
Effects of Functional Nanomaterials for Reduction of Carbon Monoxide Levels in the Workplace and Homes

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Abstract

Carbon monoxide (CO) at high concentrations is extremely poisonous to humans and other invertebrates. It is one of the leading causes of unintentional deaths in the United States. Furthermore, people with heart diseases are more vulnerable to high CO levels since they already have a reduced ability to get oxygenated blood to their hearts. Functional nanomaterials (metallic nanoparticles [NPs], carbon nanotubes [CNTs], and nanofibers [NFs]) offer a high surface area, low weight-to-volume ratio, flexibility, and high porosity, which are perfect properties for gas absorption. Many nanomaterials are currently playing an essential role in CO-capturing technologies. This paper focuses on the usage of those functional nanomaterials for CO absorption and their absorption mechanisms. Due to high surface area and porosity, these materials have been widely used to absorb pollutants, including toxic gas like CO. Fabrications, CO-absorbing mechanisms, and absorbing properties of some nanomaterials will be discussed here.

Keywords: Nanomaterials, CO capture, and removal, absorbing mechanisms

1. Introduction

Carbon monoxide (CO) is a by-product of incomplete combustion. At high concentrations, CO can cause hypoxia (lack of oxygen at the tissue level) in humans and other vertebrates because once CO enters the bloodstream through the lungs, it immediately binds to hemoglobin with an affinity of 250 times more than oxygen, thereby preventing less oxygen being transported to tissue in the body. Depending on the concentration of CO, the victim can experience headaches, dizziness, nausea, unconsciousness, respiratory arrest, brain damage, or even death (Goldstein, 2008). Furthermore, CO at certain levels is vulnerable to people with heart disease since a limited amount of oxygenated blood goes to their hearts. CO is colorless, odorless, and nonirritating, and therefore particularly dangerous because the victim cannot sense it without a particular gas detector. According to the Centers for Disease Control and Prevention (CDC) (CDC, 2019), every year in the United States, at least 430 deaths and 50,000 emergency visits account for CO poisoning. Most poisoning events take place during vehicle incidents and house fires; however, in some cases, due to faulty ventilation, smoke containing CO from wood- or coal-burning stoves, generators, gas engines, natural gas equipment, or heating systems can be trapped in place, build up over time, and can cause a threat.

Therefore, it is important to have effective ways of capturing and removing CO. Of the several methods for removing CO, catalytic oxidation is the most effective. During the past few years, in addition to conventional materials and methods used to remove CO and improve CO reduction, the implementation of nanomaterials for CO removal has been reported. Nanomaterials are materials that are smaller than 1 μm and have at least one dimension less than 100 nm. In their study of nanomaterials, researchers have concluded that, compared with bulk materials, nanomaterials can possess unusual and

extraordinary properties for the following reasons: (i) characteristic length scale, (ii) surface, and interface effect, and (iii) quantum size effect. Nanomaterials and nanotechnology have emerged in many fields of scientific, industrial, medical, and commercial sectors, with hundreds of thousands of products, such as filtration membranes, coatings, batteries, and so on (Abedin et al., 2021; R. Asmatulu & Khan, 2018; Hughes & Asmatulu, 2021; Sengul & Asmatulu, 2020). With the innovation of nanotechnology in the last two decades, many promising nanomaterials can be fabricated and utilized to treat toxic CO successfully. Among the many methods used to remove CO, catalytic oxidation in the presence of a catalyst is the most effective.

This review paper provides a brief introduction to some promising nanomaterials that have been used in recent years for CO catalytic oxidation. Materials with great surface area and high porosity, including metallic nanoparticles (NPs), carbon nanotubes (CNTs), electrospun nanofibers (NFs), or a matrix comprised of two or more of these, are great candidates for this application due to their absorption and high CO catalytic oxidation. A summary of all these nanomaterials including their size, function, and catalytic properties is listed in Table 1.

Table 1. Summary of Nanomaterials Used for CO Catalytic Oxidation

Nanomaterial	Size	Type of Catalyst	Catalytic Properties	Ref.
Pt NPs	Particle diameter: 2.2–16.7 nm	Pt/TiO ₂	<ul style="list-style-type: none"> • Pt/TiO₂ (R)-600 had highest dispersion (33.4%) • CO conversion of Pt/TiO₂ (R)-600 was 100% at 25°C, the highest conversion rate compared to other samples 	(Abedin et al., 2021)
	Cluster: 0.75 ± 0.11 nm	Pt-Cu/CeO ₂	<ul style="list-style-type: none"> • Pt nanocluster deposited on Cu-O-Ce interface with activated oxygen lattice achieved 100% CO conversion rate at 30°C 	(Liu et al., 2020)
Pd NPs	Particles: 2.7–5 nm	Pd/triptycene-based	<ul style="list-style-type: none"> • Pd loading to microporous remarkably enhanced the catalytic activity of CO oxidation • 3% loading of Pd exhibited the highest catalysis since it provided the most active sites; a 100% conversion rate of 3% Pd was at 160°C 	(Liang et al., 2013)
	Particles: ~10 nm	Pd/Graphene	<ul style="list-style-type: none"> • Large Pd NPs created nanoholes on graphene sheets; that defect structure facilitated CO • 100% CO conversion rate was at 190°C 	(Kumar et al., 2015)
	Bimetallic NPs: 3–5 nm	Pd-M/AC	<ul style="list-style-type: none"> • The addition of metallic NPs improved the catalysis of CO oxidation by providing more surface area • Pd/Cu-AC had the highest conversion rate of 50% at 30°C 	(Singhania & Gupta, 2018)
	Particles: 3.5– 13.7 nm	Pd/TiO ₂ nanosheet	<ul style="list-style-type: none"> • TiO₂ nanosheet provided a large surface area for Pd NPs, then created strong 	(Zhai et al., 2018)

Nanomaterial	Size	Type of Catalyst	Catalytic Properties	Ref.
			electronic interaction TiO ₂ -Pd, which promoted catalysis. • 100% CO conversion rate at 80°C for Pd/TiO ₂ -350 sample.	
	Particles: 2.5–10.6 nm	Pd/Co ₃ O ₄	• Pd NPs with the smallest size 2.5 nm yielded the highest dispersion 39.4%, which led to the highest catalytic activity • The formation energy of CO ₂ , endothermic, peaked at 85°C to 157°C from smallest to largest Pd NPs, indicating that smaller Pd NPs correlated to higher CO oxidation	(Huang et al., 2019)
Au NPs	Cluster: 1–6 nm dia	Au/TiO ₂	• High catalytic activity on surface Au/ TiO ₂ at 300 K (27°C) and 10 Torr • TOF peaked at 0.25 s ⁻¹ per site for 2–3 nm Au cluster diameter	(Valden et al., 1998)
	Hemispherical NPs: 3.8 ± 0.6 nm	Au/ TiO ₂	• Highly sensitivity of CO on the perimeter interface of Au NPs • Calcined Au- TiO ₂ had a conversion rate of CO to CO ₂ of 80%	(Du et al., 2014)
	Particles: 2 nm	Au/POM	• Smaller Au particles (< 2 nm) resulted in higher catalytic activity. • The catalyst's function is affected by trace water • 100% CO conversion rate occurred within -40 °C to 60°C	(Yoshida et al., 2018)
CNTs	–	Ag/CNT	• The improved interface between Ag sites and CNTs since more Ag particles deposited on CNTs surfaces; prevented the sintering of Ag • 100% conversion rate at 170°C	(Wang, 2016)
	–	Cu-Mn/MWCNTs	• Cu-Mn synergistic interaction and properties of MWCNTs resulted in remarkable catalytic activity • 100% conversion rate at 180°C	(Guo et al., 2016)
	–	CuO-CeO ₂ /MWCNTs	• High surface area and great electrical properties of MWCNTs enhanced synergistic interaction between CuO-CeO ₂ and support • Alkalis improved the dispersion of Cu and Ce oxides, which facilitated catalysis • 100% conversion rate at 175°C	(Guo et al., 2016)
	–	CuO-CeO ₂ /MWCNTs	• Excellent catalytic activity due to more surface lattice oxygen and oxygen	(Shi et al., 2018)

Nanomaterial	Size	Type of Catalyst	Catalytic Properties	Ref.
			vacancies, which resulted from the high surface area provided by MWCNTs • 100% conversion rate at 120°C	
NFs	Fiber diameter: 9.8 nm	PVA/chitosan	• CO adsorption on PVA/chitosan nanofibers could be related to hydrogen bond formation and dipolar interaction • CO adsorbed was 14 mmol/g at 1.4 bar pressure and 26.85°C	(Sargazi et al., 2019)
	Fiber diameter: 200 nm	Au/CeO ₂ NFs	• High Ce content dispersed on NFs suitable to fabricate excellent CeO ₂ support for Au catalyst • The high aspect ratio of NFs induced randomly packed bed with higher porosity • CO conversion rate was 85% at 75°C	(Calderón et al., 2015)
	Fiber diameter: 0.5–0.67 nm	Co/K-OMS-2 NFs	• Redox capacity of the catalyst correlated with a high surface area of K-OMS-2 NFs • CO conversion rate was 100% at 100°C	(Yang et al., 2017)
	Fiber diameter: 92, 108, 133 nm	RuO _x /CeO ₂ NFs	• The high surface area of NFs enhanced catalytic activity • Adsorption sites for CO and O ₂ increased; correlated with a hollow interior and porous exterior of CeO ₂ NFs • ~ 90% conversion rate below 150°C	(Liu et al., 2020)

2. Nanomaterials for CO Sorption

2.1 Noble metal nanoparticles

The oxidation of CO to CO₂, which is a less poisonous gas, has always drawn great attention in many scientific fields because it is the most effective method for removing CO that is used in air purification, three-way catalytic conversion in automobiles, and pollution control. For the past few decades, noble metals such as gold (Au), platinum (Pt), palladium (Pd), and ruthenium (Ru) have been widely studied and practically used in the CO catalytic oxidation process due to their remarkable properties because they resist both chemical and thermal reactions, and they can accelerate oxidation. These noble nanomaterials are tuned explicitly for converting CO to CO₂. The gas adsorption and separation can be increased by generating more active metal centers (e.g., exposed metal cations) that can functionalize the ligands by incorporating functional groups in the organic ligands to increase or tune the guest-host interaction.

Recently, nanotechnology has been studied extensively, resulting in a renewed interest in noble metal catalysts at the nanoscale. These metal NPs are promoted to enhance the oxidation process at lower (room) temperatures because of their fascinating properties as nanostructures. Noble metal NPs can increase the beneficial metal-support interactions because they can maximize the population of active centers, resulting in better cost-effectiveness and robust catalytic materials (Wang et al., 2020).

Figure 1 shows the mechanism of CO oxidation in the catalytic system. The fundamental concept

of this mechanism involves metal oxide support, which provides oxygen for the CO oxidation reaction, and noble metal NPs act as a catalyst to facilitate the binding of CO on the catalyst surface to facilitate oxidation. Noble metal NPs are Pt, Pd, Au, etc. Metal oxides, which are rich in oxygen, are commonly used in Fe_2O_3 , CeO_2 , Mn_3O_4 , Co_3O_4 , and so on.

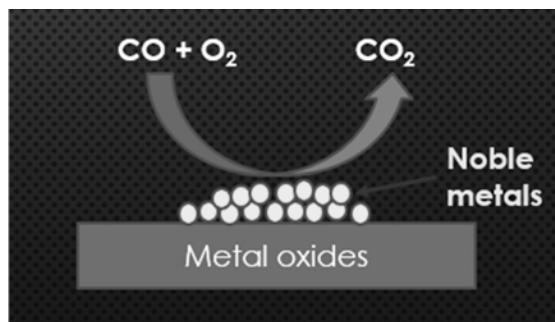


Figure 1. CO catalytic oxidation on a noble catalyst.

2.1.1 Platinum nanoparticles

Platinum is the most common noble metal used in the catalytic process in both research and commercial application. Pt has many d-orbital electrons, which facilitate its binding to other molecules so that the oxidizing reaction can be facilitated. Related to the quantum effect, the size of Pt particles has become a research interest of many scientists due to their role in catalysis in the CO oxidation process. For instance, Kim and Jhi (2011) studied the CO oxidation catalytic performance of Pt NPs on graphene support and observed that with defects on the surface of graphene, more CO was tolerated on Pt NPs than on Pt bulk material. Many recent studies have shown that modified Pt catalysts can catalyze CO oxidation at low temperatures, especially when accompanied by reducible oxides like TiO_2 , CeO_2 , or SiO_2 . For example, Kim et al. (2016) used TiO_2 as support for a mixture of the Pt metallic (PtO) and Pt valence (PtO_x) states (Pt^{2+} , Pt^{4+}) with different NP sizes, and reported that a higher Pt dispersion was associated with smaller Pt particles at room temperature when Pt/ TiO_2 catalysts were prepared and heat-treated with H_2 at different temperatures. They further discovered that at room temperature, only Pt^0 sites responded to the activation of CO better than Pt^{2+} sites; hence, higher CO oxidation activity was followed by a higher value of Pt metallic/Pt total. Liu et al. (2020) reported a strategy to activate low-temperature reactions using modified Pt-Cu- CeO_2 catalysts. They controlled the size of Pt and used oxide doping to precisely tune the interfacial reducibility and structure of the catalyst. The Cu-O-Ce interface with activated lattice oxygen accompanied by Pt subnanoclusters showed the ability of the Pt-Cu- CeO_2 catalyst to facilitate the CO oxidation at low temperatures. Furthermore, Li and his co-workers (2021) reported that not all Pt particles were active during the CO and H_2O catalytic process, only those at the perimeter of the interface of Pt NPs and SiO_2 support. Therefore, understanding NPs and their positions on the catalyst may help remove the inactive ones in order to minimize NP usage, thereby improving cost-effectiveness. This catalytic mechanism can also be implemented in many other catalytic systems (Li et al., 2021).

2.1.2 Palladium nanoparticles

As one of the metals in the platinum groups, palladium also possesses great properties for CO oxidation catalysis. In fact, Pd along with rhodium are vital components of automobile catalytic

converters. Pd NPs have also gained the attention of many researchers relative to CO oxidation catalysis. According to Liang et al. (2013), when Pd NPs were well dispersed on a triptycene-based microporous polymer, the catalytic system showed excellent CO oxidizing since the porous structure provides stability for the Pd NPs. Many studies have demonstrated the influence of NP size of Pd on the CO catalytic process (Burange et al., 2018; Christou & Efstathiou, 2007; Haneda et al., 2017; Z. Wang et al., 2010). For example, Huang et al. (2019) prepared Pd/Co₃O₄ in different sizes (2.5–10.6 nm) and observed that when different sizes of Pd NPs were dispersed on the Co₃O₄ support, smaller Pd NPs correlated with the increase in CO oxidation catalytic activity. However, particle size is not the only factor that affects the CO oxidation process. Zhai et al. (2018), in their study of the CO oxidation on Pd with TiO₂ nanosheet support, showed that higher catalytic activity and better thermal stability of Pd/TiO₂ resulted from the electronic interaction between TiO₂ spheres and Pd NPs. Pd NPs could also form nanoholes on the graphene sheet, which improved the CO oxidation as well as hydrogen storage because it increased the rate of Pd NP interdiffusion (Kumar et al., 2015). Singhania and Gupta (2018) reported that the dispersion of bimetallic Pd-M particles (M = Cu, Ni, and Co) with an average size of around 3–5 nm could contribute to excellent catalytic activity at low temperatures for CO oxidation; among all of them, the Pd/Cu-AC catalyst had the best conversion rate of 50% at 30°C. However, one of the challenges of Pd NPs used in catalysis is the rapid agglomeration of those particles; thus, to improve the stability of Pd NPs in catalysis, more studies need to be conducted, which requires considerable effort, time, and money (Zhai et al., 2018).

2.1.3 Gold nanoparticles

Being seen as far less catalytic compared to platinum and platinum metal groups, gold nanoparticles appear to have a remarkable effect on the CO oxidation reaction catalysis. This phenomenon was studied by Haruta (1997) and Haruta et al. (1987) who reported that Au NPs, around 5 nm in size, were able to oxidize CO below 0°C. This fascinating property of Au NPs then captured tremendous attention from catalytic science. For instance, Valden et al. (1998) prepared Au NPs of different sizes from 1 to 6 nm and investigated the relationship between the thickness of Au particles deposited on TiO₂ and the catalysis of CO oxidation. The highest turnover frequency (TOF) of catalytic activity was approximately 0.25 s⁻¹ per site for bilayers of Au NPs with diameters of 2–3 nm. Du et al. (2014) also studied the influence of Au NPs sizes on CO oxidation using an Au-TiO₂ catalyst. They prepared a set of 2.9, 3.8, and 5.1 nm Au NPs to deposit on TiO₂ support, calcined Au-TiO₂, and observed that different sizes of Au particles resulted in other boundaries between Au NPs with TiO₂ support. This boundary was referred to as the interface perimeter, and the greater the interface perimeter, the more catalytic activity took place. According to the analysis, the optimum size yielding the greatest interface perimeter was 3.8 ± 0.6 nm, where the conversion rate reached 80% at 60°C reaction temperature. Furthermore, Yoshida et al. (2018) mounted Au NPs with a diameter of around 2 nm on a polyoxometalate (POM) support to fabricate polyoxometalate-supported gold nanoparticulate catalysts. They observed stable catalysis of Au/POM with a 100% CO conversion rate over a wide range of temperatures (-40 °C to 60°C). The modified catalyst also showed no degradation over 35 days at 0°C.

2.2 Carbon nanotubes

Carbon nanotubes are interesting nanomaterials. Because of their nanosize (diameter varies from 0.4 to 40 nm), CNTs possess unusual mechanical strength and thermal and electrical conductivity; however, their properties of low thermal expansion coefficient, as well as high porosity and surface area, allow CNTs to have the ability to attach molecules to their walls. In fact, CNTs have already been studied and practically used in some catalytic processes since the large surface area of CNT can lead to higher deposition of metal NPs and enhance the catalytic cycle. For instance, Wang (2016) dispersed Ag NPs on

the surface of CNTs, resulting in a higher interface between the Ag particles and CNTs. This protected Ag NPs from agglomeration, thus providing more adsorption sites for CO oxidation. Guo et al. (2016) impregnated copper (Cu) and manganese (Mn) on multi-wall carbon nanotubes (MWCNTs) to facilitate the CO oxidation catalytic process by enhancing the synergistic interaction of bimetallic Cu/Mn and properties of MWCNTs. MWCNTs can be employed as support for the CuO-CeO₂ catalyst for preferential CO oxidation. According to Gao et al. (2015), the interaction between CuO and CeO₂ was strengthened due to their high dispersion on MWCNTs, and the catalytic activity of CuO-CeO₂/MWCNTs catalyst became pronounced compared to other supporting materials. Shi et al. (2018) also reported that CuO and CeO₂ dispersed uniformly on the surface of MWCNTs, which enhanced the catalytic performance by providing more lattice oxygen and oxygen vacancies on the surface. Nevertheless, CNT usage in catalytic science is still a challenge because when combined with other molecules, a covalent bond (strong bond) is formed, and that can change the structure of the CNT. The main issue left for researchers to resolve for further improvement of CO oxidation using CNTs as support in the catalyst is developing a method that respects the initial structure of CNTs and forms a covalent bond between the CNTs and other gas molecules.

2.3 Nanofibers

Electrospun nanofibers are versatile materials, and have numerous practical applications, including filtration, tissue engineering, drug delivery, biosensor, fuel cell, and solar cell, due to their extraordinary properties, which are high surface area, high porosity, low weight-to-volume ratio, especially flexibility, and, in some NF-modification cases, great mechanical strength (Uddin et al., 2021). Some of the properties of electrospun NFs can be utilized to serve a role in the mechanism of CO reduction. Sargazi et al. (2019) developed polyvinyl alcohol (PVA)/chitosan electrospun nanofibrous membrane to adsorb CO, and according to their testing model, the capacity of adsorption of this material was reported to be higher than activated carbon, zeolite, and even a metal-organic framework. Another interesting application is that electrospun nanofibers can be used as a support for the catalyst to facilitate CO oxidation since nanofibers can provide a large surface area and have high porosity.

Calderón et al. (2015) reportedly used carbon nanofibers (CNFs) as support for Pt-Ru. They observed that introducing Ru to Pt-based CNFs enhances the CO oxidation activity at 20–70°C, since there are more particles deposited on the surface of CNFs, and some oxygenated groups from CNFs are responsible for promoting CO oxidation. Eid et al. (2019) also implemented one-dimensional carbon nitrile-based nanofibers (1D gC3N-4) as support for the Au-Pd catalyst. As described, 1D gC3N-4 had unique physicochemical properties that could be synergic with the outstanding catalytic merits of Au-Pd thus creating a superior catalytic mechanism for CO oxidation. Yang et al. (2017) developed a system called cobalt-doped K-OMS-2 nanofibers in which cobalt was doped with manganese octahedral molecular sieves, which changed the K-OMS-2 structure from nanorods to nanofibers; then the framework was reported to complete the CO oxidation process at 100°C in the presence of moisture. Z. Liu et al. (2020) reported fabricating CeO₂ NFs by electrospinning, then loading RuO_x on the modified NFs to create RuO_x-CeO₂ NF catalysts. The new catalyst had good thermal stability and excellent CO conversion at low temperatures (~90% below 150°C) due to the high surface area provided by the NFs. With their extraordinary properties, NFs have become great implementations for catalysis, in the past decades, as catalytic support with uniform dispersion and stability on a large surface.

Moreover, the cost aspect and scale-up of the catalyst with NF support might become less complicated when using the electrospinning method because of the ability to disperse NPs uniformly. Nonetheless, there are still drawbacks to using NFs as support since their high-temperature resistance is not advanced compared to other metallic or CNT support (E. Asmatulu et al., 2022). More attention and studies are needed to utilize these nanomaterials in the CO catalytic reduction process successfully.

The disposal of nanomaterials generally follows the same pathways as conventional waste. Before

ending up in a landfill or incineration, nanoparticles can be thermally/chemically/physically/biochemically processed to reduce possible adverse effects on human health and the environment. Or discharged nanoparticles can be recycled through some processes (magnetic, flotation, electrostatic, chemical leaching, etc.).

Nanotechnology is a growing and emerging field. However, because it is new, protocols for safe handling and disposal are incomplete and will need more research funding, and studies to develop proper protocols for nanoparticle recycling (Khan et al., 2022).

3. Conclusion

In brief, some nanomaterials such as Au, Pt, Pd, or their combination in the form of nanoparticles, carbon nanotubes, nanofibers, or the matrices of these possess great properties to enhance the CO catalytic oxidation reaction, which is part of the CO-reduction mission in environmental and health improvement. Nanomaterials have several advantages over bulk materials because when materials are scaled down to nanometers, they own unique properties. Not all catalyst sites are active; therefore, it is necessary to minimize the materials and maximize catalytic activation, and nanomaterials can potentially solve this problem. In addition, NPs, CNTs, and NFs have a relatively higher surface area than bulk materials with the same volume, which can promote better CO adsorption and oxidation catalysis. The research exploration of nanomaterials for CO reduction, compared to that of other materials, is still in the burgeoning stage; therefore, researchers see nanomaterials as great opportunities for further studies in this field of application. Nonetheless, nanomaterials and technologies for CO catalytic oxidation have many challenges in terms of cost, stability of materials, and oxidation rate of CO on those materials. This will require the effort and dedication of researchers as well as investment in this field.

References

- Abedin, F., Asmatulu, E., & Andalib, M. N. (2021). Nanomaterials and human health: An overview. In *Nanotoxicology and Nanoecotoxicology Vol. 2*, 165–180. Springer.
- Asmatulu, E., Andalib, M. N., Subeshan, B., & Abedin, F. (2022). Impact of nanomaterials on human health: A review. *Environmental Chemistry Letters*, 1–21.
- Asmatulu, R., & Khan, W. S. (2018). *Synthesis and Applications of Electrospun Nanofibers*. Elsevier.
- Burange, A. S., Reddy, K. P., Gopinath, C. S., Shukla, R., & Tyagi, A. K. (2018). Role of palladium crystallite size on CO oxidation over CeZrO_{4-δ} supported Pd catalysts. *Molecular Catalysis*, 455, 1–5.
- Calderón, J. C., García, G., Querejeta, A., Alcaide, F., Calvillo, L., Lázaro, M. J., Rodríguez, J. L., & Pastor, E. (2015). Carbon monoxide and methanol oxidations on carbon nanofibers supported Pt–Ru electrodes at different temperatures. *Electrochimica Acta*, 186, 359–368.
- Centers for Disease Control and Prevention. (2019, January 25). Picture of America: Poisoning. https://www.cdc.gov/pictureofamerica/pdfs/Picture_of_America_Poisoning.pdf
- Christou, S. Y., & Efstathiou, A. M. (2007). Effects of Pd particle size on the rates of oxygen back-spillover and CO oxidation under dynamic oxygen storage and release measurements over Pd/CeO₂ catalysts. *Topics in Catalysis*, 42(1), 351–355.

- Du, M., Sun, D., Yang, H., Huang, J., Jing, X., Odoom-Wubah, T., Wang, H., Jia, L., & Li, Q. (2014). Influence of Au particle size on Au/TiO₂ catalysts for CO oxidation. *The Journal of Physical Chemistry C*, *118*(33), 19150–19157.
- Eid, K., Sliem, M. H., Eldesoky, A. S., Al-Kandari, H., & Abdullah, A. M. (2019). Rational synthesis of one-dimensional carbon nitride-based nanofibers atomically doped with Au/Pd for efficient carbon monoxide oxidation. *International Journal of Hydrogen Energy*, *44*(33), 17943–17953.
- Gao, Y., Xie, K., Wang, W., Mi, S., Liu, N., Pan, G., & Huang, W. (2015). Structural features and catalytic performance in CO preferential oxidation of CuO–CeO₂ supported on multi-walled carbon nanotubes. *Catalysis Science & Technology*, *5*(3), 1568–1579.
- Goldstein, M. (2008). Carbon monoxide poisoning. *Journal of Emergency Nursing*, *34*(6), 538–542.
- Guo, Y., Lin, J., Li, C., Lu, S., & Zhao, C. (2016). Copper manganese oxides supported on multi-walled carbon nanotubes as an efficient catalyst for low temperature CO oxidation. *Catalysis Letters*, *146*(11), 2364–2375.
- Haneda, M., Todo, M., Nakamura, Y., & Hattori, M. (2017). Effect of Pd dispersion on the catalytic activity of Pd/Al₂O₃ for C₃H₆ and CO oxidation. *Catalysis Today*, *281*, 447–453.
- Haruta, M. (1997). Size- and support-dependency in the catalysis of gold. *Catalysis Today*, *36*(1), 153–166. [https://doi.org/10.1016/S0920-5861\(96\)00208-8](https://doi.org/10.1016/S0920-5861(96)00208-8)
- Haruta, M., Kobayashi, T., Sano, H., & Yamada, N. (1987). Novel gold catalysts for the oxidation of carbon monoxide at a temperature far below 0°C. *Chemistry Letters*, *16*(2), 405–408. <https://doi.org/10.1246/cl.1987.405>
- Huang, R., Kim, K., Kim, H. J., Jang, M. G., & Han, J. W. (2019). Size-controlled Pd nanoparticles loaded on Co₃O₄ nanoparticles by calcination for enhanced CO oxidation. *ACS Applied Nano Materials*, *3*(1), 486–495.
- Hughes, S., & Asmatulu, E. (2021). Nanotoxicity and nanoecotoxicity: Introduction, principles, and concepts. In *Nanotoxicology and Nanoecotoxicology Vol. 1*, 1–19. Springer.
- Khan, W.S., Asmatulu, E., Uddin, M.N. and Asmatulu, R. (2022). Recycling and Reusing of Engineering Materials: Recycling for Sustainable Developments. Paperback ISBN: 9780128224618
- Kim, G. J., Kwon, D. W., & Hong, S. C. (2016). Effect of Pt particle size and valence state on the performance of Pt/TiO₂ catalysts for CO oxidation at room temperature. *The Journal of Physical Chemistry C*, *120*(32), 17996–18004.
- Kim, G., & Jhi, S.-H. (2011). Carbon monoxide-tolerant platinum nanoparticle catalysts on defect-engineered graphene. *ACS Nano*, *5*(2), 805–810.
- Kumar, R., Oh, J.-H., Kim, H.-J., Jung, J.-H., Jung, C.-H., Hong, W. G., Kim, H.-J., Park, J.-Y., & Oh, I.-K. (2015). Nanohole-structured and palladium-embedded 3D porous graphene for ultrahigh hydrogen storage and CO oxidation multifunctionalities. *ACS Nano*, *9*(7), 7343–7351.

- Li, Y., Kottwitz, M., Vincent, J. L., Enright, M. J., Liu, Z., Zhang, L., Huang, J., Senanayake, S. D., Yang, W.-C. D., & Crozier, P. A. (2021). Dynamic structure of active sites in ceria-supported Pt catalysts for the water gas shift reaction. *Nature Communications*, *12*(1), 1–9.
- Liang, Q., Liu, J., Wei, Y., Zhao, Z., & MacLachlan, M. J. (2013). Palladium nanoparticles supported on a triptycene-based microporous polymer: Highly active catalysts for CO oxidation. *Chemical Communications*, *49*(79), 8928–8930.
- Liu, X., Jia, S., Yang, M., Tang, Y., Wen, Y., Chu, S., Wang, J., Shan, B., & Chen, R. (2020). Activation of subnanometric Pt on Cu-modified CeO₂ via redox-coupled atomic layer deposition for CO oxidation. *Nature Communications*, *11*(1), 4240. <https://doi.org/10.1038/s41467-020-18076-6>
- Liu, Z., Lu, Y., Confer, M. P., Cui, H., Li, J., Li, Y., Wang, Y., Street, S. C., Wujcik, E. K., & Wang, R. (2020). Thermally Stable RuO_x-CeO₂ Nanofiber Catalysts for Low-Temperature CO Oxidation. *ACS Applied Nano Materials*, *3*(8), 8403–8413.
- Sargazi, G., Afzali, D., Mostafavi, A., Shadman, A., Rezaee, B., Zarrintaj, P., Saeb, M. R., Ramakrishna, S., & Mozafari, M. (2019). Chitosan/polyvinyl alcohol nanofibrous membranes: Towards green super-adsorbents for toxic gases. *Heliyon*, *5*(4), e01527.
- Sengul, A. B., & Asmatulu, E. (2020). Toxicity of metal and metal oxide nanoparticles: A review. *Environmental Chemistry Letters*, *18*(5), 1659–1683.
- Shi, L., Zhang, G., & Wang, Y. (2018). Tailoring catalytic performance of carbon nanotubes confined CuO/CeO₂ catalysts for CO preferential oxidation. *International Journal of Hydrogen Energy*, *43*(39), 18211–18219.
- Singhania, A., & Gupta, S. M. (2018). Low-temperature CO oxidation: Effect of the second metal on activated carbon supported Pd catalysts. *Catalysis Letters*, *148*(3), 946–952.
- Uddin, M. N., Desai, F. J., Subeshan, B., Rahman, M. M., & Asmatulu, E. (2021). Sustainable atmospheric fog water generator through superhydrophobic electrospun nanocomposite fibers of recycled expanded polystyrene foams. *Surfaces and Interfaces*, *25*, 101169.
- Valden, M., Lai, X., & Goodman, D. W. (1998). Onset of catalytic activity of gold clusters on titania with the appearance of nonmetallic properties. *Science*, *281*(5383), 1647–1650.
- Wang, F. (2016). Effect of support carbon materials on Ag catalysts used for CO oxidation in the presence and absence of H₂. *Journal of Environmental Chemical Engineering*, *4*(4), 4258–4262.
- Wang, Z., Li, B., Chen, M., Weng, W., & Wan, H. (2010). Size and support effects for CO oxidation on supported Pd catalysts. *Science China Chemistry*, *53*(9), 2047–2056.
- Wang, G., Lu, K., Yin, C., Meng, F., Zhang, Q., Yan, X., Bing, L., Wang, F., & Han, D. (2020). One-Step Fabrication of PtSn/ γ -Al₂O₃ Catalysts with La Post-Modification for Propane Dehydrogenation. *Catalysts*, *10*(9), 1042.

- Yang, J., Zhou, H., Wang, L., Zhang, Y., Chen, C., Hu, H., Li, G., Zhang, Y., Ma, Y., & Zhang, J. (2017). Cobalt-Doped K-OMS-2 Nanofibers: A Novel and Efficient Water-Tolerant Catalyst for the Oxidation of Carbon Monoxide. *ChemCatChem*, *9*(7), 1163–1167.
- Yoshida, T., Murayama, T., Sakaguchi, N., Okumura, M., Ishida, T., & Haruta, M. (2018). Carbon Monoxide Oxidation by Polyoxometalate-Supported Gold Nanoparticulate Catalysts: Activity, Stability, and Temperature- Dependent Activation Properties. *Angewandte Chemie*, *130*(6), 1539–1543. <https://doi.org/10.1002/ange.201710424>
- Zhai, X., Liu, C., Chang, Q., Zhao, C., Tan, R., Peng, H., Liu, D., Zhang, P., & Gui, J. (2018). TiO₂-nanosheet-assembled microspheres as Pd-catalyst support for highly-stable low-temperature CO oxidation. *New Journal of Chemistry*, *42*(22), 18066–18076.