

# We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

186,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index  
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?  
Contact [book.department@intechopen.com](mailto:book.department@intechopen.com)

Numbers displayed above are based on latest data collected.  
For more information visit [www.intechopen.com](http://www.intechopen.com)



# Platinum Group Metal Based Nanocatalysts for Environmental Decontamination

*Sarre M.K. Nzaba, Bhekie B. Mamba and Alex T. Kuvarega*

## Abstract

Research and development in chemical engineering is currently focused on design of highly active and selective catalytic systems for process intensification. In recent years, there has been growing interest in the use of catalysts based on nanosized metal particles to improve catalytic processes. Among the many metal catalysts, platinum group metals (PGMs) have received greater attention because of their physical and catalytic properties. They have found applications in a wide range of chemical conversion and environmental decontamination reactions due to their chemical stability and enhanced catalytic reactivity in the nano range. This chapter reviews some of the major innovative applications of PGM nanocatalysts for catalytic environmental decontamination.

**Keywords:** nanocatalyst, decontamination, platinum group metal, organic transformation, water treatment

## 1. Introduction

Industrialization and rapid population growth has resulted in energy shortages and environmental contamination which has raised concern of a potential global crisis. For sustainable human society development, technologies for environmental decontamination need urgent attention. Among numerous available technologies, catalysis has gained considerable attention because of the diverse potentials in energy and environmental applications. Generally, catalysts for environmental applications are based on less expensive materials that will not cause secondary environmental pollution [1]. The major advantage of environmental catalysis is the chemical conversion of pollutants into non-hazardous and less toxic products. Pollutants can be degraded and transformed efficiently through homogenous or heterogeneous oxidation and reduction processes under ambient conditions or conditions in which external energy such as light may be required [2]. Therefore, the present book chapter aims to provide analysis in the use of PGMs nanocatalysts in the recent development and appraise their potential applications in environmental decontamination.

### 1.1 Nanotechnology and the environment

Nanotechnology refers to the research and development of materials at the atomic, molecular or macromolecular scale. Materials at nanoscale find applications in a myriad of areas, such as magnetic and optoelectronic, biomedical, pharmaceutical, cosmetic, energy, electronic, catalytic, and environmental domains. Because of the

potential of nanotechnology, there has been a worldwide increase in investment in nanotechnology research and development [3]. The unique properties of materials and their stupendous performance at nanoscale are the main reason for the increased growth in this area. Controlled assembly of nanoparticles has been proposed as one of the most ways to achieve the target technologies [4]. Nanotechnology has immense potential in environmental decontamination through the use of materials such as adsorbents and nanocatalysts. Therefore, it is necessary to develop novel processes for the fabrication of nanomaterials that can be used as the basis for the development of highly efficient new technologies for solving environment challenges.

## 1.2 Platinum group metals

Platinum group metals (PGMs) including iridium (Ir), osmium (Os), platinum (Pt), palladium (Pd), rhodium (Rh) and ruthenium (Ru) have high resistance to corrosion and oxidation in moist air, unlike most base metals [5]. Their precious nature derives from their rarity in Earth's crust. It has been reported by Grabowska et al., that PGMs such as platinum and palladium allow the extension of light absorption of semiconductors such as  $\text{TiO}_2$  into the visible region [6].

Recently, Dozzi et al. has investigated the catalytic effect of PGMs metal for the degradation of formic acid using Pt, Au doped  $\text{TiO}_2$  [7]. On the other hand, Kisch et al. modified  $\text{TiO}_2$  with chloride complexes of Pt for the photocatalytic degradation of 4-chlorophenol [8]. The presence of PGMs nanocatalysts gave rise to an enhanced charge carrier separation hence improving the photocatalytic performances of the modified photocatalyst systems. According to Yoon et al., the surface of PGMs serves as visible light absorbing sensitizers and centers of charge separation [9]. The possibility of designing and applying nanosized PGM catalysts has been demonstrated in a number of studies [9–12]. This has resulted in interest in considering their application in environmental remediation, water treatment, chemical transformation and microbial disinfection. A priority task of present day science is to solve the problem of environmental contamination of planetary resources which requires development of efficient technologies employing nanocatalysts. PGMs catalysts have already found applications in a number of industrially important R&D niche areas, including environmental cleanup. The effectiveness of the PGM nanocatalysts depends on a number of factors, including their size, morphology of the particles and their packaging into usable devices and systems. In most of these applications, the cost of PGMs cannot be ignored. Platinum has been reported to be a very good catalyst but a trade-off has to be established between efficacy and cost. In the nano-range the amount of the catalyst is usually kept very low while huge improvements in efficiency are realized. However, there is still need for more effort in design of viable systems for environmental decontamination using PGM based nanocatalysts. Potential up-scaling of these devices and systems is currently an area of increasing research interest.

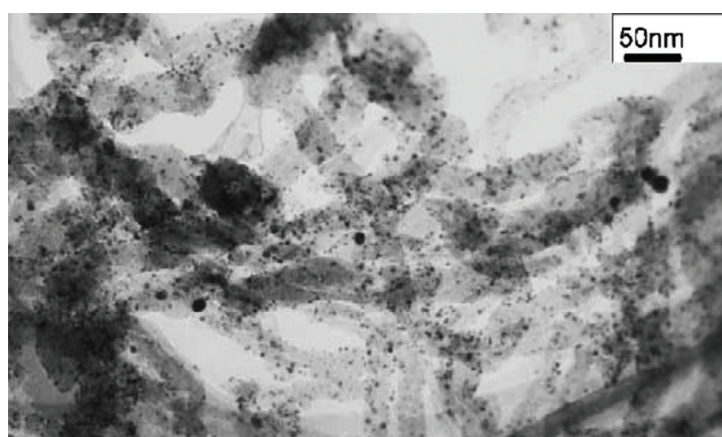
## 2. Synthesis of PGM nanocatalysts

Designing a new class of highly selective and active catalytic systems with the use of recent developments in chemistry has become one of the main concerns faced in contemporary engineering. As compared to bulk material, nanoparticles have an increased surface area and high dispersity and, thus provide high reactivity and allow fabrication of efficient catalysts with lower noble metal loading. Controlling the growth, size, and monodispersity of metal nanoparticles is a subject of interest in designing of nanosized catalytic systems. Therefore, different methods have been used for the synthesis of nanocatalysts. For instance, in 2005, Wong et al., successfully

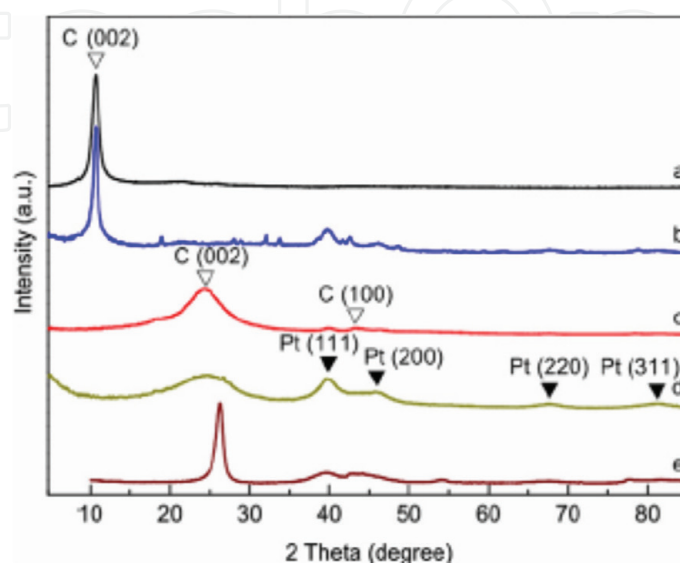
synthesized a bimetallic catalyst using Pd-on-Au NPs through the Turkevich–Frens (citrate reduction) method and obtained particles with an average diameter of about 20 nm [10]. Paula and co-workers synthesized Pd/C-catalyst using one-pot method for synthesis of secondary amines by hydrogenation of nitrocompounds as single starting materials [11]. Additionally, Coleman et al. synthesized and Pt/TiO<sub>2</sub> catalyst by the photodeposition method in the presence of a sacrificial organic hole scavenger [12]. Barakat et al., synthesized Pt doped TiO<sub>2</sub> catalyst by immobilizing colloidal Pt nanoparticles onto titanium dioxide (rutile) [13]. Kuvarega et al., used a modified sol gel method for the synthesis of nitrogen, PGM co doped TiO<sub>2</sub>. In these studies spherical particles of average size between 2 and 5 nm were reported [14].

### 3. Characterization of PGMs based nanocatalysts

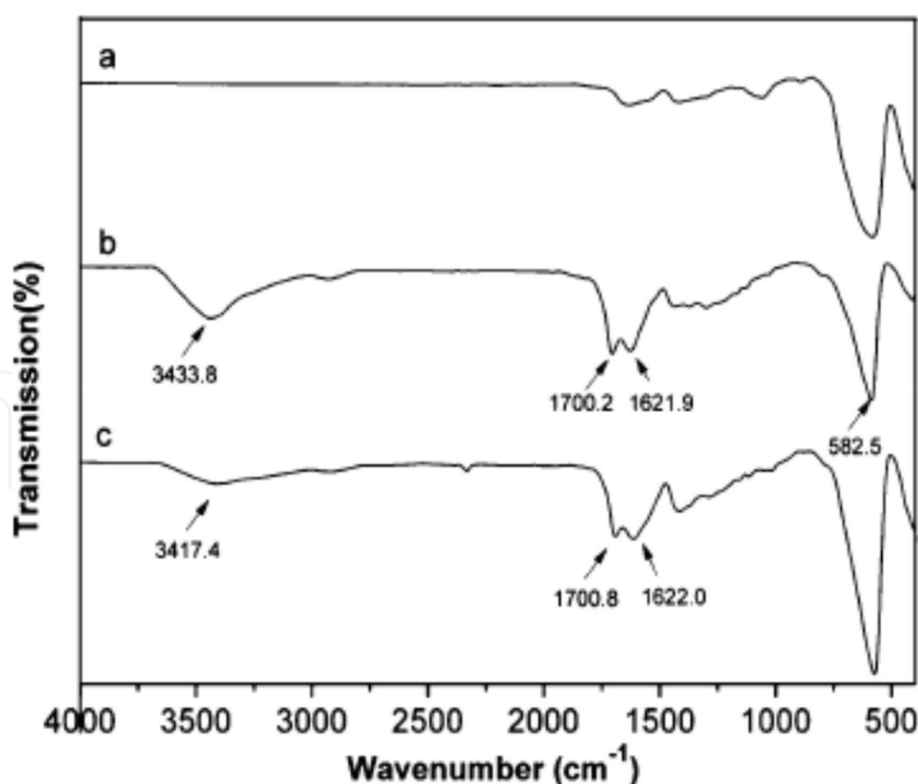
Many different physico-chemical techniques are used to characterize nanocatalysts among them scanning electron microscopy (SEM) used for the morphology of the materials. Transmission electron microscopy (TEM) is also used for particles size and morphology. Chun-Hua et al. used TEM to analyze 3% Pt nanoparticles supported on CNT particles is shown in **Figure 1**. In another study, Pt catalyst containing 3% metal



**Figure 1.**  
TEM image of 3% Pt/CNT particles (Copyright, J. Mol. Catal. A: Chem., Ref. [17]).



**Figure 2.**  
XRD patterns of (a) GO, (b) Pt/RGO-HH, (c) Pt/RGO-EG, (d) Pt/AC-EG and (e) Pt/MWCNT-EG. (Copyright Carbon 50 (2012) 586-596, Ref [18]).



**Figure 3.** FT-IR spectra of (a) the  $\text{Fe}_3\text{O}_4$  microspheres, (b) the  $\text{Fe}_3\text{O}_4@\text{C}$  composite, (c) the  $\text{Fe}_3\text{O}_4@\text{C}@\text{Pt}$  catalyst (reproduced with permission from the Royal Society of Chemistry).

supported on activated carbon (AC) was prepared and the particle size varied from 8 to 10 nm [15]. In addition, techniques such as X-Ray Photoelectron Spectroscopy (XPS) have been used to give information on the oxidation states of the PGM and the nature of bonding between the metals and the supports.

Raman spectroscopy (RS) and X-ray diffraction (XRD) are conducted to identify the crystalline phases and estimate particle sizes of nanocatalysts. For instance, Renfeng et al. used XRD to identify the Pt in Pt/RGO [16]. The Pt peak was conspicuous in the samples containing Pt (**Figure 2**).

Xie and co-workers used Fourier Transform infrared spectroscopy (FTIR) to verify the bond vibrations related to functionalities on the surfaces of their synthesized materials (**Figure 3**) [17].

## 4. Application of PGMs based nanocatalysts

### 4.1 Environmental decontamination

PGMs nanocatalysts have become a new class of environmental remediation materials that could provide affordable solutions to some of the environmental challenges. At nanoscale, PGMs particles have high surface areas and surface reactivity. As such, they provide more flexibility for in situ applications. PGMs nanocatalysts have proven to be an excellent choice for the transformation and decontamination of a wide variety of common environmental contaminants, such as organochlorine pesticides and chlorinated organic compounds. The major consumer of PGMs is the automobile industry. PGMs such as Pt, Rh and Pd are used as catalysts in the automobile industry in order to reduce the level of unburnt hydrocarbons, carbon monoxide (CO) and nitrogen oxide present in the exhaust gases. Generally, a typical automobile converter contains 0.04% Pd, 0.005–0.007%



and 0.08% Pt and Rh supported on a base [18]. Iridium has become the new entrant in this application area. A typical example is the introduction of iridium-containing catalytic converters in their direct injection engines by Mitsubishi of Japan [19].

A typical example is the reduction of nitrogen oxides to nitrogen used in car exhaust systems for abatement of emissions from petrol/rich-burn engines. There is a huge number of reports on use of Rhodium as it is the most effective element in the conversion of nitrous oxides to nitrogen [20, 21].

Jianbing et al., in their study, investigated the catalytic ozonation of dimethyl phthalate (DMP) in aqueous solution and DBP precursors in natural water using Ru/AC. These two kinds of organics are both recalcitrant to biodegradation and will cause severe hazards to human health.

Ru/AC was an active nanocatalysts in the catalytic ozonation of dimethyl phthalate and had the ability to complete mineralize the DMP in a semi-batch experiment. On the other hand, the total organic carbon (TOC) removals were stable around 75% for a duration of 42 h and no trace of Ru was observed from the reactor in the continuous experiments of Ru/AC catalyzed ozonation of DMP. Consequently, Ru/AC catalyzed ozonation was found to be more efficient than ozonation alone for TOC removals in the natural water treatment [22].

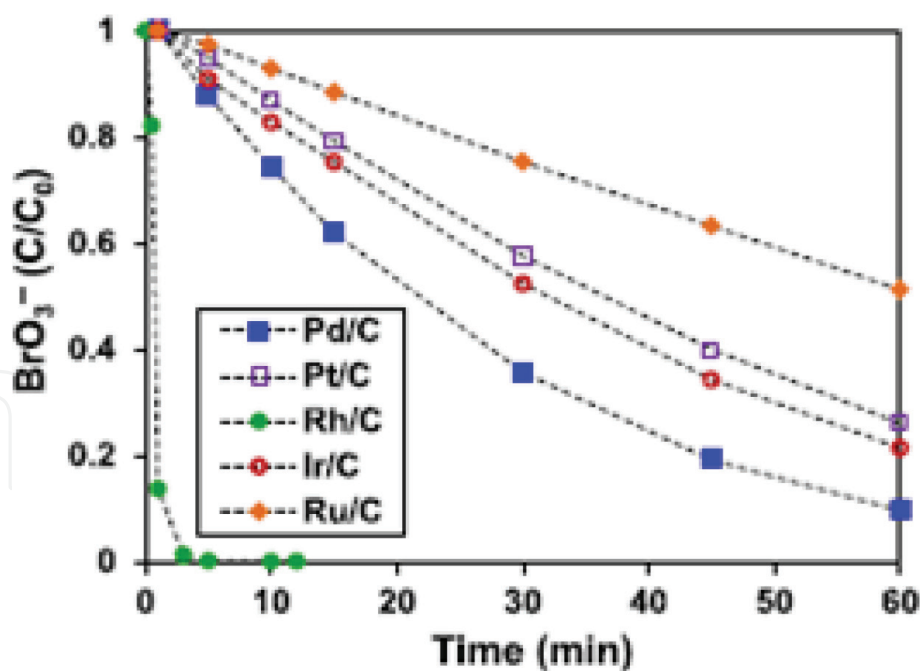
## 4.2 Water treatment

Oxyanions, such as  $\text{BrO}_3^-$ ,  $\text{ClO}_3^-$ ,  $\text{NO}_3^-$  and  $\text{ClO}_4^-$  are toxic and they are pervasive in drinking water. These oxyanions originate from both anthropogenic and natural sources. Furthermore, they are also produced during water treatment processes such as ozonation, desalination, electrochemical treatment and chlorination [23–26]. These ions have mutagenic, endocrine disrupting and carcinogenic effects [27, 28]. Ion exchange and reverse osmosis cannot completely degrade these oxyanions [28, 29]. Thus, it would be preferable to apply destructive treatment technologies based on nanocatalysts for sustainable drinking water treatment processes [30]. Pd-based heterogeneous catalysis has garnered momentous attention as a potential solution for reduction of these oxyanions and for other highly oxidized contaminants such as halogenated and nitro organics [31]. Chen et al., have used PGMs for the reduction of  $\text{BrO}_3^-$  [32]. Five activated carbon supported on metal namely (with a 5 wt % Pd, Pt, Rh, Ru and 1 wt% for Ir) with a M/C of 0.1 g L catalysts loading were used for the catalytic reduction of bromated ( $\text{BrO}_3^-$ ) **Figure 4**. From **Figure 4**, it is noticeable that Rh/C was significantly more active than the other PGMs/C catalysts used for the reduction of  $\text{BrO}_3^-$ .

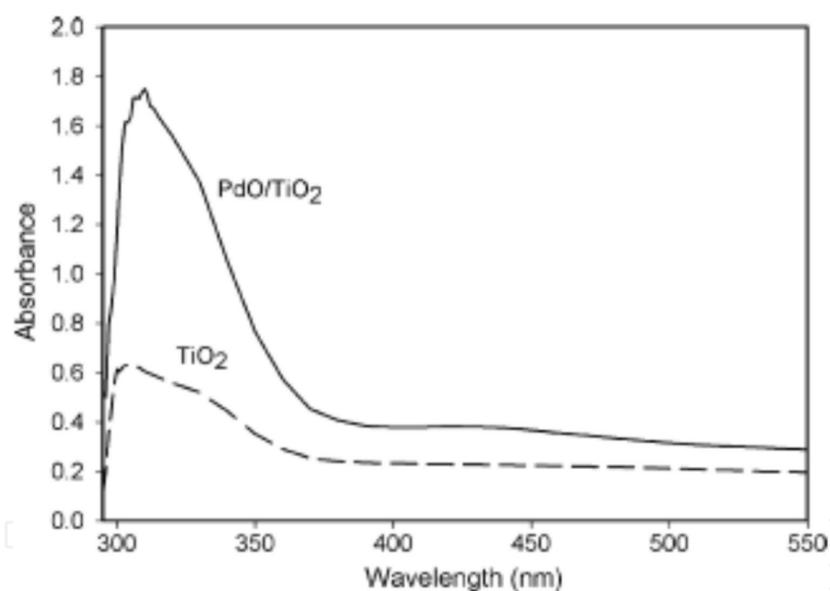
When catalyst loading  $0.1 \text{ g L}^{-1}$  was used, a reduction of 1 mM  $\text{BrO}_3^-$  was achieved in approximately 5 minutes. Rh/C had a much higher activity than most supported metal catalyst reported in literature when compared with metal mass- normalized basis. While each metal catalyst dispersion differs, it was vital to compare the activity of metals hydrogenation using the initial turnover frequency values ( $\text{TOF}_0$ ) [33–35]. Additionally, Rh/C had the best performance compared to the other four catalysts at pH 7.2. On the other hand, Ir/C had a slightly lower apparent reactivity with  $\text{BrO}_3^-$  than that of Pd/C but was the second highest performance. Therefore, the incorporation of the two PGMs catalysts namely Rh and Ir led to the highest activity for the catalytic reduction of  $\text{BrO}_3^-$  under condition that are suitable for the water treatment systems.

## 4.3 Antimicrobial

Microbial contamination and growth on the surfaces are risks to human health. The chemicals used to tackle microbes such as detergents, alcohols and chlorine are very aggressive and hence not environmentally friendly besides being



**Figure 4.** Kinetics of  $1 \text{ mM BrO}_3^-$  by  $0.1 \text{ g L}^{-1} \text{ M/C}$  catalyst at  $1 \text{ atm H}_2$ ,  $\text{pH } 7.2$  and  $22^\circ \text{C}$  (with  $5 \text{ wt\%}$  metal for Pd, Rh, Ru, and Pt;  $1 \text{ wt\%}$  metal for Ir). (Copyright Chemical Engineering Journal, 313, 2017, 745-752, Ref. [28]).



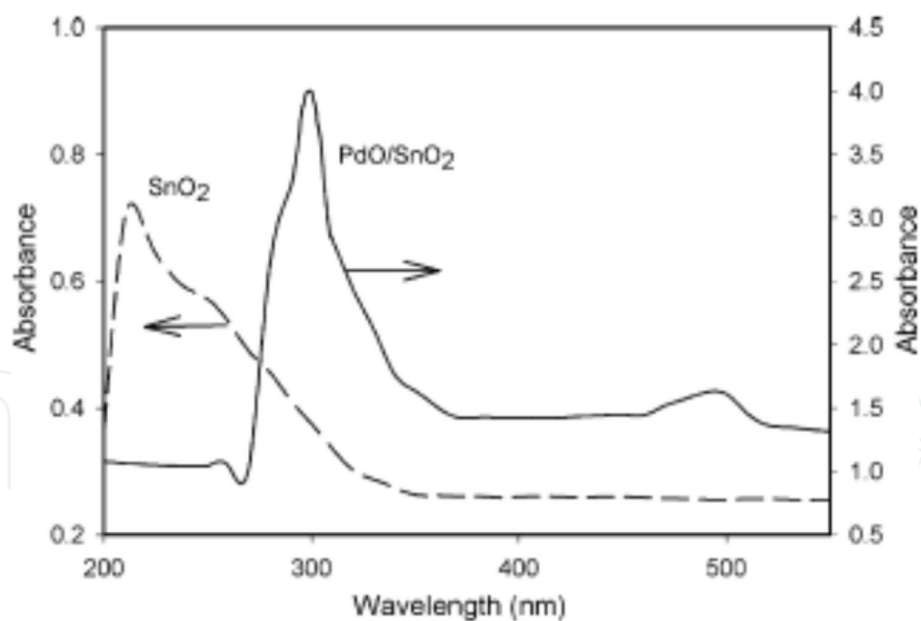
**Figure 5.** UV-vis spectra of bare  $\text{TiO}_2$  and  $\text{PdO/TiO}_2$  samples. (Copyright, Chemistry 184 (2006) [34]).

ineffective for long-term disinfection. Therefore, a myriad of studies are being conducted in order to tackle these challenges. Arcan et al. doped  $\text{SnO}_2$  and  $\text{TiO}_2$  with Pd for microbial inactivation of *E. coli*, *S. aureus* and *S. cerevisiae* [36].

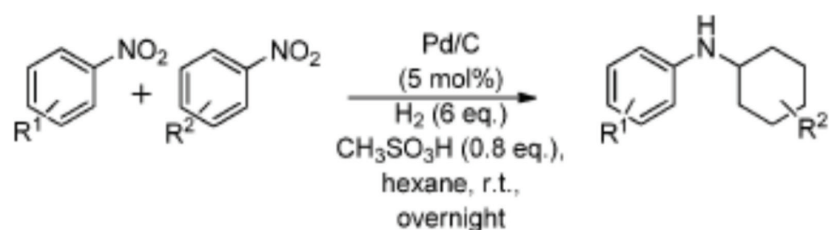
The addition of Pd led to an enhancement in the photocatalytic efficiency observed for the degradation of microorganisms when 1% of Pd was used. In addition, the UV-Vis showed an extension of the absorption edge into the visible range without affecting the phase of the catalysts (**Figures 5 and 6**).

#### 4.4 Chemical transformation

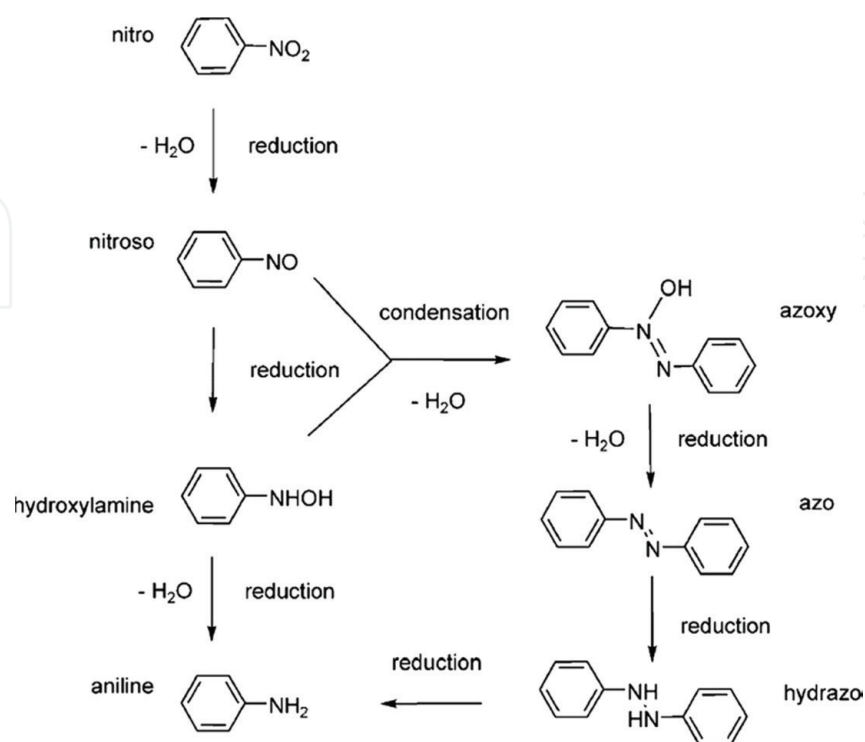
PGM nanoparticles have proven to be efficient heterogeneous and homogeneous catalysts with advantages such as a high specific surface area due to their small



**Figure 6.**  
 UV-vis spectra of bare  $\text{SnO}_2$  and  $\text{PdO/SnO}_2$  samples. (Copyrights Chemistry 184 (2006) Ref. [34]).

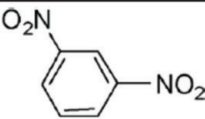
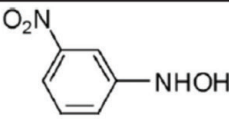
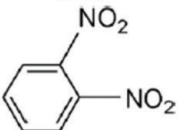
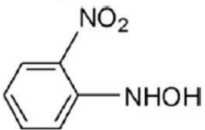

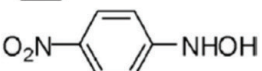
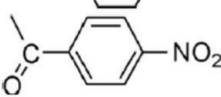
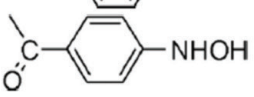
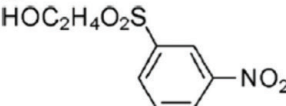
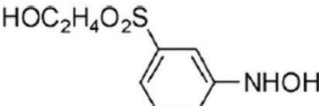


**Figure 7.**  
 Pd/C-catalyzed one-pot synthesis of secondary amines by hydrogenation of nitrocompounds. (Copyright Chem. Commun., 2013, 49, 8160, Ref [10]).



**Figure 8.**  
 Proposed mechanism for the hydrogenation of nitroarenes. (Copyright ChemCatChem, 2009, 1, 210–221, Ref. [38]).



Entry	Substrate	Product	t/min	Conv./%	Sel./%
1 <sup>a</sup>			190	100	92.3
2 <sup>b</sup>			170	100	91.9
3 <sup>b</sup>			115	100	86.3
4 <sup>b</sup>			65	100	86.3
5 <sup>c</sup>			210	100	93.4

**Table 1.**

Hydrogenations performed using Pt/C as catalysts (*Catal. Sci. Technol.*, 2014, 2445, Ref. [39]).

size resulting in a high number of potential catalytic sites [37]. Owing to these phenomena, there has been in the past two decades an increase in the use of metal nanoparticles in catalysis [38, 39]. Rong et al., reported the synthesis of supported Pt NPs and their use as catalysts in the partial hydrogenation of nitroarenes to arylhydroxylamines [40]. The particles were prepared by reduction of  $\text{H}_2\text{PtCl}_6$  with  $\text{NaBH}_4$  in the presence of the carbon support. The hydrogenation of several substituted nitroarenes was performed under soft conditions ( $10.15^\circ\text{C}$ , 1 bar  $\text{H}_2$ ) to favor the formation of hydroxylamines, showing excellent activity and selectivity in this transformation. Pd supported on C has also been successfully used as catalysts for the conversion of nitrobenzenes to secondary amines (**Figure 7**).

The proposed mechanism for the hydrogenation of nitrobenzene was proposed as shown in **Figure 8**. During this process, there is generation of intermediates such as hydroxylamines, azo and azoxy derivatives.

For example, in the case of m-dinitrobenzene, a catalyst containing 2 wt% Pt/C yielded 92.3% of the corresponding hydroxylamine after 190 min of reaction in THF (**Table 1**).

In a study, Zeming et al. used carbon as Pt colloid support for the hydrogenation of arylhydroxylamines. The Pt colloid supported on carbon was an active and selective catalyst for the partial hydrogenation of nitroaromatics with electron-withdrawing substituents to the corresponding N-arylhydroxylamine, indicating an additive-free green catalytic approach for arylhydroxylamine synthesis. Very encouraging results were obtained with N-arylhydroxylamine bearing electron-withdrawing substituents. Since N-arylhydroxylamine can be further converted to highly valuable compounds through several reactions like Bamberger rearrangement, this result will generally contribute to a simpler and greener synthetic methodology of N-arylhydroxylamine derivatives.

## 5. Future perspectives

Progress has been reported in the application of nano-PGMs for heterogeneous catalysis reactions. While most of the applications have centered on organic transformations, there is potential for extending the catalytic potential of these metals to other fields such as pollutant degradation and microbial inactivation in water

treatment processes. On their own, PGM at the nanoscale tend to aggregate and thus limited application has been realized. However, the use of supports has greatly enhanced the activity of the PGM nanocatalysts in various fields. Mono and bimetallic systems have been reported on. In environmental decontamination processes there is still need to find the most suitable supports and application devices. While encouraging findings have started appearing in literature, more work still needs to be done to in environmental catalysis for water treatment.

## 6. Conclusion

Several efforts have been devoted to the preparation of PGM nanocatalysts for application in environment decontamination. The high number of literature reports highlights the interest in this family of catalysts for catalytic transformation, both in terms of reactivity and selectivity. There is potential for application of PGMs nanocatalysts for environmental decontamination, water treatment, antimicrobial and chemical transformation. Further studies are necessary to better understand parameters influencing the reactivity as well as enhancing the conversion rates and efficiencies.

## Acknowledgements

Appreciation towards funding received from the University of South Africa (UNISA), the National Research Fund (NRF) and support from the Nanotechnology and Water Sustainability and Research Unit (NanoWS) is highly expressed.

## Conflict of interest


The authors declare that there is no conflict of interests concerning the publication of this book chapter.

## Author details

Sarre M.K. Nzaba, Bhekie B. Mamba and Alex T. Kuvarega\*  
Nanotechnology and Water Sustainability Research Unit, College of Science,  
Engineering and Technology, University of South Africa, Florida Campus,  
Johannesburg, South Africa

\*Address all correspondence to: [kuvarat@unisa.ac.za](mailto:kuvarat@unisa.ac.za)

## IntechOpen

© 2019 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

## References

- [1] Zhang Y et al. TiO<sub>2</sub>–graphene nanocomposites for gas-phase photocatalytic degradation of volatile aromatic pollutant: Is TiO<sub>2</sub>–graphene truly different from other TiO<sub>2</sub>–carbon composite materials? *ACS Nano*. 2010;**4**(12):7303-7314
- [2] Barber J, Tran PD. From natural to artificial photosynthesis. *Journal of the Royal Society Interface*. 2013;**10**(81):20120984
- [3] Dunphy Guzmán KA, Taylor MR, Banfield JF. Environmental risks of nanotechnology: National Nanotechnology Initiative funding, 2000–2004. *Environmental Science & Technology*. 2006;**40**(5):1401-1407
- [4] Biswas P, Wu C-Y. Nanoparticles and the environment. *Journal of the Air & Waste Management Association*. 2005;**55**(6):708-746
- [5] Teh CM, Mohamed AR. Roles of titanium dioxide and ion-doped titanium dioxide on photocatalytic degradation of organic pollutants (phenolic compounds and dyes) in aqueous solutions: A review. *Journal of Alloys and Compounds*. 2011;**509**(5):1648-1660
- [6] Grabowska E, Remita H, Zaleska A. Photocatalytic activity of TiO<sub>2</sub> loaded with metal clusters. *Physicochemical Problems of Mineral Processing*. 2010;**45**:29-38
- [7] Dozzi MV, Saccomanni A, Selli E. Cr (VI) photocatalytic reduction: Effects of simultaneous organics oxidation and of gold nanoparticles photodeposition on TiO<sub>2</sub>. *Journal of Hazardous Materials*. 2012;**211**:188-195
- [8] Kisch H. Semiconductor photocatalysis—Mechanistic and synthetic aspects. *Angewandte Chemie International Edition*. 2013;**52**(3):812-847
- [9] Yoon J-W. Dispersion of nanosized noble metals in \$ TiO\_2 \$ matrix and their photoelectrode properties. *Journal of the Korean Crystal Growth and Crystal Technology*. 2009;**19**(5):251-255
- [10] Wong MS et al. Cleaner water using bimetallic nanoparticle catalysts. *Journal of Chemical Technology & Biotechnology: International Research in Process, Environmental & Clean Technology*. 2009;**84**(2):158-166
- [11] Rubio-Marqués P, Leyva-Pérez A, Corma A. A bifunctional palladium/ acid solid catalyst performs the direct synthesis of cyclohexylanilines and dicyclohexylamines from nitrobenzenes. *Chemical Communications*. 2013;**49**(74):8160-8162
- [12] Coleman HM, Chiang K, Amal R. Effects of Ag and Pt on photocatalytic degradation of endocrine disrupting chemicals in water. *Chemical Engineering Journal*. 2005;**113**(1):65-72
- [13] Barakat M et al. Pt nanoparticles/ TiO<sub>2</sub> for photocatalytic degradation of phenols in wastewater. *Environmental Technology*. 2014;**35**(2):137-144
- [14] Kuvarega AT, Krause RW, Mamba BB. Comparison between base metals and platinum group metals in nitrogen, M codoped TiO<sub>2</sub> (M=Fe, Cu, Pd, Os) for photocatalytic removal of an organic dye in water. *Journal of Nanomaterials*. 2014;**2014**:199
- [15] Li C-H et al. Nitrobenzene hydrogenation with carbon nanotube-supported platinum catalyst under mild conditions. *Journal of Molecular Catalysis A: Chemical*. 2005;**226**(1):101-105
- [16] Nie R et al. Platinum supported on reduced graphene oxide as a catalyst for hydrogenation of nitroarenes. *Carbon*. 2012;**50**(2):586-596

- [17] Xie M et al. Pt nanoparticles supported on carbon coated magnetic microparticles: An efficient recyclable catalyst for hydrogenation of aromatic nitro-compounds. *RSC Advances*. 2013;**3**(26):10329-10334
- [18] Balcerzak M. Analytical methods for the determination of platinum in biological and environmental materials: A review. *Analyst*. 1997;**122**(5):67R-74R
- [19] Rao C, Reddi G. Platinum group metals (PGM); occurrence, use and recent trends in their determination. *TrAC Trends in Analytical Chemistry*. 2000;**19**(9):565-586
- [20] Acres GJK, Harrison B. The development of catalysts for emission control from motor vehicles: Early research at Johnson Matthey. *Topics in Catalysis*. 2004;**28**(1):3-11
- [21] Twigg MV. Twenty-five years of autocatalysts. *Platinum Metals Review*. 1999;**43**(4):168-171
- [22] Wang J et al. Catalytic ozonation of dimethyl phthalate and chlorination disinfection by-product precursors over Ru/AC. *Journal of Hazardous Materials*. 2009;**166**(1):502-507
- [23] Snyder SA, Vanderford BJ, Rexing DJ. Trace analysis of bromate, chlorate, iodate, and perchlorate in natural and bottled waters. *Environmental Science & Technology*. 2005;**39**(12):4586-4593
- [24] Weinberg HS, Delcomyn CA, Unnam V. Bromate in chlorinated drinking waters: Occurrence and implications for future regulation. *Environmental Science & Technology*. 2003;**37**(14):3104-3110
- [25] Butler R et al. Bromate environmental contamination: Review of impact and possible treatment. *Critical Reviews in Environmental Science and Technology*. 2005;**35**(3):193-217
- [26] Oh BS et al. Formation of hazardous inorganic by-products during electrolysis of seawater as a disinfection process for desalination. *Science of the Total Environment*. 2010;**408**(23):5958-5965
- [27] Boorman GA. Drinking water disinfection byproducts: Review and approach to toxicity evaluation. *Environmental Health Perspectives*. 1999;**107**(suppl 1):207-217
- [28] McAdam E, Judd S. Biological treatment of ion-exchange brine regenerant for re-use: A review. *Separation and Purification Technology*. 2008;**62**(2):264-272
- [29] Liu J et al. Application of a Re-Pd bimetallic catalyst for treatment of perchlorate in waste ion-exchange regenerant brine. *Water Research*. 2013;**47**(1):91-101
- [30] Choe JK et al. Comparative assessment of the environmental sustainability of existing and emerging perchlorate treatment technologies for drinking water. *Environmental Science & Technology*. 2013;**47**(9):4644-4652
- [31] Chaplin BP et al. Critical review of Pd-based catalytic treatment of priority contaminants in water. *Environmental Science & Technology*. 2012;**46**(7):3655-3670
- [32] Chen X et al. Exploring beyond palladium: Catalytic reduction of aqueous oxyanion pollutants with alternative platinum group metals and new mechanistic implications. *Chemical Engineering Journal*. 2017;**313**:745-752
- [33] Restivo J et al. Metal assessment for the catalytic reduction of bromate in water under hydrogen. *Chemical Engineering Journal*. 2015;**263**:119-126
- [34] Soares OS et al. Bromate reduction in water promoted by metal catalysts

prepared over faujasite zeolite. *Chemical Engineering Journal*. 2016;**291**:199-205

[35] Chen H et al. Aqueous bromate reduction by catalytic hydrogenation over Pd/Al<sub>2</sub>O<sub>3</sub> catalysts. *Applied Catalysis B: Environmental*. 2010;**96**(3-4):307-313

[36] Erkan A, Bakir U, Karakas G. Photocatalytic microbial inactivation over Pd doped SnO<sub>2</sub> and TiO<sub>2</sub> thin films. *Journal of Photochemistry and Photobiology A: Chemistry*. 2006;**184**(3):313-321

[37] Zhou B, Han S, Raja R, Somorjai G. *Nanotechnology in Catalysis*. New York: Kluwer Academic/Plenum Publisher; 2003

[38] Somorjai GA, Park JY. Molecular surface chemistry by metal single crystals and nanoparticles from vacuum to high pressure. *Chemical Society Reviews*. 2008;**37**(10):2155-2162

[39] Vries JGD. *The Handbook of Homogeneous Hydrogenation*. Wiley-Vch; 2007

[40] Rong Z et al. Carbon supported Pt colloid as effective catalyst for selective hydrogenation of nitroarenes to arylhydroxylamines. *Chemical Communications*. 2010;**46**(9):1559-1561

[41] Blaser HU, Steiner H, Studer M. Selective catalytic hydrogenation of functionalized nitroarenes: An update. *ChemCatChem*. 2009;**1**(2):210-221