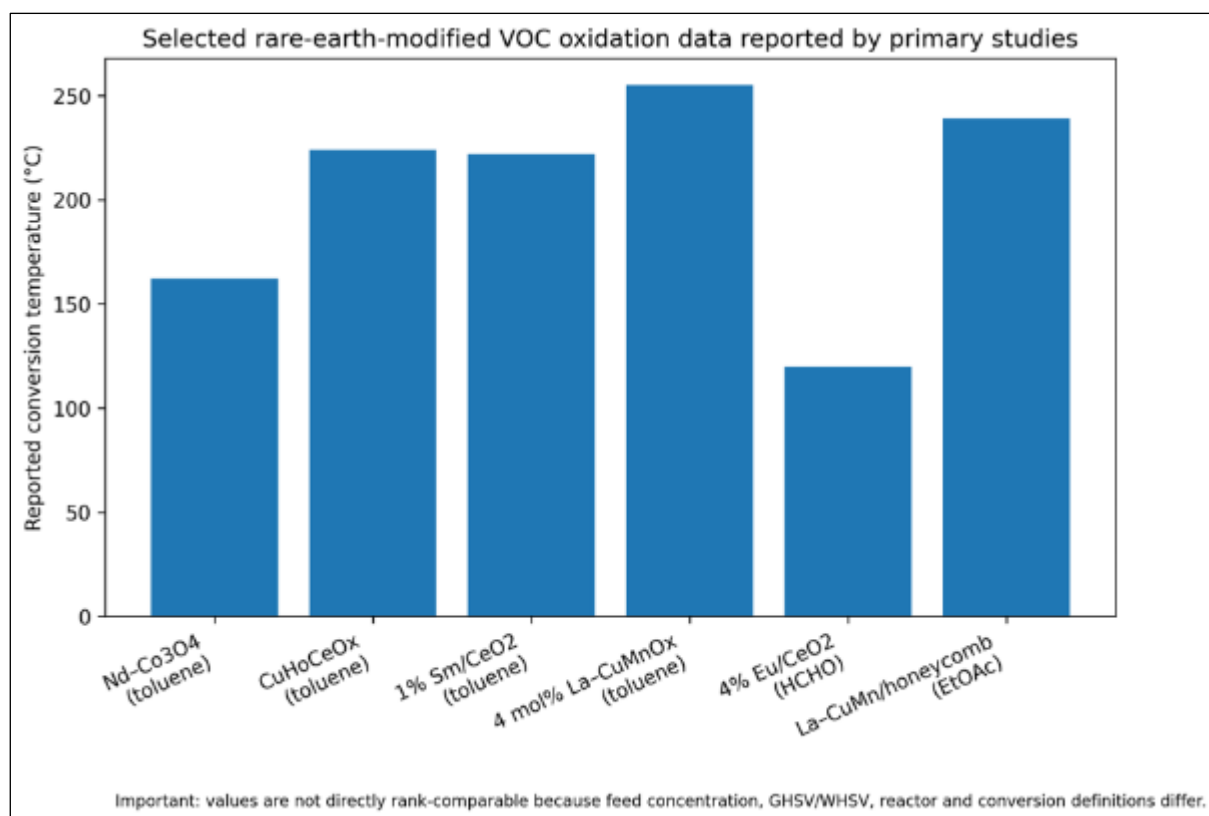


Figure 3: Selected reported conversion temperatures from primary studies. This is an original plot generated from the data in Table 1; it is not a ranking because reaction conditions differ among studies.

Table 1: Primary-study performance data for selected rare-earth-modified VOC catalysts

Catalyst	RE modifier	VOC	Reported performance	Key reaction conditions	Main reported descriptor	Source
CuHoCeO _x	Ho	Toluene	T ₅₀ 206; T ₉₀ 204	900 ppm; GHSV 50,000 h ⁻¹	MVK; oxygen vacancies	[5]
1% Sm/CeO ₂	Sm	Toluene	T ₅₀ 194; T ₁₀₀ 202	WHHSV 60,000 mL g ⁻¹ h ⁻¹	vacancies/reducibility; moisture tolerance	[7]
Nd-Co ₃ O ₄	Nd	Toluene	T ₅₀ 160; T ₉₀ 162	reported in primary study	Co ³⁺ /Co ²⁺ ; lattice oxygen; vacancies	[9]
CuMn/La-4 mol%	La	Toluene	T ₅₀ 217; T ₉₀ 255	1000 ppm; GHSV 30,000 h ⁻¹	Mn ³⁺ ; chemisorbed O; vacancies	[10]
La-CuMn/honeycomb	La	Ethyl acetate	T ₁₀₀ 239	1000 ppm; GHSV 12,500 h ⁻¹	reducibility; vacancies; monolith	[11]
CoCeYO _x	Y	Chlorobenzene	T ₉₀ 256	reported in primary study	redox/oxygen mobility; chlorine tolerance	[12]
MnO ₂ @GdO _x	Gd	Chlorobenzene	not extracted	18 h stability reported	Mn ⁴⁺ /Mn ³⁺ 1.10; Oads/Olatt 0.45	[13]

Ce-doped LaCoO ₃	Ce	Chlorobenzene	not extracted	45 h stability reported	Co ²⁺ /Co ³⁺ ; Ce ³⁺ /Ce ⁴⁺ ; vacancies	[14]
4% Eu/CeO ₂ nanosheets	Eu	Formaldehyde	T ₁₀₀ 120	100 h stability reported	surface defects; redox; high surface area	[15]
15 wt% La _{0.8} Ce _{0.2} MnO ₃ /cordierite	La/Ce	Toluene	T ₅₀ 167; T ₉₀ 273	monolith; primary study conditions	surface area; vacancies; reducibility	[16]
La-doped Co ₁ Mn _{1.9} La _{0.1}	La	Toluene	rate 20.74× at 200 °C	relative to undoped Co ₁ Mn ₂	vacancies increased ~1.4×	[18]
Cu/Ce–Ln	Gd/La/Pr/Nd/Sm	Ethyl acetate	complete conversion <290 °C for best systems	20 wt% Cu; comparative study	redox/reducible lattice oxygen	[6]

Note: T₅₀/T₉₀/T₁₀₀ are reproduced as reported by the primary studies. Where the source did not provide a directly comparable value in the verified record, the table states “not extracted.” The table is an original compilation and does not reproduce any published table verbatim.

10 STABILITY, WATER RESISTANCE, AND REALISTIC STREAMS

Water is often competitive with VOCs and oxygen for adsorption sites and can block defect sites. Some RE-doped systems show strong water tolerance, but this property is not universal. Sm/CeO₂ maintained strong toluene activity under high moisture [7], whereas other oxide systems can suffer significant inhibition. Sulfur dioxide is particularly problematic because sulfate formation can be persistent. Chlorinated VOCs introduce additional poisoning pathways. Future studies should therefore report activity under controlled humidity, SO₂, CO₂, and multicomponent VOC conditions and quantify recovery after poison removal. Monoliths and structured catalysts are another key translational issue. Powder light-off curves are useful for fundamental screening, but industrial reactors require low pressure drop, mechanical strength, high mass transfer, and thermal management. The La-modified Cu–Mn honeycomb study demonstrates the value of combining RE chemistry with a practical reactor architecture [11].

11 DATA-REPORTING STANDARDS PROPOSED FOR FUTURE STUDIES

For meaningful cross-study comparison, every VOC oxidation paper should report: catalyst composition and dopant loading; synthesis route and calcination conditions; BET surface area; phase composition; dopant location if known; Ce³⁺/Ce⁴⁺ or relevant transition-metal ratios; oxygen-vacancy evidence and method; catalyst mass; VOC concentration; O₂ concentration; balance gas; GHSV or WHSV; inlet humidity; reactor dimensions; particle size or monolith geometry; conversion and CO₂ selectivity; T₁₀/T₅₀/T₉₀ where available; stability duration; and post-reaction characterization. Oxygen-vacancy claims should be supported by at least two complementary techniques where possible, for example XPS/EPR combined with Raman, O₂-TPD, XAS, or isotopic oxygen exchange. XPS O 1s deconvolution alone should not be treated as quantitative proof of oxygen-vacancy concentration [20].

11.1 Research gaps and future directions

First, the field needs a quantitative descriptor linking RE ionic radius/valence to oxygen-vacancy formation and oxygen-transfer kinetics. Second, catalyst testing should move from single-VOC feeds toward mixtures containing aromatics, oxygenates, sulfur compounds, chlorine, CO₂, and water. Third, long-term stability should be extended from tens of hours to hundreds or thousands of hours under cyclic thermal and humidity conditions. Fourth, monolithic and coated catalysts should be evaluated at realistic gas velocities and pressure drops. Fifth, operando XAS, Raman, DRIFTS, isotopic oxygen exchange, and DFT/microkinetic modeling should be combined to distinguish lattice-oxygen, adsorbed-oxygen, and interfacial pathways. Sixth, life-cycle and techno-economic assessments are needed because rare-earth supply, synthesis energy, and catalyst regeneration affect practical sustainability. An additional opportunity is data-driven catalyst design. A curated database containing dopant identity, ionic radius, oxidation state, vacancy concentration, reducibility, adsorption energies, and standardized kinetic parameters could enable machine-learning models to identify promising RE combinations. Such models should be trained only on measurements collected under sufficiently standardized conditions.

12 CONCLUSION

Rare-earth metal modification is a powerful strategy for improving VOC oxidation catalysts because it couples defect chemistry, redox regulation, oxygen transport, adsorption control, and structural stabilization. The strongest experimental evidence is obtained when the RE dopant is varied within one catalyst family. Across the literature, La, Ce, Pr, Nd, Sm, Eu, Gd, Ho, and Y can all provide useful promotion, but their effects are strongly dependent on the host oxide and dopant loading. Representative studies show very low toluene light-off temperatures for Nd-modified Co_3O_4 and CuHoCeO_x , strong moisture-tolerant performance for Sm/ CeO_2 , improved aromatic VOC oxidation after La modification of $\text{CuMn}_2\text{O}_4/\text{CoMn}_2\text{O}_4$, and low-temperature formaldehyde oxidation using Eu- or La-modified ceria. The principal design lesson is that rare-earth doping should not be viewed simply as adding more oxygen vacancies. High-performance results arise from a balanced combination of vacancy accessibility, oxygen mobility, redox-state distribution, VOC adsorption, and structural stability. Future work should prioritize standardized reporting, realistic multicomponent feeds, monolithic architectures, operando mechanistic characterization, and quantitative descriptors that can guide rational selection of rare-earth dopants.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare no competing financial interests.

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