Kinetics of CO Oxidation Catalyzed by Supported Gold: A Tabular Summary of the Literature

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Abstract The literature of CO oxidation catalyzed by supported gold is extensive, but reports of the kinetics of the reaction are incomplete and fragmented. This paper is a summary of such information presented in tables that state (1) how the catalysts were made, treated, and tested; (2) their physical properties, such as the average gold particle size; and (3) kinetics data, including turnover frequencies, reaction orders, and apparent activation energies.

Keywords Gold catalyst · Supported gold · CO oxidation · Kinetics of CO oxidation

1 Introduction

Extensive research on catalysis by supported gold has been reported since the pioneering discoveries by Hutchings [1] and Haruta [2] demonstrating high catalytic activities of highly dispersed gold. CO oxidation and the water gas shift are among the best investigated of the reactions catalyzed by supported gold; most of the work has focused on the former [3], as it apparently offers the advantages of taking place at low temperatures combined with the simplicity of small reactant molecules and the value of CO as a sensitive probe of surface structure [4].

Notwithstanding the extensive research on supported gold catalysts for CO oxidation, the mechanism(s) of the reaction and the catalytically active species remain matters of debate, and the reports of quantitative kinetics of the reaction, although numerous, are largely incomplete. The lack of thorough kinetics data reflects the complexities of the catalyst performance, influenced by catalyst activation and deactivation, which are often rapid; it is sometimes difficult to determine from published reports whether the reaction rates or conversions characterize fresh or deactivated catalysts.

Our goal was to provide a summary facilitating access to the literature of the kinetics of CO oxidation catalyzed by supported gold. The literature is summarized here in tabular form; earlier, much less complete summaries were reported by Bond et al. [5], Deng et al. [6], and Kung et al. [7]. Some issues regarding the challenges of comparing supported gold catalysts on the basis of performance were addressed by Long et al. [8]. We have limited the content here by excluding catalysts with doped supports (except when they were part of a set including undoped supports) and results characterizing “preferential oxidation” of CO in the presence of excess H₂. Otherwise, the compilation contains most of the literature that includes kinetics data for CO oxidation catalyzed by supported gold, although it is not exhaustive, with a number of examples of only partially documented kinetics data being omitted.

2 Tables of Data

The data are presented in three tables, with the entries linked by the entry number shown in the left-hand column of each table. Table 1 is a list of supported gold catalysts used for CO oxidation, how they were made and treated, their gold contents and surface areas, and the average gold particle sizes and methods used to determine them. Table 2 is a summary of the conditions under which the kinetics data were determined, with information about the degree of deactivation of the catalyst. Table 3 is a summary of the kinetics data,
Table 1 Characteristics of the supported gold CO oxidation catalysts

| Entry number | Catalyst     | Catalyst surface area (m²/g) | Catalyst precursor | Preparation method⁴ | Catalyst treatment | Gold content (wt %) | Average gold particle size (nm) | Method of determining gold particle size | References |
|--------------|--------------|------------------------------|--------------------|----------------------|-------------------|---------------------|-------------------------------|----------------------------------------|------------|
| 1            | Au/SiO₂      | Not stated                   | AuCl₃              | IW                   | 1 h in H₂ (1 bar, 2,500 h⁻¹) at 723 K | 1.8                 | 30                            | XRD [9]                               |            |
| 2            | Au/TiO₂      | 2 hi nH₂ at 473 K, 1 bar, 2,500 h⁻¹ | 2.3 | 25                             |                  |                    |                              |                                        |            |
| 3            | Au/TiO₂      | 1 h in H₂ at 773 K, 1 bar, 2,500 h⁻¹ | 2.3 | 25                             |                  |                    |                              |                                        |            |
| 4            | Au/TiO₂      | 1 h in H₂ at 773 K, 1 bar, 2,500 h⁻¹ | 2.3 | 25                             |                  |                    |                              |                                        |            |
| 5            | Au/TiO₂      | 1 h in H₂ at 773 K, 1 bar, 2,500 h⁻¹ | 2.3 | 25                             |                  |                    |                              |                                        |            |
| 6            | Au/TiO₂      | 1 h in H₂ at 773 K, 1 bar, 2,500 h⁻¹ followed by a calcination with 20% O₂ in He at 673 K for 1 h, then 2 h under H₂ at 473 K 1 bar, 2,500 h⁻¹ | 2.3 | 25                             |                  |                    |                              |                                        |            |
| 7            | Au/TiO₂ (after deactivation) | 1 h in H₂ at 773 K 1 bar, 2,500 h⁻¹ followed by a calcination with 20% O₂ in He at 673 K for 1 h, then 2 h under H₂ at 473 K 1 bar, 2,500 h⁻¹ after deactivation | | | | | | | |
| 8            | Au/TiO₂(HTR/C/LTR)-I | 1 h in H₂ at 773 K 1 bar, 2,500 h⁻¹ followed by a calcination with 20% O₂ in He at 673 K for 1 h, then 2 h under H₂ at 473 K 1 bar, 2,500 h⁻¹ | | | | | | | |
| 9            | Au/TiO₂(HTR/C/LTR)-I | 1 h in H₂ at 773 K 1 bar, 2,500 h⁻¹ followed by a calcination with 20% O₂ in He at 673 K for 1 h, then 2 h under H₂ at 473 K 1 bar, 2,500 h⁻¹ | | | | | | | |
| 10           | Au/Fe₂O₃      | Not stated                   | HAuCl₄             | CP                   | Calcination at 673 K in air for 4 h | 10 | 3.6 | XRD [10] |            |
| 11           | Au/Co₃O₄      | 73                           |                    |                     |                   |                    |                              |                                        |            |
| 12           | Au/Co₃O₄      | 69                           |                    |                     |                   |                    |                              |                                        |            |
| 13           | Au/Co₃O₄      | 116                          |                    |                     |                   |                    |                              |                                        |            |
| 14           | Au/Fe₂O₃      | 20                           | HAuCl₄             | CP                   | Calcination in air at 673 K for 4 h | 5⁶ | Not stated | Not stated [11] |            |
| 15           | Au/MnO₂       | Not stated                   |                    |                     |                   |                    |                              |                                        |            |
| 16           | Au/CeO₂       | 74c                          |                    |                     |                   |                    |                              |                                        |            |
| 17           | Au/Co₂O₂      | Not stated                   | Au(CH₃)(C₅H₇O₂)₂   | GR                   | 48 h under CO oxidation conditions at 353 K | 1 | Mononuclear Au species EXAFS [12, 13] |            |
| 18           | Au/Co₂O₂      | 173.3c                       | Au(CH₃)(C₅H₇O₂)₂   | GR                   | 48 h under CO oxidation conditions at 353 K followed by 48 h under CO oxidation conditions at 303 K | 1 | 0.8 | EXAFS [12, 13] |            |
| 19           | Au/TiO₂       | 173.3c                       | HAuCl₄             | DP                   | Calcination in air at 673 K for 4 h | 0.7 | 3.1 ± 0.7 | TEM [14] |            |
| 20           | Au/TiO₂       | 50c                          | HAuCl₄             | DP                   | Calcination in air at 673 K for 4 h | 0.7–1.8 | 2.7 ± 0.6 | TEM [15] |            |
| 21           | Au/TiO₂       | DP                           |                    |                     |                   |                    |                              |                                        |            |
| 22           | Au/TiO₂       | DP                           |                    |                     |                   |                    |                              |                                        |            |
| 23           | Au/TiO₂       | DP                           |                    |                     |                   |                    |                              |                                        |            |
| Entry number | Catalyst | Catalyst surface area (m²/g) | Catalyst precursor | Preparation methoda | Catalyst treatment | Gold content (wt %) | Average gold particle size (nm) | Method of determining gold particle size | References |
|-------------|----------|------------------------------|-------------------|--------------------|-------------------|-------------------|-------------------------------|--------------------------------|-------------|
| 26          | Au/TiO₂  | DP                           |                   |                    |                   | 1.8               | 2.7 ± 0.6                     |                                 |             |
| 27          | Au/TiO₂  | DP                           |                   |                    |                   | 2.3               | 2.5 ± 0.6                     |                                 |             |
| 28          | Au/TiO₂  | DP                           |                   |                    |                   | 3.1               | 2.9 ± 0.5                     |                                 |             |
| 29          | Au/TiO₂  | DP                           |                   |                    |                   | 1.0               | 4.6 ± 1.5                     |                                 |             |
| 30          | Au/TiO₂  | PD                           |                   |                    |                   | 3.6               | 6.0 ± 2.5                     |                                 |             |
| 31          | Au/TiO₂  | IMP                          |                   | No treatment       |                   | 1.0               | Not stated                    |                                 |             |
| 32          | Au/TiO₂  | Not stated                   | HAuCl₄            | DP (supplied by the World Gold Council) | Calcined at 573 K | 1.5               | 3.7                          | TEM                          | [16]        |
| 33          | Au/MgO   | Not stated                   | Not stated        | Gold clusters prepared on single crystal surfaces of TiO₂ | Not stated | Not stated | 2.5–6 | STM/STS/STM [17] |
| 34          | Unsupported nanoporous gold | Not stated               | Silver/gold alloy | Deallloying of silver from silver/gold alloy | Not stated | Not stated | 5–20 | SEM [18] |
| 35          | Nanoporous gold foams      | Not stated               | Silver/gold alloy | Selective leaching of silver from a silver/gold alloy | Untreated | Not stated | ~Tens | SEM [19] |
| 36          | Au/MgO   | Not stated                   | Au₄[(p-tolyl)NCN(p-tolyl)]₄ | GR | Treated in O₂ at 773 K for 3 h. Annealing at 972 | Not stated | Not stated | TEM [20] |
| 37          | Au/MgO   | Not stated                   | HAuCl₄            | DP (supplied by the World Gold Council) | Not stated | 4.3               |                                 |                     |
| 38          | Au/MgO   | Not stated                   | Au₄[(p-tolyl)NCN(p-tolyl)]₄ | GR | Treated in O₂ at 773 K for 3 h. Annealing at 1,073 | Not stated | 3.8               |                                 |                     |
| 39          | Au/MgO   | Not stated                   | High purity gold foils | VD | None | Not stated | 2.6               | XPS, LHSI (low energy ion spectroscopy) [23] |
| 40          | Au/TiO₂  | Not stated                   | Gold clusters prepared on single crystal surfaces of TiO₂ | Not stated | Not stated | 2–4.5 | STM [21] |
| 41          | Au/TiO₂  | Not stated                   | HAuCl₄            | DP (supplied by the World Gold Council) | Not stated | 1.47 | 3.7 | TEM [22] |
| 42          | Au/TiO₂  | Not stated                   | High purity gold foils | VD | None | Not stated | 2.6 | XPS, LHSI (low energy ion spectroscopy) [23] |
| 43          | Au/TiO₂  | 50⁰F                         | HAuCl₄            | CP | Calcined in air at 673 K for 5 h | 3.3 | 3.6 ± 1.3 | EXAFS, TEM, XRD [24] |
| 44          | Au/Fe₂O₃ | 37⁰F                         | HAuCl₄            | CP | Calcined in air at 673 K for 5 h | 0.66 | 4.0 | |
| 45          | Au/Co₃O₄ | 59⁰F                         | HAuCl₄            | CP | Calcined in air at 673 K for 5 h | 1.1 | 6–7 | |
| Entry number | Catalyst | Catalyst surface area (m²/g) | Catalyst precursor | Preparation method | Catalyst treatment | Gold content (wt %) | Average gold particle size (nm) | Method of determining gold particle size | References |
|--------------|----------|-------------------------------|-------------------|-------------------|------------------|-------------------|-------------------------------|------------------------------------------|------------|
| 46           | Au/Fe₂O₃ | Not stated                     | HAuCl₄            | DP                | Calcined in O₂ at 673 K for 30 min (20 mL/min, 100 mbar) | Not stated | 2.3–7                         | STEM, XRD [25]                         |            |
| 47           | Au/Fe₂O₃ | Not stated                     | Not stated        |                   |                  |                   |                               |                                          |            |
| 48           | Au/Fe₂O₃ | CP                            |                  | CP                |                  |                   |                               |                                          |            |
| 49           | AuNiO₂   | CP                            |                  | CP                |                  |                   |                               |                                          |            |
| 50           | AuCoO₂   | IMP                           |                  | IMP              |                  |                   |                               |                                          |            |
| 51           | AuTiO₂   | IMP                           |                  | IMP              |                  |                   |                               |                                          |            |
| 52           | AuMg(OH)₂| CP                            |                  | CP                |                  |                   |                               |                                          |            |
| 53           | AuMgO    | CP                            |                  | CP                |                  |                   |                               |                                          |            |
| 54           | AuAl₂O₃  | IMP                           |                  | IMP              |                  |                   |                               |                                          |            |
| 55           | AuAl₂O₃  | Not stated                    | HAuCl₄            | DP                | Calcined in He at 673 K for 4 h (100 mL/min) | 1.08    | 2.5 ± 1.1                     | STEM, EXAFS [26]                       |            |
| 56           | AuFe₂O₃  | Not stated                    | HAuCl₄            | DP                |                  |                  |                               |                                          |            |
| 57           | AuFe₂O₃  | Not stated                    | HAuCl₄            | DP                |                  |                  |                               |                                          |            |
| 58           | AuFe₂O₃  | Not stated                    | HAuCl₄            | DP                |                  |                  |                               |                                          |            |
| 59           | AuFe₂O₃  | 63                            | 6 h, air, 673 K⁰   |                   |                  | 2.8               | 12                            |                                          |            |
| 60           | AuFe₂O₃  | 99                            | 20 h, vacuum, 573 K⁰, air, 673 K |                   |                  | 3.5               | 9                             |                                          |            |
| 61           | AuFe₂O₃  | 76                            | 4 h, air, 673 K⁰   |                   |                  | 2.9               | 11                            |                                          |            |
| 62           | AuFe₂O₃  | 130                           | 4 h, air, 673 K⁰   |                   |                  | 3.5               | 9                             |                                          |            |
| 63           | AuFe₂O₃  | Not stated                    | HAuCl₄            | DP                | Heating from room temperature to 573 K in N₂ followed by 30 min in H₂/O₂/N₂ 25/25/50 | Not stated | 3.0 ± 0.6                      | TEM [8]                                    |            |
| 64           | AuAl₂O₃  | Not stated                    | HAuCl₄            | DP                |                  |                   |                               |                                          |            |
| 65           | AuAl₂O₃  | 44.2                          |                  |                  |                  |                   |                               |                                          |            |
| 66           | AuAl₂O₃  | 41.1                          |                  |                  |                  |                   |                               |                                          |            |
| 67           | AuAl₂O₃  | Not stated                    | Leached           |                  |                  | 0.7               | Not stated                    |                                          |            |
| 68           | AuAl₂O₃  | 146.3                         |                  |                  |                  | 4.7               | 5.0                          |                                          |            |
| 69           | AuAl₂O₃  | 161.6                         |                  |                  |                  | 0.5               | Not stated                    |                                          |            |
| 70           | AuAl₂O₃  | Not stated                    | Leached           |                  |                  | 0.5               | Not stated                    |                                          |            |
| 71           | AuAl₂O₃  | Not stated                    | Leached           |                  |                  | 0.5               | Not stated                    |                                          |            |
| 72           | AuAl₂O₃  | Not stated                    | Leached           |                  |                  | 0.5               | Not stated                    |                                          |            |
| 73           | AuAl₂O₃  | Not stated                    | Leached           |                  |                  | 0.5               | Not stated                    |                                          |            |
| 74           | AuAl₂O₃  | 21⁰c                          |                  |                  |                  | 1                 | 2–7                          |                                          |            |
| 75           | AuAl₂O₃  | 21⁰c                          |                  |                  |                  | 1                 | 2–7                          |                                          |            |
| 76           | AuAl₂O₃  | Not stated                    | HAuCl₄            | DP                |                  |                   |                               |                                          |            |
| 77           | AuAl₂O₃  | Not stated                    | HAuCl₄            | DP                |                  |                   |                               |                                          |            |
| 78           | AuAl₂O₃  | 150c                          |                  |                  |                  | 4.4               | 2                            |                                          |            |
| 79           | AuMgO    | 60⁰c                          |                  |                  |                  | 1.0               | 3.0                          |                                          |            |

a The abbreviations regarding the preparation methods are as follows: DP deposition precipitation, JW incipient wetness, CP co-precipitation, IMP impregnation, PD photochemical deposition, GR grafting, VD vapor deposition

b Atom %

c This value corresponds to the surface area of the support

d Treatment of the support
Table 2 Reaction conditions under which the supported gold CO oxidation catalysts were tested

| Entry number | Catalyst | Degree of deactivation | Catalyst mass (mg) | Reactor type | Total feed flow rate (mL/min) | Feed flow conditions | Space velocity (mL/min gcat) | Feed partial Pressures (mbar) | Reaction temperature (K) | References |
|--------------|----------|------------------------|-------------------|-------------|-------------------------------|---------------------|-----------------------------|-----------------------------|--------------------------|-----------|
| 1            | Au/SiO<sub>2</sub> | Not stated | 600–1,000 | Plug flow | 50 | Normal temperature and pressure | 50–83.3 | 50.7 | 49.3 | 313 | [9] |
| 2            | Au/TiO<sub>2</sub> | | | | | | | | | | |
| 3            | Au/TiO<sub>2</sub> | | | | | | | | | | |
| 4            | Au/TiO<sub>2</sub> | | | | | | | | | | |
| 5            | Au/TiO<sub>2</sub> | | | | | | | | | | |
| 6            | Au/TiO<sub>2</sub> | Not stated | 350 | Plug flow | 35 | Normal temperature and pressure | 100 | 50.7 | 48 | 313 | |
| 7            | Au/TiO<sub>2</sub> (after deactivation) | | | | | | | | | | |
| 8            | Au/TiO<sub>2</sub> | | | | | | | | | | |
| 9            | Au/TiO<sub>2</sub> | | | | | | | | | | |
| 10           | Au/Fe<sub>2</sub>O<sub>3</sub> | Not stated | 200 | Fixed bed | 66 | Normal temperature and pressure | 330 | 10.1 | 208 | 203 | [10] |
| 11           | Au/Co<sub>3</sub>O<sub>4</sub> | | | | | | | | | | |
| 12           | Au/NiO | | | | | | | | | | |
| 13           | Au/CoO | | | | | | | | | | |
| 14           | Au/Fe<sub>2</sub>O<sub>3</sub> | Initial activities are above 90% decreasing 10% after 167 h | 150 | Fixed bed (integral mode; high X) | 10 | 1 bar | 66.6 | 10.1 | 5.1 | 303,323,348 | [11] |
| 15           | Au/MnO<sub>2</sub> | | | | | | | | | | |
| 16           | Au/Co<sub>3</sub>O<sub>4</sub> | | | | | | | | | | |
| 17           | Au/Co<sub>3</sub>O<sub>4</sub> | Activates during CO oxidation at 353 K increasing activity during CO oxidation at room temperature | 25 | Plug flow | 200 | 298 K, 1 bar | 800 | 20.3 | 10.1 | 298 | [12, 13] |
| 18           | Au/Co<sub>3</sub>O<sub>4</sub> | Catalyst activated during CO oxidation at 353 K then stabilized at 303 K after 48 h of reaction | 25 | Plug flow | 200 | 298 K, 1 bar | 800 | 20.3 | 20.3 | 303 | [12, 13] |
| 19           | Au/TiO<sub>2</sub> | Not stated | 200 | Fixed bed | 67 | Normal temperature and pressure | 1,340 | 10.1 | 208 | 300 | [14] |
| 20           | Au/TiO<sub>2</sub> | | | | | | | | | | |
| 21           | Au/TiO<sub>2</sub> | | | | | | | | | | |
| 22           | Au/TiO<sub>2</sub> | | | | | | | | | | |
| 23           | Au/TiO<sub>2</sub> | Not stated | 50 | Fixed bed | 17 | Normal temperature and pressure | 340 | 10.1 | 208 | 313 | [15] |
| 24           | Au/TiO<sub>2</sub> | | | | | | | | | | |
| 25           | Au/TiO<sub>2</sub> | | | | | | | | | | |
| 26           | Au/TiO<sub>2</sub> | | | | | | | | | | |
| 27           | Au/TiO<sub>2</sub> | | | | | | | | | | |
| 28           | Au/TiO<sub>2</sub> | | | | | | | | | | |
| 29           | Au/TiO<sub>2</sub> | | | | | | | | | | |
| 30           | Au/TiO<sub>2</sub> | | | | | | | | | | |
| 31           | Au/TiO<sub>2</sub> | | | | | | | | | | |
| 32           | Au/TiO<sub>2</sub> | Not stated | 55 | Fixed bed | 25 | Not stated | 454.5 | 10.1 | 10.1 | 243–363 | [16] |
| 33           | Au/MgO | Not stated | Not stated | Fixed bed UHV | Not stated | Total pressure: 53.3 mbar | Not stated | 8.6 | 43.3 | 300 | [17] |
| Entry number | Catalyst | Degree of deactivation | Catalyst mass (mg) | Reactor type | Total feed flow rate (mL/min) | Feed flow conditions | Space velocity (mL/min gcat) | Feed partial Pressures (mbar) | Reaction temperature (K) | References |
|--------------|----------|------------------------|-------------------|-------------|-----------------------------|----------------------|-----------------------------|-----------------------------|-----------------------------|------------------------|
| 34           | Unsupported nanoporous gold | Not stated | 66.7 | Not stated | 10.1 | 101.3 | 243, 273, 303 | [18] |
| 35           | Nanoporous gold | Not stated | 60 | Fixed bed | 15 | 1 bar | 187.5 | [19] |
| 36           | Au/MgO | Not stated | Not stated | Fixed bed | 45 | Not stated | 373 | 222.3 | 10.1 | [18] |
| 37           | Au/MgO | Not stated | Not stated | Fixed bed | 45 | Not stated | 373 | 222.3 | 10.1 | [18] |
| 38           | Au/MgO | Not stated | Not stated | Fixed bed | 45 | Not stated | 373 | 222.3 | 10.1 | [18] |
| 39           | Au/MgO | Not stated | Not stated | Plug flow | Not stated | 373 | 222.3 | 10.1 | [18] |
| 40           | Au/TiO₂ | Not stated | Not stated | Plug flow | Not stated | 373 | 222.3 | 10.1 | [18] |
| 41           | Au/TiO₂ | Not stated | Not stated | Plug flow | Not stated | 373 | 222.3 | 10.1 | [18] |
| 42           | Au/TiO₂ | Not stated | 200 | Fixed bed | 67 | Not stated | 373 | 222.3 | 10.1 | [18] |
| 43           | Au/Fe₂O₃ | Not stated | Not stated | Plug flow | Not stated | 373 | 222.3 | 10.1 | [18] |
| 44           | Au/Co₃O₄ | Not stated | Not stated | Plug flow | Not stated | 373 | 222.3 | 10.1 | [18] |
| 45           | Au/Fe₂O₃ | Not stated | Not stated | Plug flow | Not stated | 373 | 222.3 | 10.1 | [18] |
| 46           | Au/Fe₂O₃ | Not stated | Not stated | Plug flow | Not stated | 373 | 222.3 | 10.1 | [18] |
| 47           | Au/Fe₂O₃ | Not stated | Not stated | Plug flow | Not stated | 373 | 222.3 | 10.1 | [18] |
| 48           | Au/Fe₂O₃ | Not stated | Not stated | Plug flow | Not stated | 373 | 222.3 | 10.1 | [18] |
| 49           | Au/CoOₓ | Not stated | Not stated | Plug flow | Not stated | 373 | 222.3 | 10.1 | [18] |
| 50           | Au/CoOₓ | Not stated | Not stated | Plug flow | Not stated | 373 | 222.3 | 10.1 | [18] |
| 51           | Au/TiOₓ | Not stated | Not stated | Plug flow | Not stated | 373 | 222.3 | 10.1 | [18] |
| 52           | Au/Mg(OH)₂ | Not stated | Not stated | Plug flow | Not stated | 373 | 222.3 | 10.1 | [18] |
| 53           | Au/MgO | Not stated | Not stated | Plug flow | Not stated | 373 | 222.3 | 10.1 | [18] |
| 54           | Au/Al₂O₃ | Not stated | Not stated | Plug flow | Not stated | 373 | 222.3 | 10.1 | [18] |
| 55           | Au/Al₂O₃ | Not stated | Not stated | Plug flow | Not stated | 373 | 222.3 | 10.1 | [18] |
| 56           | Au/Al₂O₃ | Not stated | Not stated | Plug flow | Not stated | 373 | 222.3 | 10.1 | [18] |
| 57           | Au/TiO₂ | Not stated | Not stated | Plug flow | Not stated | 373 | 222.3 | 10.1 | [18] |
| 58           | Au/TiO₂ | Not stated | 200 | Fixed bed | 67 | Not stated | 373 | 222.3 | 10.1 | [18] |
| 59           | Au/TiO₂ | Not stated | 200 | Fixed bed | 67 | Not stated | 373 | 222.3 | 10.1 | [18] |
| 60           | Au/TiO₂ | Not stated | 200 | Fixed bed | 67 | Not stated | 373 | 222.3 | 10.1 | [18] |
| 61           | Au/TiO₂ | Not stated | 200 | Fixed bed | 67 | Not stated | 373 | 222.3 | 10.1 | [18] |
| 62           | Au/TiO₂ | Not stated | 200 | Fixed bed | 67 | Not stated | 373 | 222.3 | 10.1 | [18] |
| Entry number | Catalyst | Degree of deactivation | Catalyst mass (mg) | Reactor type | Total feed flow rate (mL/min) | Feed flow conditions | Space velocity (mL/min gcat) | Feed partial pressures (mbar) | Reaction temperature (K) | References |
|--------------|----------|------------------------|-------------------|-------------|-------------------------------|---------------------|--------------------------|-----------------------------|--------------------------|------------|
| 63           | Au/\(\text{TiO}_2\) | Catalyst activity showed a slight decrease in activity in the first hour on stream | 0.2               | Plug flow   | 27                            | 1 bar, room temperature | 135,000                  | 10.1                        | 208                       | 293        | [8]        |
| 64           | Au/\(\text{Al}_2\text{O}_3\) | Not stated             | 5–100             | Plug flow   | 75–250                        | 1 bar, room temperature | 1,000–15,000             | 3–70                        | 3–70                      | 298        | [29]       |
| 65           | Au/\(\text{Fe}_2\text{O}_3\) | Not stated | 10–50            | Plug flow   | 150                          | 1 bar, room temperature | 3,000–15,000             | 20.3                        | 10.1                      | 303        | [6]        |
| 66           | Au/\(\text{Fe}_2\text{O}_3\) | Not stated | 10–50            | Plug flow   | 150                          | 1 bar, room temperature | 3,000–15,000             | 20.3                        | 10.1                      | 303        | [6]        |
| 67           | Au/\(\text{Fe}_2\text{O}_3\) | Not stated | 10–50            | Plug flow   | 150                          | 1 bar, room temperature | 3,000–15,000             | 20.3                        | 10.1                      | 303        | [6]        |
| 68           | Au/\(\text{CeO}_2\) | Not stated | Not stated       | Plug flow   | Not stated                    | 1 bar, room temperature | 15,000\(^a\)            | 10.1                        | 208                       | 298        | [30]       |
| 69           | Au/\(\text{CeO}_2\) | Not stated | Not stated       | Plug flow   | Not stated                    | 1 bar, room temperature | 333–1,333                | 10.1                        | 208                       | 200–500    | [31]       |
| 70           | Au/\(\text{CeO}_2\) | Not stated | Not stated       | Plug flow   | Not stated                    | 1 bar, room temperature | 333–1,333                | 10.1                        | 208                       | 200–500    | [31]       |
| 71           | Au/\(\text{Al}_2\text{O}_3\) | Not stated | Not stated       | Plug flow   | Not stated                    | 1 bar, room temperature | 15,000\(^a\)            | 10.1                        | 208                       | 298        | [30]       |
| 72           | Au/\(\text{Al}_2\text{O}_3\) | Not stated | Not stated       | Plug flow   | Not stated                    | 1 bar, room temperature | 333–1,333                | 10.1                        | 208                       | 200–500    | [31]       |
| 73           | Au/\(\text{Al}_2\text{O}_3\) | Not stated | Not stated       | Plug flow   | Not stated                    | 1 bar, room temperature | 333–1,333                | 10.1                        | 208                       | 200–500    | [31]       |
| 74           | Au/\(\text{SiO}_2\) | Not stated | Not stated       | Plug flow   | Not stated                    | 1 bar, room temperature | 333–1,333                | 10.1                        | 208                       | 200–500    | [31]       |
| 75           | Au/\(\text{TiO}_2\) | Not stated | Not stated       | Plug flow   | Not stated                    | 1 bar, room temperature | 333–1,333                | 10.1                        | 208                       | 200–500    | [31]       |
| 76           | Au/\(\text{TiO}_2\) | Not stated | Not stated       | Plug flow   | Not stated                    | 1.22 bar, room temperature | 1,500–8,500             | 20.2                        | 20.2                      | 273        | [32]       |
| 77           | Au/\(\text{Al}_2\text{O}_3\) | Not stated | Not stated       | Plug flow   | Not stated                    | 1.22 bar, room temperature | 1,500–8,500             | 20.2                        | 20.2                      | 273        | [32]       |
| 78           | Au/\(\text{Al}_2\text{O}_3\) | Not stated | Not stated       | Plug flow   | Not stated                    | 1.22 bar, room temperature | 1,500–8,500             | 20.2                        | 20.2                      | 273        | [32]       |
| 79           | Au/\(\text{MgO}\) | Not stated | Not stated       | Plug flow   | Not stated                    | 1.22 bar, room temperature | 1,500–8,500             | 20.2                        | 20.2                      | 273        | [32]       |

\(^a\) CO in feed, was \(^{13}\text{C}\text{O}\); total pressure was greater than atmospheric (1,216 mbar)

\(^b\) Oxygen in feed was \(^{16}\text{O}_2\)

\(^c\) Values are for gas hour space velocity
Table 3  Kinetics data reported for the supported gold CO oxidation catalysts considered in this work

| Entry number | Catalyst | Conversion (%) | Temperature range (K) for activation energy | Apparent activation energy (kJ/mol) | TOF (s⁻¹) | Details about TOF calculations | Reaction order | Comments | References |
|--------------|----------|----------------|---------------------------------------------|-----------------------------------|-----------|--------------------------------|---------------|----------|------------|
| 1            | Au/SiO₂  | <15            | 312–454                                    | 15.1⁺                             | 2.0 × 10⁻² | Lower limit based on total number of Au atoms | Not stated   | Not stated | [9]        |
| 2            | Au/TiO₂  | Not stated     | Not stated                                 | Not stated                        | 0.2–0.6 b, c | 0.4 b, c                       |               |          |            |
| 3            | Au/TiO₂  | Not stated     | Not stated                                 | Not stated                        | 0.2–0.6 b, c | 0.4 b, c                       |               |          |            |
| 4            | Au/TiO₂  | Not stated     | Not stated                                 | Not stated                        | 0.2–0.6 b, c | 0.4 b, c                       |               |          |            |
| 5            | Au/TiO₂  | Not stated     | Not stated                                 | Not stated                        | 0.2–0.6 b, c | 0.4 b, c                       |               |          |            |
| 6            | Au/TiO₂  | <15            | 312–454                                    | 3.1 ± 1.6⁺                        | 2.4 × 10⁻¹ | Not stated                      |               |          |            |
| 7            | Au/TiO₂  | (after deactivation) | Not stated                                 | Not stated                        | 0.2–0.6 b, c | 0.4 b, c                       |               |          |            |
| 8            | Au/TiO₂  | Not stated     | Not stated                                 | Not stated                        | 0.2–0.6 b, c | 0.4 b, c                       |               |          |            |
| 9            | Au/TiO₂  | Not stated     | Not stated                                 | Not stated                        | 0.2–0.6 b, c | 0.4 b, c                       |               |          |            |
| 10           | Au/CoO₃  | 50             | Not stated                                 | Not stated                        | Not stated | Not stated                      |               |          |            |
| 11           | Au/MnO   | 50             | Not stated                                 | Not stated                        | Not stated | Not stated                      |               |          |            |
| 12           | Au/CuO   | 50             | Not stated                                 | Not stated                        | Not stated | Not stated                      |               |          |            |
| 13           | Au/Fe₂O₃ | ~100           | 313                                        | 33³                              | Not stated | Not stated                      |               |          |            |
| 14           | Au/Fe₂O₃ | ~100           | 313                                        | 8.4⁺                             | Not stated | Not stated                      |               |          |            |
| 15           | Au/MnO   | 50             | Not stated                                 | Not stated                        | Not stated | Not stated                      |               |          |            |
| 16           | Au/CoO₂  | >80            | Not stated                                 | Not stated                        | Not stated | Not stated                      |               |          |            |
| 17           | Au/CoO₂  | <5             | 333–348                                    | 138 ± 2⁺                         | (6.5 ± 0.6) × 10⁻⁴ | Lower limit based on total number of Au atoms | Not stated   | Not stated | [12, 13]  |
| 18           | Au/CoO₂  | <5             | 303–333                                    | 54 ± 8⁺                          | (5.6 ± 0.2) × 10⁻² | Lower limit based on total number of Au atoms | 0.19         | 0.18      | ~0.4       |
| 19           | Au/TiO₂  | <15            | 243–310                                    | 19⁺                              | 3.4 × 10⁻² | Lower limit based on total number of Au atoms | Zero         | 0.25      | Not stated |
| 20           | Au/TiO₂  | Not stated     | Not stated                                 | Not stated                        | 0.2–0.6 b, c | 0.4 b, c                       |               |          |            |
| 21           | Au/TiO₂  | Not stated     | Not stated                                 | Not stated                        | 0.2–0.6 b, c | 0.4 b, c                       |               |          |            |
| 22           | Au/TiO₂  | Not stated     | Not stated                                 | Not stated                        | 0.2–0.6 b, c | 0.4 b, c                       |               |          |            |
| 23           | Au/TiO₂  | <15            | 190–250                                    | 75⁺                              | 3.7 × 10⁻² | Lower limit based on total number of Au atoms | Not stated   | Not stated | [14]       |
| 24           | Au/TiO₂  | Not stated     | Not stated                                 | Not stated                        | 0.2–0.6 b, c | 0.4 b, c                       |               |          |            |
| 25           | Au/TiO₂  | 364–526       | 19⁺                                        | 3.4 × 10⁻² | 3.7 × 10⁻² | Lower limit based on total number of Au atoms | Not stated   | Not stated | [15]       |
| 26           | Au/TiO₂  | 323–434       | 18⁺                                        | 1.2 × 10⁻¹ | 3.7 × 10⁻² | Lower limit based on total number of Au atoms | Not stated   | Not stated | [15]       |
| 27           | Au/TiO₂  | Not stated     | Not stated                                 | Not stated                        | 3.4 × 10⁻² | 1.2 × 10⁻¹                      |               |          |            |
| 28           | Au/TiO₂  | Not stated     | Not stated                                 | Not stated                        | 2.6 × 10⁻¹ | 6.8 × 10⁻²                      |               |          |            |
| 29           | Au/TiO₂  | Not stated     | Not stated                                 | Not stated                        | 2.6 × 10⁻¹ | 6.8 × 10⁻²                      |               |          |            |
| 30           | Au/TiO₂  | Not stated     | Not stated                                 | Not stated                        | 2.6 × 10⁻¹ | 6.8 × 10⁻²                      |               |          |            |
| 31           | Au/TiO₂  | 450–1,060     | 58⁺                                        | 8.3 × 10⁻⁶ | Not stated | Based on surface metal atoms determined assuming fcc structure, amount of gold loading determined by ICP, X-ray fluorescence and TEM | Not stated   | Not stated |            |
| Entry number | Catalyst | Conversion (%) | Temperature range (K) for activation energy | Apparent activation energy (kJ/mol) | TOF (s⁻¹) | Details about TOF calculations | Reaction order | Comments | References |
|--------------|----------|----------------|---------------------------------------------|------------------------------------|-----------|---------------------------------|---------------|----------|------------|
| 32           | Au/TiO₂  | Not stated     | Not stated                                  | Not stated                         | Not stated| Not stated                      |               | e        | [16]       |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
| 33           | Au/MgO   | Not stated     | Not stated                                  | (5 × 10⁻²)- (2.5 × 10⁻¹)           | Not stated| Based on surface metal atoms determined by constant–current topographic images |               | Not stated| [17]       |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
| 34           | Unsupported nanoporous gold | ~100 | Not stated                                  | 3.4 × 10⁻²                     | Not stated| Not stated                      |               | Not stated| [18]       |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
| 35           | Nanoporous gold foams | 60–100 | Not stated                                  | Not stated                         | Not stated| Not stated                      |               | Not stated| [19]       |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
| 36           | Au/MgO   | 1              | Not stated                                  | Not stated                         | Not stated| Not stated                      |               | Not stated| [20]       |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
| 37           | Au/MgO   | 3              | Not stated                                  | Not stated                         | Not stated| Not stated                      |               | Not stated| [20]       |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
| 38           | Au/MgO   | 12             | Not stated                                  | Not stated                         | Not stated| Not stated                      |               | Not stated| [20]       |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
| 39           | Au/MgO   | 22             | Not stated                                  | Not stated                         | Not stated| Not stated                      |               | Not stated| [20]       |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
| 40           | Au/TiO₂  | Not stated     | Not stated                                  | (7.1 × 10⁻¹)-(2 × 10⁻⁰)           | Not stated| Lower limit based on total number of Au atoms |               | Not stated| [21]       |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
| 41           | Au/TiO₂  | Not stated     | Not stated                                  | 4.3 × 10⁻²                         | Not stated| Lower limit based on total number of Au atoms |               | Not stated| [22]       |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
| 42           | Au/TiO₂  | 294–385 K      | 11.4 ± 2.8⁸                                 | Not stated                         | 1.1 ± 0.1|h | Proposed rate-determining step is decomposition of carbonate intermediates |               | Not stated| [23]       |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
|              |          |                |                                             |                                    |           |                                 |               |          |            |
| 43           | Au/TiO₂  | <10            | 263–338                                    | 3.5 × 10⁻²                         | 0.05      | Based on surface metal atoms determined by TEM assuming fcc structure |               | 0.24     | [24]       |
|              |          |                |                                             |                                    |           |                                 |               |          |            |

Authors suggested that CO₂ desorption appears to be rate-limiting step, suggesting negative reaction order in CO₂.

Another finding is that carbon oxide species formed on the surface of Au/TiO₂ authors suggested these were only spectators.

Gold supported on crystalline surfaces of TiO₂ (a low-surface-area model support).

Authors claimed that metallic gold plays a catalytic role in CO oxidation.

Authors carried out similar experiments with catalyst having higher loadings of silver. These samples had activities almost the same as others. Authors ruled out role of silver in CO oxidation catalysis.

Authors claimed strong metal–support interactions responsible for catalytic activity of Au/TiO₂. Model catalyst: support was thin TiO₂ film on Mo(112).

Authors concluded that desorption of CO₂ is a rate-limiting step in CO oxidation.

Proposed rate-determining step is decomposition of carbonate intermediates.

Authors concluded CO oxidation is structure sensitive. Rate of CO oxidation independent of or only slightly dependent on P_{CO} and P_{O₂}.

Authors proposed that CO₂ formation results from decomposition of bidentate carbonate species.
| Entry number | Catalyst | Conversion (%) | Temperature range (K) for activation energy | Apparent activation energy (kJ/mol) | TOF (s\(^{-1}\)) | Details about TOF calculations | Reaction order CO | Reaction order O\(_2\) | Reaction order CO\(_2\) | Comments | References |
|-------------|----------|----------------|---------------------------------------------|------------------------------------|----------------|--------------------------------|-----------------|-----------------|-----------------|-----------|------------|
| 44          | AuFe\(_2\)O\(_3\) |                 |                                             | 35.1\(^a\)                         | 3.0 × 10\(^{-2}\) | 0.05                           | Not stated      | 0.05            | Not stated      | Dominant reaction pathway concluded to involve adsorption of a mobile, molecular oxygen species on support, dissociation at the gold—support interface and reaction on gold particles and/or at the interface with CO adsorbed on the gold | [25]      |
| 45          | AuCo\(_3\)O\(_4\) | Not stated     |                                             | 16.3\(^a\)                         | Not stated      | Not stated                       | Not stated      | 0.27            | Not stated      |                       |            |
| 46          | AuFe\(_2\)O\(_3\) | <20            | Not stated                                  | 29\(^d\)                           | 1.3–3\(^d\)     | Lower limit based on total number of Au atoms | Not stated      | Not stated      | Not stated      |                       |            |
| 47          | AuFe\(_2\)O\(_3\) | Not stated     |                                             | Not stated                          | 2.9–6.7         | Not stated                       | Not stated      | 1.6–3          |                | Lower limit based on total number of Au atoms |            |
| 48          | AuFe\(_2\)O\(_3\) | Not stated     |                                             | Not stated                          | 3.2–3.4         | Not stated                       | Not stated      | 1.3–2          |                |                       |            |
| 49          | AuNiO\(_x\) | Not stated     |                                             | Not stated                          | 1.3\(^f\)       | Not stated                       | Not stated      | 1.3–3          |                |                       |            |
| 50          | AuCoO\(_x\) | Not stated     |                                             | Not stated                          | 1.8\(^g\)       | Not stated                       | Not stated      | 1.8–4          |                |                       |            |
| 51          | AuTiO\(_2\) | 21\(^d\)       |                                             | 1.6\(^d\)                           | Not stated      | Not stated                       | Not stated      | 1.6–2          |                |                       |            |
| 52          | AuMg(OH)\(_2\) | Not stated     |                                             | Not stated                          | 0.5–0.9\(^j\)   | Not stated                       | Not stated      | 0.5–0.9        |                |                       |            |
| 53          | AuMgO    | Not stated     |                                             | Not stated                          | 0.3\(^j\)       | Not stated                       | Not stated      | 0.3–1        |                |                       |            |
| 54          | AuAl\(_2\)O\(_3\) | Not stated    |                                             | Not stated                          | 0.35\(^j\)      | Not stated                       | Not stated      | 0.35–0.5      |                |                       |            |
| 55          | AuAl\(_2\)O\(_3\) | 13–23          | 273–329                                     | 10                                 | 1.6             | Steady-state isotopic transient kinetics analysis used to evaluate the intrinsic turnover frequency | Not stated      | 0.05–0.8       | 0.05–1        | Oxygen exchange proposed to occur between supports and CO\(_2\). | [26]      |
| 56          | AuTiO\(_2\) |                 |                                             |                                    |                 |                                | Not stated      | 0.05–0.8       | 0.05–1        | Labeled oxygen found in H\(_2\)O exiting reactor appeared to originate from \(^{18}\)O associated with CO\(_2\) reactant |            |
| 57          | AuTiO\(_2\) | 5–20           | 303–353                                     | 72\(^d\), 20\(^d\)                 | Not stated      | Not stated                       | Not stated      | 0.05–0.8       | 0.05–1        | Authors concluded that dissociative adsorption of O\(_2\) not reversible and observed that oxygen in CO\(_2\) was exchanged by oxidation of C\(^{18}\)O with \(^{18}\)O\(_2\) of the support | [27]      |
| 58          | AuTiO\(_2\) | 5–20           | 303–353                                     | 33 ± 3                             | 1.6\(^d\)       | Not stated                       | Not stated      | 0.05–0.8       | 0.05–1        | Authors concluded that the formation of a reaction inhibiting carbonate adlayer is the main origin or deactivation | [28]      |
| 59          | AuTiO\(_2\) | 5–20           | 303–353                                     | 36 ± 4                             | 1.2\(^d\)       | Not stated                       | Not stated      | 0.05–0.8       | 0.05–1        | Authors concluded that the formation of a reaction inhibiting carbonate adlayer is the main origin or deactivation | [28]      |
| 60          | AuTiO\(_2\) | 5–20           | 303–353                                     | 34 ± 4                             | 1.6\(^d\)       | Not stated                       | Not stated      | 0.05–0.8       | 0.05–1        | Authors concluded that the formation of a reaction inhibiting carbonate adlayer is the main origin or deactivation | [28]      |
| 61          | AuTiO\(_2\) | 5–20           | 303–353                                     | 31 ± 3                             | 2.2\(^d\)       | Not stated                       | Not stated      | 0.05–0.8       | 0.05–1        | Authors concluded that the formation of a reaction inhibiting carbonate adlayer is the main origin or deactivation | [28]      |
| 62          | AuTiO\(_2\) | 5–20           | 303–353                                     | 28 ± 3                             | 2.0\(^d\)       | Not stated                       | Not stated      | 0.05–0.8       | 0.05–1        | Authors concluded that the formation of a reaction inhibiting carbonate adlayer is the main origin or deactivation | [28]      |
| 63          | AuTiO\(_2\) | 1–2            | 260–294                                     | 28                                 | Not stated      | Not stated                       | Zero            | 0.18–0.20      | 0.18–0.20    | Catalyst was thiol monolayer-protected gold clusters prepared from dendrimer templates and deposited onto high-surface-area titania, followed by removal of thiol in H\(_2\)/N\(_2\). Authors concluded that the monolayer-protected gold clusters are comparable in terms of gold particle size, rate laws, and apparent activation energies, to the standard catalysts available from the World Gold Council (WGC); however, these catalysts are 50% more active than the ones from WGC | [8]       |

References:
[25]...
[26]...
[27]...
[28]...
| Entry number | Catalyst | Conversion (%) | Temperature range (K) for activation energy | Apparent activation energy (kJ/mol) | TOF (s\(^{-1}\)) | Details about TOF calculations | Reaction order | Comments | References |
|--------------|----------|----------------|---------------------------------------------|-----------------------------------|----------------|-------------------------------|----------------|----------|------------|
|              |          |                |                                             |                                   |                |                               |                |          |            |
| 64           | Au/Al\(_2\)O\(_3\) | 10              | 298–377                                     | 12                                | 0.02 at 298 K, 0.04 at 373 K | The turnover frequency is the reaction rate per Au atom in the catalyst normalized by the fraction of metal exposed | 0.32           | 0.36     | [29]       |
| 65           | Au/Fe\(_2\)O\(_3\) | <5              | 324–343                                     | 13.4                              | Not stated      | Not stated                    | Authors concluded that dry CO oxidation is much more facile on Au0 than on oxidized gold clusters | [6]        |
| 66           | Au/Fe\(_2\)O\(_3\) | <5              | 560–573                                     | 32.6                              | Not stated      | Not stated                    |                   |          |            |
| 67           | Au/Fe\(_2\)O\(_3\) | <5              | 560–573                                     | 9.9                               | Not stated      | Not stated                    |                   |          |            |
| 68           | Au/CeO\(_2\) | <5              | Not stated                                  | 29.5                              | Not stated      | Not stated                    |                   |          |            |
| 69           | Au/CeO\(_2\) | <5              | Not stated                                  | 50.8                              | Not stated      | Not stated                    |                   |          |            |
| 70           | Au/CeO\(_2\) | <5              | Not stated                                  | 39.9                              | Not stated      | Not stated                    |                   |          |            |
| 71           | Au/Al\(_2\)O\(_3\) | 22              | 298–373                                     | 2.7                               | 0.25            | Not stated                    | Not stated       |          |            |
| 72           | Au/Al\(_2\)O\(_3\) | <5              | 23.7                                         | 0.07                              | Not stated      | Not stated                    | Al\(_2\)O\(_3\) support was one-dimensional nanofibers | [30]       |
| 73           | Au/Al\(_2\)O\(_3\) | Not stated | 238–500                                     | 22                                | 3 \times 10\(^{-3}\)–2 \times 10\(^{-4}\) Values per surface Au atom | Not stated       |                   |            |
| 74           | Au/SiO\(_2\) | Not stated | Not stated                                  | 1 \times 10\(^{-3}\)–4 \times 10\(^{-2}\) | Not stated      | Not stated                    |                      |          | [31]       |
| 75           | Au/TiO\(_2\) | Not stated | 200–263                                     | 25–26                             | 3 \times 10\(^{-1}\) \text{–Saturation of CO conversion} | Not stated       |                      |            |
| 76           | Au/TiO\(_2\) | <37             | 196–360                                     | 29                                | 3.4 \times 10\(^{-1}\) Calculated dividing the global reaction rate by the dispersion of gold. Fraction of exposed gold was estimated from the inverse of the surface-average gold particle size determined by STEM | 0.2             | 0.25                 | Authors suggested intrinsic rate of CO oxidation nearly independent of the support, suggesting that the ability of Au metal oxide to activate O\(_2\) is a key feature in determining the global reaction rate | [32]       |
| 77           | Au/Al\(_2\)O\(_3\) | <20             | 196–360                                     | 8                                 | 1.8 \times 10\(^{-1}\) | Not stated | Not stated |            |
including values of TOF and how they were determined, reaction orders, and apparent activation energies.

We believe that these tables provide the most complete available statement of kinetics of CO oxidation catalyzed by supported gold.

### 3 Generalizations Based on the Data

Table 2 is a summary of the catalysts tested for CO oxidation; the catalysts were investigated at temperatures in the range of 203–373 K. Haruta [35] referred to a low-temperature regime (typically, ~210 K) and a high-temperature regime (typically, >300 K). The O₂ partial pressures were varied between 4 and 200 mbar, and the CO partial pressures between 10 and 40 mbar. The results indicate orders of reaction in CO and in O₂ in the range 0.0–0.6. The reaction order in CO has been approximated as zero by some researchers [24]. Correspondingly, numerous researchers have postulated that CO is adsorbed on the gold; some [4] have suggested that CO is bonded to gold at the gold-support interface. The roles of oxygen in the gold-catalyzed CO oxidation are evidently not fully elucidated. Some authors have postulated that oxygen adsorbed on the gold [4] or at the gold-support interface [36] may play a role. In contrast, Guzman et al. [37] reported evidence of the involvement of reactive oxygen species (such as superoxides) on their CeO₂ support; the influence of the presence of reactive oxygen species on some supports but not on others (e.g., γ-Al₂O₃ [38]) would suggest that the form of kinetics would differ from one support to another, but there are too few data to test this statement.

A few reports of the influence of CO₂ on the rate indicate that it inhibits the reaction; according to one report [16, 22], the desorption of CO₂ from Au/TiO₂ is rate limiting under some conditions. Others [39] have reported that CO₂ (rather than O₂) is the oxidizing agent of gold in supported gold catalysts, implying that the gold in the catalytic sites cycles between more than one oxidation state.

Haruta’s group [40] reported a detailed investigation of the influence of water in the reactant stream on CO oxidation catalyzed by TiO₂⁻, Al₂O₃⁻, and SiO₂⁻ supported gold. Water in low concentrations increases the activity of the catalyst.

The most thorough investigation of the kinetics of CO oxidation catalyzed by supported gold was reported by Vannice’s group [9]; the catalyst support was TiO₂. The authors tested several catalysts that had been subjected to various pretreatments, and kinetics parameters are reported for each (entry numbers 1–9 in Tables 1, 2, 3).

Many of the most active supported gold catalysts for CO oxidation are supported on TiO₂ or on various oxides of iron...
or of cerium. Turnover frequencies (rates of reaction per accessible gold site; Table 3) span a wide range, between $10^{-6}$ and $10^{-1}$ s$^{-1}$. There is one report of an intrinsic turnover frequency—that is, per active site [41] (entry numbers 55, 56, 64, 76, and 77, Tables 1, 2, 3)—determined in transient measurements with isotopically labeled reactant $^{13}$CO for Au/$\gamma$-Al$_2$O$_3$; the value is $1.6 \times 10^{-1}$ s$^{-1}$ at 296 K and CO and O$_2$ partial pressures of 24.2 mbar each.

Only a few values of apparent activation energies of CO oxidation catalyzed by gold have been reported, and the information about the conditions under which they were determined is often lacking. The apparent activation energies range from values that are essentially indistinguishable from 0 to 138 kJ/mol (Table 3).

Most reports of catalyst deactivation and how it occurs (e.g., [11]) do not include kinetics data, but the work of Vannice’s group [9] is exceptional, providing kinetics data for various catalysts before and after deactivation (Table 2).

Supported gold catalysts typically undergo rapid deactivation during CO oxidation, and this complication has hindered the collection of kinetics data. For example, the initial conversion observed with a zeolite-supported gold catalysts was about 40%, and this decreased to <5% within 15 min of operation in a once-through flow reactor at 298 K [42]. An Au/TiO$_2$ [27] catalyst, on the other hand, showed an initial conversion at 303 K of nearly 100%, and the conversion had declined to 10% after 2,000 min of operation in a flow reactor when O$_2$ was present in stoichiometric excess; but the decline in activity was more rapid when the O$_2$ was not present in stoichiometric excess. Other authors have also observed that the rate of catalyst deactivation was less when the reaction took place in an O$_2$-rich atmosphere [25].

It is clear that the available data do not lend themselves to conclusive integration and that much work remains to be done to consolidate the literature and to represent CO oxidation catalyzed by supported gold quantitatively.

4 Conclusions

The results summarized here show that the literature of CO oxidation catalyzed by supported gold is extensive but fragmented and not easily generalized; it is not easy to make meaningful comparisons of various supported gold catalysts for this reaction, and much work remains to be done to consolidate the literature of CO oxidation catalyzed by supported gold.

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