Journal of Human Environment and Health Promotion

Print ISSN: 2476-5481 Online ISSN: 2476-549X

Interactions between Vehicular Emissions of Platinum Group Elements in Roadside Soils and the Legatum Prosperity Index: A Mini-Review

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ARTICLE INFO

Article type:
Review article

Article history:
Received: 2 November 2024
Revised: 1 December 2024
Accepted: 2 January 2025

https://doi.org/10.61186/jhehp.11.1.3

Keywords:

Automobiles
Catalyst
Platinum group elements
Roadside soil
Legatum prosperity index
Natural environment pillar

ABSTRACT

A catalytic converter mitigates exhaust gas toxicity by transforming harmful emissions into less harmful substances. Platinum group elements (PGEs) are essential components of vehicle exhaust catalysts (VECs) that alleviate environmental pollution. However, the increasing reliance on PGEs in VECs has resulted in the release of platinum (Pt), palladium (Pd), and rhodium (Rh) particles into the environment, contributing to pollution. Research has concentrated on roadside soils in urban areas or near highways, as these locations are close to catalytic converter contamination sources. Studies have indicated that PGE concentrations in roadside soils exceed the average global crustal levels. The Legatum Prosperity Index (LPI) evaluates national prosperity through 12 pillars, including economic quality, investment environment, governance, education, health, enterprise conditions, infrastructure and market access, safety and security, personal freedom, social capital, living conditions, and the natural environment. Based on these dimensions, the LPI categorizes countries into low, middle, and high-welfare groups. It is hypothesized that countries with higher LPI rankings exhibit reduced pollutant emissions, particularly PGEs from automotive sources, compared to those with lower LPI rankings. This review examines catalytic converters, catalyst classifications, PGE characterization, and their worldwide industrial distribution. It discusses emission sources and soil contamination, emphasizing the relationship between LPI and PGE emissions in countries with differing welfare levels to promote further research on this topic.

1. Introduction

Over the past 30-40 years, environmental concentrations of PGEs, particularly Pt, Pd, and Rh, have been steadily increasing in urban areas around the world. Sen and Peucker-Ehrenbrink (2012) assessed the global flux of various elements and found that Pt, Pd, and Rh as three of 11 elements with anthropogenic fluxes that exceeded natural contributions (Sen & Peucker-Ehrenbrink, 2012). PGE enrichment in the environment has been documented in studies, with elevated levels reported in soils (Zereini et al., 2007), airborne particulate matter (PM) (Zereini et al., 2012), and street dust (Jarvis et al., 2001). Although PGEs are normally emitted in trace amounts in the ng kg^{-1} range, their accumulation in urban environments, as well as their demonstrated solubility in simulated lung fluids, is cause for concern (Zereini et al., 2012). Healthcare facilities, mining operations, and the petrochemical industry are all significant sources of PGE emissions (Turner & Mascorda, 2015). However, the primary contributor to environmental PGE pollution is their application as catalysts in automotive catalytic converters, introduced in the 1970s in North America and the 1980s in Europe to control pollutant emissions (Wiseman et al., 2016). Platinum has several

How to cite: Farahmandkia Z, Bakhtshokouhi S, Najafi Saleh H. Interactions between Vehicular Emissions of Platinum Group Elements in Roadside Soils and the Legatum Prosperity Index: A Mini-Review. *J Hum Environ Health Promot.* 2025; 11(1): 3-12.

advantageous properties that make it valuable as a catalyst, including high oxidation potential, chemical stability, and the ability to adsorb simple gases such as CO (Reith et al., 2014). Initially, Rh/Pt catalysts were used to reduce pollution. By the mid-1990s, Pd was used in increasing quantities, along with Rh and Pt, in three-way catalytic converters to promote hydrocarbon oxidation. Between 1998 and 2013, the global gross demand for Pd in automotive catalytic applications increased from 4,390 to 6,970 metric tons (Wiseman et al., 2016). However, future Pt use is likely to increase, as more efficient hydrogen fuel cell automotive technologies require 3-10 times the amount of Pt for effective pollution control (Alonso et al., 2012). Although PGE emissions from vehicles are lower compared to many other elements, the cumulative impact of emissions from over 700 million vehicles worldwide poses a significant risk for urban PGE pollution over time (Rauch et al., 2005). For example, Pt contamination in roadside soils in Germany has been reported to be seven times higher than background concentrations (Barefoot, 1999). This increase is attributable to the increased use of Pt in vehicles when automobile catalytic converters were introduced in Germany in 1987 (Alt et al., 1997). This review is the first comprehensive analysis of both quantitative and qualitative literature to provide a global understanding of the relationship between vehicle-emitted PGEs in roadside soils and the LPI. The analysis focuses exclusively on studies examining roadside soil contamination, excluding research on roadside dust.

2. Discussion

A literature search was performed on publications written in English indexed until May 2023 in the PubMed, ScienceDirect, Springer Link, Google Scholar, and Scopus databases. Various combinations of the keywords 〝platinum group element emission〞, 〝PGEs emission〞, 〝automobiles〞, 〝catalytic converter〞, 〝roadside contamination〞, and 〝highway side contamination〞, were used to identify studies focused on roadside soil contamination related to PGEs emissions from vehicle exhaust catalyst while excluding those addressing roadside dust. In addition, reference lists of the retrieved articles were examined to identify relevant studies potentially overlooked during the database search. A narrative review was performed for 23 papers published between 2007 and 2021. The selected studies were then compared to the LPI of countries, and the main findings were summarized in Table 1. As the LPI has been published since 2007 to rank countries based on well-being, studies conducted before 2007 were excluded from the analysis.

2.1 Vehicle catalytic converters

Catalytic converters were first introduced by General Motors in 1974 in response to the Clean Air Act and accompanying the Environmental Protection Agency regulations that required a 75% reduction in toxic emissions for all new vehicle models manufactured after 1975 (Bommi et al., 2019). Since 1993 and 1997, catalytic converters have been installed in gasoline and diesel vehicles, respectively. A catalytic converter (Figure 1) consists of a honeycomb-like ceramic monolith made from alumina or cordierite ($2MgO.2Al2O3.5SiO_2$) with traces of manganese (Mn), iron (Fe), titanium (Ti), calcium (Ca), sodium (Na), and potassium (K) that is fixed inside a stainless steel box in the vehicle exhaust system (Das et al., 2002). A wash-coat layer of alumina (Al_2O_3), cerium oxide (CeO_2), and zirconium oxide (ZrO_2) is applied to the monolith's surface (Palacios et al., 2000). The active substances, metallic nanoparticles of PGEs, are scattered at around 0.1% on this wash-coat layer (Wang & Li, 2012). First, PGE particles on the catalyst surface have diameters of <10 nm; however, sintering can cause aggregation and the formation of larger particles. For instance, PGE particles with diameters ranging from 50-400 nm have been observed in catalysts aged to 60,000 km (Palacios et al., 2000). Moreover, alkaline earth metal promoters, such as calcium (Ca), barium (Ba), and magnesium (Mg), are also added to the wash-coat to enhance catalytic performance or provide stability against degradation and aging (Le Bras et al., 2017). The functionality of catalytic converters depends on the vehicle's motorization and fuel type, with two primary systems: (1) Three-way (TW) catalytic converters (Figure 2) are used in gasoline engines and are comprised of Pt, Pd, and Rh. They perform three simultaneous functions: oxidation of carbon monoxide (CO), oxidation of unburned hydrocarbons (UHCs), and reduction of nitrogen oxides (NOx, x = 1, 2, 3). Platinum and palladium catalyze the CO and hydrocarbon oxidation reactions. Rh catalyzes NOx's redox reaction (Le Bras et al., 2017). (2) Oxidation catalytic converters for diesel engines oxidize CO and UHCs and include a particle control system that uses additives or catalyzed particulate filters. Diesel particulate filters, implemented as exhaust after-treatment systems, capture particulate emissions, primarily soot.

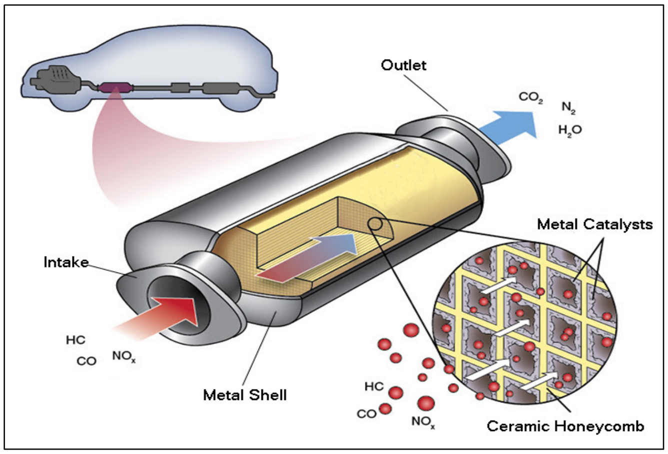

Figure 1. Schematic diagram of a catalytic converter

The use of catalytic converters has significantly reduced urban air pollution by eliminating approximately 90% of CO, UHCs, and NOx (Palacios et al., 2000). However, the high temperatures, chemical stress, and violent vibrations experienced by catalytic converters during engine operation cause abrasion and wear of the converter walls, resulting in the emission of PGE particles into the atmosphere with exhaust gas (Moldovan et al., 2002; Palacios et al., 2000). Catalytic converters are now recognized as the primary source of PGEs in the urban environment (Ravindra et al., 2004).

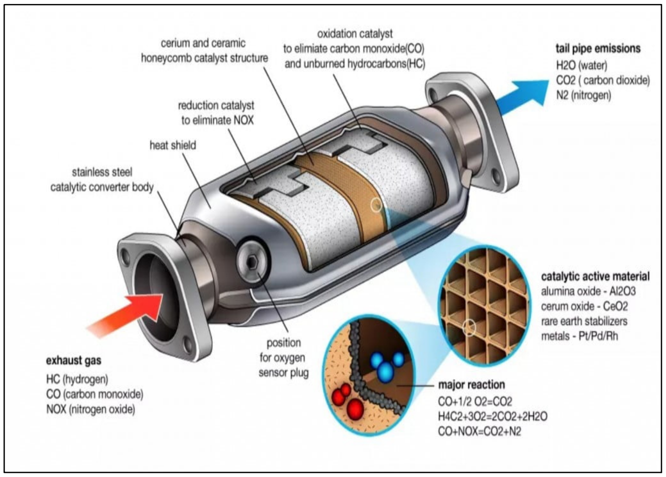

Figure 2. Schematic diagram of the working of a three-way autocatalytic converter

To function effectively, catalytic reactions require temperatures above 600 °C, a condition typically reached after driving 10-15 kilometers. Emissions are notably higher during the first kilometers of a cold start, particularly in urban settings. The average lifespan of a catalytic converter is estimated at 120,000 and 150,000 km (Gasser et al., 2014). The proportion of Pt, Pd, and Rh in catalytic converters is determined by several factors, including the manufacturer, vehicle characteristics such as engine power, fuel type (gasoline or diesel), vehicle weight, and the required catalytic functions. Generally, the PGE content of the catalytic converter is around 0.1-0.3% (w/w) (Hwang et al., 2016). Since the mid-1990s, Pd has increasingly replaced Pt due to rising Pt prices (Cicchella et al., 2003; Zereini et al., 2007). On the other hand, the Rh content remains consistently low, attributed to its high price (Gomez et al., 2002). The PGEs ratios also differ between vehicle manufacturers in the United States, Europe, and Japan and between vehicles from the same production lines (Cicchella et al., 2003). These ratios range from 5 to 12 for Pt/Pd and Pt/Rh in gasoline vehicles (gasoline-powered vehicles) (Bocca et al., 2006). Pt is primarily used in diesel vehicles with Pd and Rh, with a metal content of 7-8 g per vehicle (Omrani et al., 2020).

2.2 Factors influencing PGE emissions

PGEs emissions from exhaust gas are affected by several factors, including engine type, operating conditions, the age and initial PGEs content of the catalytic converter, driving speed, weather, and fuel type (Ravindra et al., 2004). Unfavorable operational conditions, such as failed ignitions or excessive heating, can amplify PGE emissions.

2.3 Characteristics and distribution of PGEs

The PGEs, comprising Ru, Rh, Pd, Os, Ir, and Pt, are primarily concentrated in the Earth's core and mantle due to their siderophilic nature. Their natural abundance in the upper continental crust is minimal, ranging from 0.018 µg/kg (Rh) to 0.599 µg/kg (Pt) (Park et al., 2012). Natural sources of PGEs include volcanism, rock weathering, and extraterrestrial matter deposition, contributing only minimally to environmental PGE levels (Mitra & Sen, 2017). Given that both continental crust concentrations are low and natural sources contribute only a small amount of PGE to the Earth's surface, the fate of these elements in the environment should be of little concern. However, anthropogenic PGE emissions began around the 1750s, at the start of the industrial period. This was demonstrated by observing PGE accumulation in some soils starting on that date. Because of their physical and chemical properties, such as high melting points, high corrosion resistance, mechanical strength, and ductility, PGE is used. PGE have a high economic value and are used in various applications such as catalytic converters, electronics, drugs, and chemical industry catalysts. PGE is divided into two subgroups based on their physicochemical behavior: iridium PGE, also known as IPGE and composed of Ir, Os, Ru, and palladium PGE, also known as PPGE and composed of Pd, Pt, and Rh (Rollinson, 2014). The IPGE subgroup elements are more siderophile, refractory, and associated with chromites as alloys and sulfides in dunites. PPGE elements are more chalcophile than IPGE elements and are associated with sulfides of Fe, Cu, Ni, gabbros, norites, and dunites (Rollinson, 2014). Over the last thirty years, the increased use of PPGE and releasing of these elements has resulted in environmental contamination. Figure 3 gives an overview of the relative distribution of PPGE by industry regarding the manufacture and use of products containing these elements. Automobile catalysts are responsible for the main percentage of emissions of PPGE into the environment. Since the early 1970s, PGEs have been used as catalysts, with the catalytic converter industry now representing the highest global demand for these elements (Hwang et al., 2016; Palacios et al., 2000). As the number of vehicles on the road continues to increase, PGEs are expected to rise correspondingly. Pt and Pd are particularly effective in oxidizing CO and hydrocarbon species, while Rh is highly efficient in reducing NO. The introduction of the second generation of three-way catalytic converters in 1979 led to a significant increase in PGE emissions, contributing to environmental contamination (Heck et al., 2016). Catalytic converters typically contain 0.1-0.3% (w/w) PGEs, although the exact composition varies depending on vehicle type, such as gasoline-powered versus diesel-powered vehicles (Hwang et al., 2016). Ash et al. (2014) measured PGES in crushed monolith and reported mean concentrations of Pt, Pd, and Rh in gasoline catalysts of 800, 30, and 120 µg/g, respectively. In contrast, light-duty diesel catalysts contained 2600, 690, and 5 µg/g of Pt, Pd, and Rh, respectively, while heavy-duty diesel catalysts showed concentrations of 1800, 5, and 5 µg/g, respectively. Pt utilization is declining and being replaced by Pd due to higher Pt prices and the introduction of ultra-low sulfur diesel (Hwang et al., 2016). PGE emissions from modern three-way catalysts vary greatly depending on catalyst type, vehicle age, mileage, driving speed, road conditions, and other variables. Although PGE emissions are relatively low and no discernible ecological effects have been observed, the growing number of vehicles and deficient background levels have raised concerns about environmental contamination.

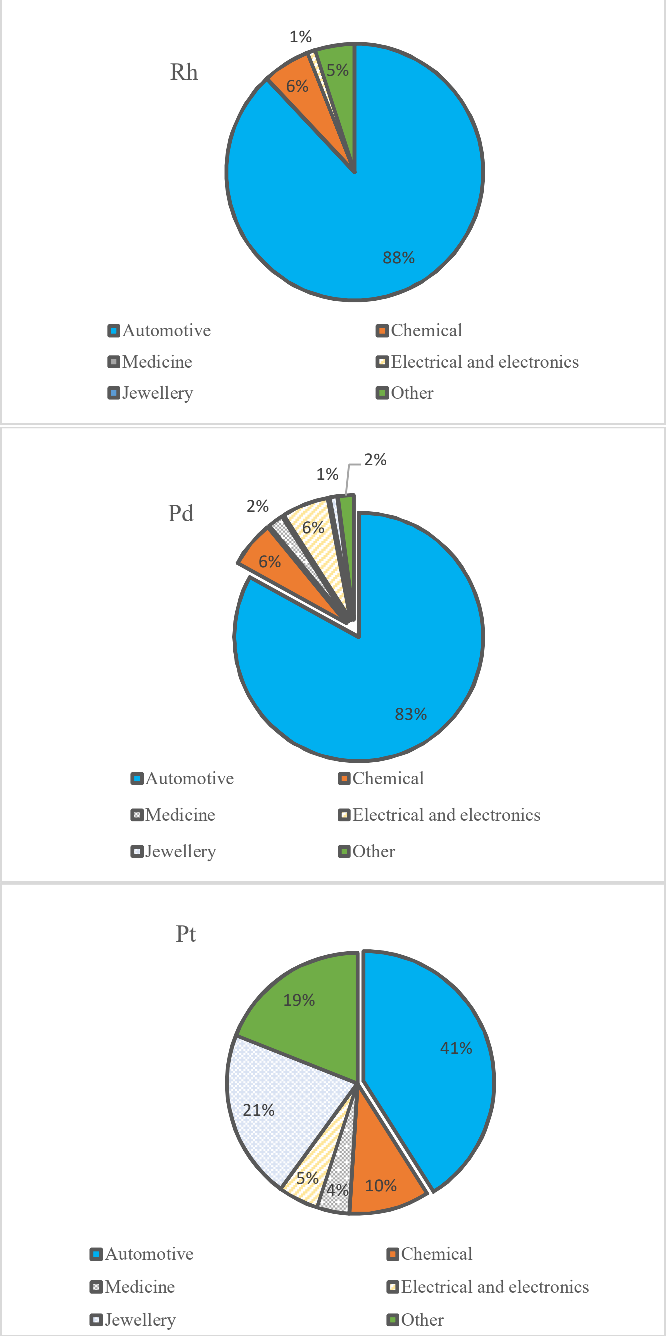

Figure 3. Percentage demand for Pt, Pd, and Rh by type of activities in 2022 (Mattey, 2022)

Although PGEs are much less water soluble than other constituents of concern (e.g., lead, copper, and zinc), bioaccumulation of PGEs has been observed in various aquatic organisms, including zebra mussels, freshwater isopods, and fish (Osterauer et al., 2009). PGEs appear to cause cellular disruption, DNA tissue damage, and bioaccumulation. Acute toxicity tests have revealed that PGES is far less toxic than Cd, Cr, Hg, and Pb and toxic in the same way as Se and Ce, with LC50 values ranging from 225 to 1500 nmol L^{-1} (Borgmann et al., 2005).

2.4 Background concentration of PPGE in roadside soil

Determining background concentration is critical for assessing contamination levels and identifying pollution sources. Because almost all PPGE contamination studies focus on roadside environments, background values are typically taken as PPGE concentrations in areas with low population density and low traffic, with no further details or selection criteria. While this approach is common in roadside contamination studies, it may not always provide a reliable baseline, especially in regions where PPGE accumulation is naturally elevated. The influence and composition of the local bedrock should also be considered, particularly in areas without active PPGE mining, to ensure accurate assessments. Soil acts as a sink for toxic elements emitted by vehicles, such as PGEs (Wang et al., 2017). The accumulation of these elements in roadside topsoil is primarily caused by atmospheric deposition (Li et al., 2001). Due to their non-biodegradability and long residence time in soils, potentially toxic elements have been known as "chemical time bombs" (Stigliani et al., 1991). Rain, surface runoff, wind, and gravity all play significant roles in dispersing potentially toxic element deposits on the soil surface. The re-entrainment of toxic elements emitted by vehicles is also affected by the surrounding topography, soil properties, toxic element solubility, traffic volumes, horizontal and ventral distance from the road, and wind direction (De Silva et al., 2021). Because soil appears to be the final main reservoir for dust, wind plays an important role in toxic element entrainment (Chen et al., 2010). While toxic elements emitted by vehicles are primarily found in the soil's surface layer (0-5 cm), they can also leach deeper into the soil profile (Wong et al., 2006). Studies have shown that vehicle exhausts contribute to the accumulation of potentially toxic elements in roadside soils, with depositions extending up to 100 meters from the road (Hamurcu et al., 2010). Toxic element concentrations in soil typically decrease with increasing distance from the road and depth within the soil profile (Bernardino et al., 2019). Research on PPGE contamination in roadside soils has primarily focused on areas in cities or near highways, as these locations are near the primary source of contamination from vehicle catalytic converters. The median values of PPGE concentrations measured in various cities around the world are summarized in Table 1. All of the median (or average) values reported in the cited studies exceed the natural abundance of these elements in the Earth's crust. Most studies have focused on the distribution of PPGE concentrations at varying distances from the road. The findings reveal a consistent pattern: high concentrations of Pt, up to several hundred µg/g, and Pd and Rh, up to 10 µg/g, are observed near the road.

Table 1. Summary of Studies reporting PGEs concentrations in roadside soil from peer-reviewed literature worldwide. Data sourced using Scopus, PubMed, Springer Link, Web of Science, and Google Scholar

Country	Concentration (µg/kg)	Background level	NE rank	LPI rank	Reference
Australia	Pt = nd Pd = 137 Rh = nd	-	19	15	(De Silva et al., 2016)
Greece	Pt = 44-820 Pd = 36-1100 Rh = 3-35	-	29	40	(Οικονόμου-Ηλιοπούλου & Σφεντόνη, 2010)
	Pt = 39.9-78.4 Pd = 6-8.8 Rh = 18.5-27.2	Pt = 4.4 Pd = 1.13 Rh = 0.74			(Tsogas et al., 2009)
US	Pt = 51.8 Pd = 29.1 Rh = 5.18	-	28	19	(Sutherland et al., 2008)
Brazil	Pt = 27.2 Pd = 78.2 Rh = 6.2	-	18	66	(Ribeiro et al., 2012)
China	Pt = 31.4 Pd = 24.2 Rh = 7.6	Pt = < 1 µg/kg Pd = < 1 µg/kg Rh = < 0.1 µg/kg	139	54	(Pan et al., 2009)
	Pt = 10.89 Pd = 13.81 Rh = 1.28	Pt = 0.28 Pd = 0.64 Rh = 0.019			(Qi et al., 2011)
	Pt = 34.92 Pd = 57.77 Rh = 20.17	Pt = 0.4 Pd = 0. 4 Rh = 0.06			(Liu et al., 2015)
Czech Republic	Pt = 8.5	-	27	25	(Komendova & Jezek, 2019)
	Pt = 9.27 Pd = 3.45 Rh = 0.21	-			(Mihaljevič et al., 2013)
Canada	Pt = 8.7 Pd = 63 Rh = 1.7	-	20	13	(Wiseman et al., 2016)
Germany	Pt = 7.17 Pd = 5.21 Rh = 1.43	Pt = 1.1 Pd = 1.02 Rh = 0.1	12	9	(Wichmann et al., 2007)
	Pt = 2.03 Pd = 0.95 Rh = 0.19	Pt < 0.5 Pd = 0.07 Rh = 0.01			(Birke et al., 2018)
Bulgaria	Pt = 25 Pd = 42	nd	64	48	(Lyubomirova & Djingova, 2015)
Italy	Pt = 10.75	Pt = 3.8	31	30	(Angelone et al., 2007)
	Pt = 1 Pd = 1 Rh = 0.4	-			(Cicchella et al., 2020)
	Pt = 68	-			(Orecchio & Amorello, 2011)
	Pt = 0.1-278 Pd = 0.5-432 Rh = 0.07-47	Pt = 1.86 Pd = 1.62 Rh = 0.44			(Cicchella et al., 2008)
UK	Pt = 164 Pd = 272	-	22	12	(Jackson et al., 2007)
India	Pt = 5.9 Pd = 9.16 Rh = 0.83	Pt = < 1 µg/kg Pd = < 1 µg/kg Rh = < 0.1 µg/kg	161	103	(Pan et al., 2009)
South Korea	Pt = 49.7	2.4	63	29	(Lee et al., 2012)
Russia	Pt = 88.5 Pd = 34.2 Rh = 6.7	-	76	77	(Ladonin, 2018)
South Africa	Pt = 0.06-1.12 Pd = 0.48-5.44 Rh = 0.08-0.64	-	140	75	(Van der Horst et al., 2018)
Turkey	Pt = 7.6 Pd = 304 Rh = 13	-	86	95	(Murat et al., 2021)

2.5 Legatum prosperity index

While the main objective of many economic policies is to achieve higher economic growth, the environmental risks resulting from economic activities have become a controversial issue (Pazhouyan & Moradhasel, 2007). The relationship between economic development and environmental degradation remains a complex and vital issue. Natural resources and the environment provide many of the inputs for production, which not only generates desirable outputs, such as consumer goods, but also produces undesirable byproducts, including environmental pollutants. Without advancements in production techniques and processes, the negative impacts of these undesirable outputs are likely to outweigh the benefits of desirable production outputs. This issue is of greater importance at the macro level. Various countries call for balanced economic growth and sustainable development, which requires appropriate planning to achieve high economic growth with minimal adverse environmental effects. The consequences will be irreversible if production occurs without considering the negative environmental impact (Mehnatfar & Ghobadi, 2015). Uncontrolled exploitation of natural resources, accumulation of waste, and focus on pollutants can lead to a decrease in biodiversity, and ultimately, despite an increase in income, it can lead to the deterioration of environmental quality and a reduction of human well-being. On the other hand, some people believe that the fastest way to improve the environment is through economic growth, in such a way that as income levels increase, the demand for goods and services that use fewer materials increases, and this gradually leads to the acceptance of environmental protection criteria in the production process (Jafari Samimi & Ahmadpour, 2011). Economics is the science of optimal use of resources. Awareness of this science and its use enables humans to use scarce natural resources desirably. Optimal use of natural resources should be in the direction of collective benefits, considering future generations' interests and minimizing environmental degradation and pollution. Generally, there is a two-way relationship between the economy and the environment. Businesses use economic resources, including raw materials and energy, to produce goods and services. In this process, they return some of the used inputs as waste and pollution to the environment. These wastes, mainly in the form of carbon monoxide, carbon dioxide, sulfur dioxide, or solid waste and wastewater, cause pollution or impose external costs on society. Therefore, it is observed that every decision made in the economy comes with an opportunity cost or lost opportunities. Most studies measuring growth and welfare have used economic indicators such as Gross Domestic Product (GDP), Gross National Product (GNP), or Gross Domestic Product per capita. Economic growth is necessary for improving people's living standards, but it is insufficient (Yousefinejad et al., 2015). Since GDP and GDP per capita only measure the value of market goods and services produced and consumed in an economy, they cannot be considered economic welfare indicators. Therefore, some economists have tried to create alternative indicators encompassing macroeconomic activities and social inequalities and calculating economic growth's environmental impacts (Bakhtiyari et al., 2012). Indices such as the Legatum, IEWB, and Genuine Progress Indicator (GPI) are among these indicators. Among these indices, the Legatum index is designed to go beyond traditional economic measures, such as GDP per capita, and to provide a more comprehensive view of prosperity by taking into account a wide range of factors that contribute to well-being. The Legatum Prosperity Index (LPI) measures countries' prosperity across 12 pillars, including economic quality, investment environment, governance, education, health, enterprise conditions, infrastructure and market access, safety and security, personal freedom, social capital, living conditions, and natural environment. For instance, the natural environment pillar measures the aspects of the physical environment that have a direct effect on people in their daily lives and changes that might impact the prosperity of future generations. The living conditions pillar measures the degree to which a reasonable quality of life is experienced by all, including material resources, shelter, basic services, and connectivity. The 2023 LPI is based on 300 different indicators analyzed across 167 nations around the world. For 167 nations, the Index uses the same indicators and combines them in the same way to create elements and pillars. Using the Index, it is possible to compare the relative performance of each country for overall prosperity and each of the 12 pillars of prosperity, such as health, education, and social capital, as well as the 67 actionable policy areas (elements) within the pillars (figure 4). The elements have been established to represent key policy areas, such as investor protections, primary education, government integrity, and air pollution, to help facilitate more targeted action. The index is based on data from a variety of sources, including the World Bank, the United Nations, and other international organizations. According to the pillars and indicators, the Legatum Institute ranks the countries into three groups: low-welfare, middle-welfare, and high-welfare countries. It finds that the wealthiest nations in the world are not necessarily those with the highest GDP but those with free, happy, and healthy citizens. This index is the only global index that measures the factors that contribute to economic growth and citizen happiness and provides a global evaluation of wealth and happiness.

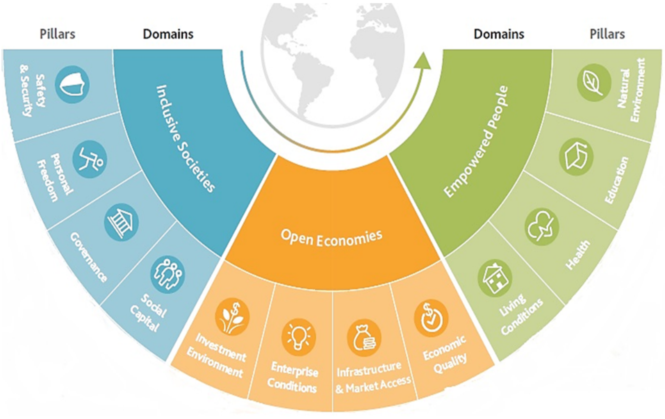

Figure 4. The domains and pillars of the LPI (Prosperity Institute, 2023)

In terms of pollutant emissions into the environment, it is assumed that in countries with high LPI, where the quality of life is high. There are better economic conditions, people tend to use the newer with low mileage automobiles and typically replace their vehicles with more recent models after a few years. Therefore, pollutant emissions from vehicles, especially PGEs from automotive catalytic converters, should be lower in countries with a higher LPI than countries with a lower LPI, where older automobiles with high mileage and more inferior technology are used. In countries with low LPI and adverse environmental conditions, it is expected that the emission level of PGEs into the environment will be high due to the more prolonged use of vehicle catalysts, older technology of the catalytic converter, and their failure to be replaced promptly (Omrani et al., 2020). However, some studies showed that emission rates of PGEs decrease with the age of the catalytic converter (Omrani et al., 2020; Palacios et al., 2000). For example, according to Palacios et al the emission rate of PGEs by new three-way gasoline catalytic converters was reported to be 110 ng km^{-1} for Pt, 250 ng km^{-1} for Pd, and 50 ng km^{-1} for Rh, which were decreased to 6-8, 12-16, and 3-12 ng km^{-1}, respectively when the catalyst was aged up to 30,000 km; but it was noted that an aged gasoline catalyst released more soluble and highly mobile PGE than a new one (Jarvis et al., 2001; Palacios et al., 2000). However, the concentration of PGE released into the environment has increased with the decrease in the countries' ranking. Looking at the PGE values reported in the literature and their R-squared correlations with the countries' ranking based on the Natural Environment (NE) pillar and LPI (Figure 5) shows that the correlation between PGE values and LPI rankings is not strong, attributing this to the complex and varied factors influencing emissions, such as (1) Technological and Infrastructure Variations: High-LPI countries might have newer vehicles and better-maintained infrastructure, which could lower PGE emissions but may also exhibit higher vehicle speeds that increase emissions. (2) Age and Condition of Vehicles: Low-LPI countries often rely on older vehicles with outdated catalytic converter technologies, leading to higher PGE emissions. (3) Environmental Policies and Fuel Quality: Different regulatory standards and fuel qualities impact PGE emissions, yet these are not uniformly addressed across contexts. In other studies, it has also been pointed out that various and complex factors affect the release of PGEs from vehicle catalysts. That is factors such as type of catalyst, age of the car, miles traveled, type of engine, the operating conditions of the engine (for example, the abrasion and wearing of the catalytic washcoat surface due to high temperatures, physical and chemical stress such as volatilization and sintering during engine operation, resulting in the emission of PGEs particles with exhaust gases), the age and initial PGEs content of catalyst, vehicle speed, way of driving, weather condition, the type of fuel (gasoline or diesel), etc. (Hwang et al., 2016; Omrani et al., 2020; Ravindra et al., 2004). High urban density often correlates with increased traffic congestion and vehicle idling times, which may elevate PGE emissions despite advanced vehicle technologies. Contrastingly, densely populated areas in high-LPI countries may have better traffic management systems or encourage alternative transportation modes, reducing emissions. Countries with extensive and efficient public transit systems (often high on the LPI) might see reduced dependence on personal vehicles, which would lower overall PGE emissions. This aspect could be explored to highlight its mitigating role in urban pollution.

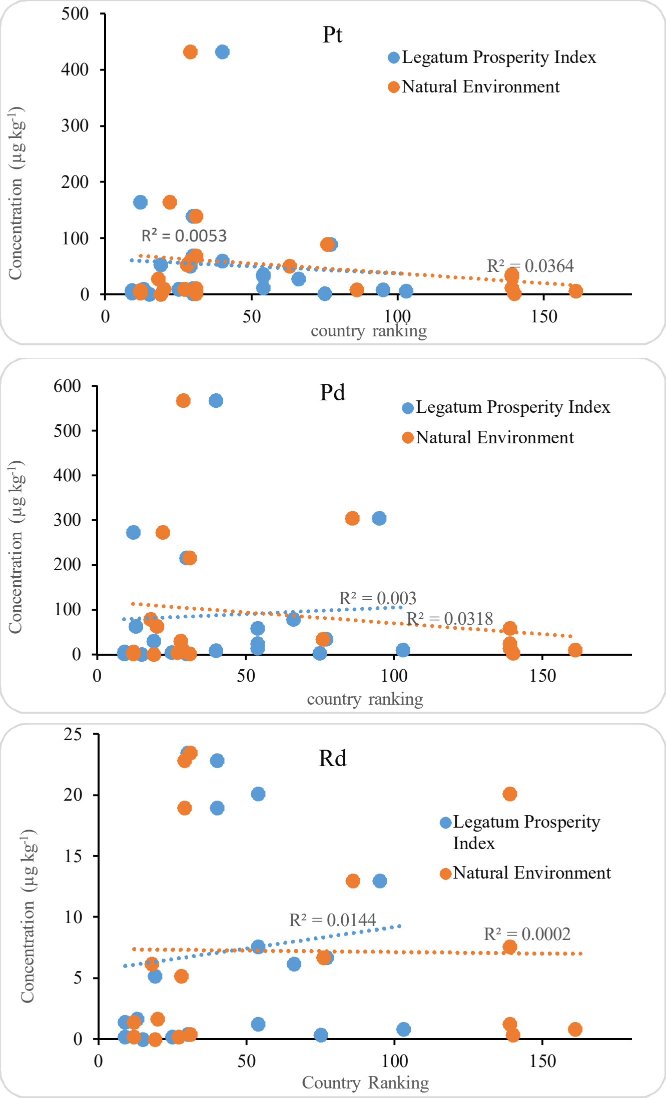

Figure 5. Correlation between PGE values and countries' ranking based on the NE pillar and LPI

The strength and enforcement of environmental regulations, such as emissions standards for vehicles or incentives for electric vehicle adoption, vary widely and can significantly impact PGE emissions. High-LPI countries might prioritize stricter regulations, while low-LPI countries might struggle with implementation due to economic or infrastructural constraints. Examining how these factors interact with LPI rankings could reveal critical pathways for reducing PGE emissions tailored to a country′s specific socio-economic and environmental context. For instance, it could analyze if high-LPI countries offset emissions through public transportation, even with a higher number of vehicles per capita. To mitigate these generalizations, further research could segment findings by regional or national contexts, considering specific economic, technological, and environmental conditions. This approach would ensure more nuanced conclusions that reflect the multifaceted relationship between welfare and PGE emissions. Also, by considering and analyzing other information and indicators, such as the Human Development Index of Countries (HDI), which provides a metric based on three dimensions: a long and healthy life, knowledge, and a decent standard of living (World Population Review, 2024), a fuller picture of the relationship between PGE emissions and the countries' position in terms of various development indicators can be obtained. Advancements in catalytic converter technology, such as developing non-PGE alternatives or improving the durability of existing designs, can significantly reduce PGE emissions. Similarly, promoting cleaner fuel alternatives like ultra-low sulfur fuels and transitioning to electric or hybrid vehicles can address the primary sources of PGE release. Regulatory measures also play a critical role in mitigating emissions. Implementing stricter emission standards and mandatory vehicle inspections can ensure the proper functioning of catalytic converters, particularly in countries where older vehicle technologies dominate. Moreover, enhancing public transportation systems and implementing traffic management strategies, such as congestion charges and carpooling incentives, could reduce vehicle usage and associated emissions. Beyond preventive approaches, recycling and recovery of PGEs offer sustainable solutions to address existing environmental contamination. Recycling programs targeting end-of-life catalytic converters can reclaim valuable PGEs, reducing reliance on mining. Further, investing in advanced technologies to recover PGEs from roadside soils and urban runoff could mitigate environmental pollution and provide secondary sources of these metals.

3. Conclusion

This review evaluates the existing scientific literature to explore the relationship between a nation's welfare index and the emission of PGEs from vehicle catalytic converters in the roadside soil environment. Catalytic converters are emission control devices that reduce the toxicity of exhaust gases by converting them into less toxic pollutants. However, despite the reduction of pollutants from automobile exhausts by catalytic converters, the emission of catalyst elements to the environment is an issue. The emission of PGEs from catalytic converters has emerged as a serious environmental concern worldwide. As the production of vehicles equipped with PGE-based catalytic converters increases, the ecological exposure to these elements rises accordingly. Research indicates that PGEs concentrations in roadside soils are higher than the average global crustal concentrations. In this review, the concentration of PGEs in roadside soils was evaluated in relation to the welfare statuses of nations, as defined by the LPI. The LPI provides a holistic measure of prosperity, incorporating over 300 indicators across 167 countries to assess well-being beyond traditional economic metrics such as GDP per capita. Based on the LPI, nations are categorized into three welfare groups: low-welfare, middle-welfare, and high-welfare. The correlation between roadside PGE concentrations and countries' LPI ranking was not significant. This lack of correlation suggests that PGE emissions from vehicle catalytic converters are influenced by complex factors such as catalyst type, vehicle age, engine type and operating conditions, fuel type, vehicle speed, meteorological conditions, and the age of the catalyst. These findings imply that regardless of a country's rank on the LPI, the issue of PGE emissions from catalytic converters warrants equal attention and mitigation efforts worldwide.

Authors' Contributions

Zohre Farahmandkia: Conceptualization; Supervision; Project administration. Sepideh Bakhtshokouhi: Investigation; Writing-original draft preparation; Data curation. Hossein Najafi Saleh: Methodology; Investigation; Writing-original draft preparation; Writing-review and editing; Visualization.

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgements

We extend our gratitude to Farima Fathi for her invaluable efforts.

Ethical considerations

There were no ethical considerations in this research.

Using artificial intelligence

The authors declare that they have not used any artificial intelligence techniques in this research.

References

1. Alonso, E., Field, F. R., & Kirchain, R. E. (2012). Platinum availability for future automotive technologies. *Environmental Science & Technology*, *46*(23), 12986-12993.

2. Alt, F., Eschnauer, H., Mergler, B., Messerschmidt, J., & Tölg, G. (1997). A contribution to the ecology and enology of platinum. *Fresenius' Journal of Analytical Chemistry*, *357*, 1013-1019.

3. Angelone, M., Spaziani, F., Cremisini, C., & Salluzzo, A. (2007). Determination of PGE and REE in urban matrices and fingerprinting of traffic emission contamination. In *Highway and urban environment: proceedings of the 8th highway and urban environment symposium* (pp. 271-281). Springer Netherlands.

4. Ash, P. W., Boyd, D. A., Hyde, T. I., Keating, J. L., Randlshofer, G., Rothenbacher, K., . . . & Toner, B. M. (2014). Local structure and speciation of platinum in fresh and road-aged North American sourced vehicle emissions catalysts: An X-ray absorption spectroscopic study. *Environmental Science & Technology*, *48*(7), 3658-3665.

5. Bakhtiyari, S., Ranjbar, H., & Ghorbani, S. (2012). Composite index of economic well-being and its measurement for a selection of developing countries. *Economic Growth and Development Research*, *3*(9), 41-58.
6. Barefoot, R. (1999). Distribution and speciation of platinum group elements in environmental matrices. *TrAC Trends in Analytical Chemistry*, *18*(11), 702-707.
7. Bernardino, C. A., Mahler, C. F., Santelli, R. E., Freire, A. S., Braz, B. F., & Novo, L. A. (2019). Metal accumulation in roadside soils of Rio de Janeiro, Brazil: impact of traffic volume, road age, and urbanization level. *Environmental Monitoring and Assessment*, *191*, 1-14.
8. Birke, M., Rauch, U., Stummeyer, J., Lorenz, H., & Keilert, B. (2018). A review of platinum group element (PGE) geochemistry and a study of the changes in PGE contents in the topsoil of Berlin, Germany, between 1992 and 2013. *Journal of Geochemical Exploration*, *187*, 72-96.
9. Bocca, B., Caimi, S., Smichowski, P., Gómez, D., & Caroli, S. (2006). Monitoring Pt and Rh in urban aerosols from Buenos Aires, Argentina. *Science of the Total Environment*, *358*(1-3), 255-264.
10. Bommi, R., Monika, V., ArockiaKoncy, A. A., & Patra, C. (2019). A surveillance smart system for air pollution monitoring and management. *International Conference on Intelligent Data Communication Technologies and Internet of Things (ICICI) 2018*, *26*, 1407-1418.
11. Borgmann, U., Couillard, Y., Doyle, P., & Dixon, D. G. (2005). Toxicity of sixty-three metals and metalloids to Hyalella azteca at two levels of water hardness. *Environmental Toxicology and Chemistry: An International Journal*, *24*(3), 641-652.
12. Chen, X., Xia, X., Zhao, Y., & Zhang, P. (2010). Heavy metal concentrations in roadside soils and correlation with urban traffic in Beijing, China. *Journal of Hazardous Materials*, *181*(1-3), 640-646.
13. Cicchella, D., De Vivo, B., & Lima, A. (2003). Palladium and platinum concentration in soils from the Napoli metropolitan area, Italy: possible effects of catalytic exhausts. *Science of the Total Environment*, *308*(1-3), 121-131.
14. Cicchella, D., Fedele, L., De Vivo, B., Albanese, S., & Lima, A. (2008). Platinum group element distribution in the soils from urban areas of the Campania region (Italy). *Geochemistry: Exploration, Environment, Analysis*, *8*(1), 31-40.
15. Cicchella, D., Zuzolo, D., Albanese, S., Fedele, L., Di Tota, I., Guagliardi, I., . . . & Lima, A. (2020). Urban soil contamination in Salerno (Italy): concentrations and patterns of major, minor, trace and ultra-trace elements in soils. *Journal of Geochemical Exploration*, *213*, 106519.
16. Das, R. N., Madhusoodana, C., Panda, P., & Okada, K. (2002). Evaluation of thermal shock resistance of cordierite honeycombs. *Bulletin of Materials Science*, *25*, 127-132.
17. De Silva, S., Ball, A. S., Huynh, T., & Reichman, S. M. (2016). Metal accumulation in roadside soil in Melbourne, Australia: effect of road age, traffic density and vehicular speed. *Environmental Pollution*, *208*, 102-109.
18. De Silva, S., Ball, A. S., Indrapala, D. V., & Reichman, S. M. (2021). Review of the interactions between vehicular emitted potentially toxic elements, roadside soils, and associated biota. *Chemosphere*, *263*, 128135.
19. Gasser, I., Rybicki, M., & Wollner, W. (2014). Optimal control of the temperature in a catalytic converter. *Computers & Mathematics with Applications*, *67*(8), 1521-1544.
20. Gomez, B., Palacios, M. A., Gomez, M., Sanchez, J. L., Morrison, G., Rauch, S., . . . & Wass, U. (2002). Levels and risk assessment for humans and ecosystems of platinum-group elements in the airborne particles and road dust of some European cities. *Science of the Total Environment*, *299*(1-3), 1-19.
21. Hamurcu, M., Özcan, M. M., Dursun, N., & Gezgin, S. (2010). Mineral and heavy metal levels of some fruits grown on the roadsides. *Food and Chemical Toxicology*, *48*(6), 1767-1770.
22. Heck, R. M., Farrauto, R. J., & Gulati, S. T. (2016). Automotive catalyst: chapter 6. In *Catalytic air pollution control: commercial technology* (pp: 101-175). John Wiley & Sons.
23. Hwang, H. M., Fiala, M. J., Park, D., & Wade, T. L. (2016). Review of pollutants in urban road dust and stormwater runoff: part 1. Heavy metals released from vehicles. *International Journal of Urban Sciences*, *20*(3), 334-360.
24. Jackson, M. T., Sampson, J., & Prichard, H. M. (2007). Platinum and palladium variations through the urban environment: evidence from 11 sample types from Sheffield, UK. *Science of the Total Environment*, *385*(1-3), 117-131.
25. Jafari Samimi, A., & Ahmadpour, S. M. (2011). Investigating the relationship between environmental performance index and economic growth in developed countries. *Environmental and Energy Economics Quarterly*, *1*(1), 55-72.
26. Jarvis, K. E., Parry, S. J., & Piper, J. M. (2001). Temporal and spatial studies of autocatalyst-derived platinum, rhodium, and palladium and selected vehicle-derived trace elements in the environment. *Environmental Science & Technology*, *35*(6), 1031-1036.
27. Komendova, R., & Jezek, S. (2019). The distribution of platinum in the environment in large cities: a model study from Brno, Czech Republic. *International Journal of Environmental Science and Technology*, *16*, 3109-3116.
28. Ladonin, D. (2018). Platinum-group elements in soils and street dust of the southeastern administrative district of Moscow. *Eurasian Soil Science*, *51*, 268-276.
29. Le Bras, S., Deniau, H., Bogey, C., & Daviller, G. (2017). Development of compressible large-eddy simulations combining high-order schemes and wall modeling. *AIAA Journal*, *55*(4), 1152-1163.
30. Lee, H. Y., Chon, H. T., Sager, M., & Marton, L. (2012). Platinum pollution in road dust, roadside soils, and tree barks in Seoul, Korea. *Environmental Geochemistry and Health*, *34*, 5-12.
31. Li, X., Poon, C. S., & Liu, P. S. (2001). Heavy metal contamination of urban soils and street dust in Hong Kong. *Applied Geochemistry*, *16*(11-12), 1361-1368.
32. Liu, Y., Wang, Z., Zhang, L., Tian, F., & Liu, C. (2015). Spatial and temporal distribution of platinum group elements (PGEs) in roadside soils from Shanghai and Urumqi, China. *Journal of Soils and Sediments*, *15*, 1947-1959.
33. Lyubomirova, V., & Djingova, R. (2015). Accumulation and distribution of Pt and Pd in roadside dust, soil and vegetation in Bulgaria. *Platinum Metals in the Environment*, 243-255.
34. Mattey, J. (2022). *PGM Market Report May 2022*. https://www.prnewswire.com/in/news-releases/johnson-matthey publishes-latest-pgm-market-report-2022-887951524.html
35. Mehnatfar, Y., & Ghobadi, N. (2015). The effect of environmental performance index on economic growth using panel data The first national conference on geography, tourism, natural resources and sustainable development.
36. Mihaljevič, M., Galušková, I., Strnad, L., & Majer, V. (2013). Distribution of platinum group elements in urban soils, comparison of historically different large cities Prague and Ostrava, Czech Republic. *Journal of Geochemical Exploration*, *124*, 212-217.
37. Mitra, A., & Sen, I. S. (2017). Anthrobiogeochemical platinum, palladium and rhodium cycles of earth: emerging environmental contamination. *Geochimica et Cosmochimica Acta*, *216*, 417-432.
38. Moldovan, M., Palacios, M. A., Gomez, M. M., Morrison, G., Rauch, S., McLeod, C., . . . & Santamarıa, J. (2002). Environmental risk of particulate and soluble platinum group elements released from gasoline and diesel engine catalytic converters. *Science of the Total Environment*, *296*(1-3), 199-208.

39. Murat, Ö., ÖZEN, S. A., & ÇEVi, K. U. (2021). Vehicular and industrial sources of PGEs, Au and Ce in surface soil and roadside soils and dusts from two cities of Turkey. *Sakarya University Journal of Science*, *25*(2), 484-497.

40. Οικονόμου-Ηλιοπούλου, Μ., & Σφεντόνη, Τ. (2010). Environmental impact of Pt, Pd, Rh and Au from catalytic converters along roadsides: the case of Attica, Greece. *Επιστημονική Επετηρίδα του Τμήματος Γεωλογίας (ΑΠΘ)*, *100*, 47-54.

41. Omrani, M., Goriaux, M., Liu, Y., Martinet, S., Jean-Soro, L., & Ruban, V. (2020). Platinum group elements study in automobile catalysts and exhaust gas samples. *Environmental Pollution*, *257*, 113477.

42. Orecchio, S., & Amorello, D. (2011). Platinum levels in urban soils from Palermo (Italy); analytical method using voltammetry. *Microchemical Journal*, *99*(2), 283-288.

43. Osterauer, R., Haus, N., Sures, B., & Köhler, H. R. (2009). Uptake of platinum by zebrafish (Danio rerio) and ramshorn snail (Marisa cornuarietis) and resulting effects on early embryogenesis. *Chemosphere*, *77*(7), 975-982.

44. Palacios, M. A., Gomez, M. M., Moldovan, M., Morrison, G., Rauch, S., McLeod, C., . . . & Torrens, J. M. (2000). Platinum-group elements: quantification in collected exhaust fumes and studies of catalyst surfaces. *Science of the Total Environment*, *257*(1), 1-15.

45. Pan, S., Zhang, G., Sun, Y., & Chakraborty, P. (2009). Accumulating characteristics of platinum group elements (PGE) in urban environments, China. *Science of the Total Environment*, *407*(14), 4248-4252.

46. Park, J. W., Hu, Z., Gao, S., Campbell, I. H., & Gong, H. (2012). Platinum group element abundances in the upper continental crust revisited-new constraints from analyses of Chinese loess. *Geochimica et Cosmochimica Acta*, *93*, 63-76.

47. Pazhouyan, J., & Moradhasel, N. (2007). Investigating the impact of economic growth on air pollution. *Economic Research Quarterly*, *4*, 141-160.

48. Qi, L., Zhou, M. F., Zhao, Z., Hu, J., & Huang, Y. (2011). The characteristics of automobile catalyst-derived platinum group elements in road dusts and roadside soils: a case study in the pearl river delta region, South China. *Environmental Earth Sciences*, *64*(6), 1683-1692.

49. Rauch, S., Hemond, H. F., Barbante, C., Owari, M., Morrison, G. M., Peucker-Ehrenbrink, B., & Wass, U. (2005). Importance of automobile exhaust catalyst emissions for the deposition of platinum, palladium, and rhodium in the northern hemisphere. *Environmental Science & Technology*, *39*(21), 8156-8162.

50. Ravindra, K., Bencs, L., & Van Grieken, R. (2004). Platinum group elements in the environment and their health risk. *Science of the Total Environment*, *318*(1-3), 1-43.

51. Reith, F., Campbell, S., Ball, A., Pring, A., & Southam, G. (2014). Platinum in earth surface environments. *Earth-Science Reviews*, *131*, 1-21.

52. Ribeiro, A., Figueiredo, A., Sarkis, J., Hortellani, M., & Markert, B. (2012). First study on anthropogenic Pt, Pd, and Rh levels in soils from major avenues of São Paulo City, Brazil. *Environmental Monitoring and Assessment*, *184*, 7373-7382.

53. Rollinson, H. R. (2014). Using trace element data: chapter 4. In *Using geochemical data: evaluation, presentation, interpretation* (pp. 150-159). Routledge, Taylor & Francis.

54. Sen, I. S., & Peucker-Ehrenbrink, B. (2012). Anthropogenic disturbance of element cycles at the earth's surface. *Environmental Science & Technology*, *46*(16), 8601-8609.

55. Stigliani, W. M., Doelman, P., Salomons, W., Schulin, R., Smidt, G. R., & Van der Zee, S. E. (1991). Chemical time bombs: predicting the unpredictable. *Environment: Science and Policy for Sustainable Development*, *33*(4), 4-30.

56. Sutherland, R. A., Pearson, D. G., & Ottley, C. J. (2008). Grain size partitioning of platinum-group elements in road-deposited sediments: implications for anthropogenic flux estimates from autocatalysts. *Environmental Pollution*, *151*(3), 503-515.

57. Prosperity Institute. (2023). *The Legatum Centre for National Prosperity.* https://index.prosperity.com/about-prosperity/prosperity-index

58. Tsogas, G. Z., Giokas, D. L., Vlessidis, A. G., Aloupi, M., & Angelidis, M. O. (2009). Survey of the distribution and time-dependent increase of platinum-group element accumulation along urban roads in Ioannina (NW Greece). *Water, Air, and Soil Pollution*, *201*, 265-281.

59. Turner, A., & Mascorda, L. (2015). Particle-water interactions of platinum-based anticancer drugs in river water and estuarine water. *Chemosphere*, *119*, 415-422.

60. Van der Horst, C., Silwana, B., Iwuoha, E., & Somerset, V. (2018). Spectroscopic and voltammetric analysis of platinum group metals in road dust and roadside soil. *Environments*, *5*(11), 120.

61. Wang, H., Nie, L., Xu, Y., & Lv, Y. (2017). The effect of highway on heavy metal accumulation in soil in turfy swamps, Northeastern China. *Water, Air, & Soil Pollution*, *228*, 1-14.

62. Wang, Y., & Li, X. (2012). Health risk of platinum group elements from automobile catalysts. *Procedia Engineering*, *45*, 1004-1009.

63. Wichmann, H., Anquandah, G. A., Schmidt, C., Zachmann, D., & Bahadir, M. A. (2007). Increase of platinum group element concentrations in soils and airborne dust in an urban area in Germany. *Science of the Total Environment*, *388*(1-3), 121-127.

64. Wiseman, C. L., Pour, Z. H., & Zereini, F. (2016). Platinum group element and cerium concentrations in roadside environments in Toronto, Canada. *Chemosphere*, *145*, 61-67.

65. Wong, C. S., Li, X., & Thornton, I. (2006). Urban environmental geochemistry of trace metals. *Environmental Pollution*, *142*(1), 1-16.

66. World Population Review. (2024). *Human development index (HDI) by country 2024.* https://worldpopulationreview.com/country-rankings/hdi-by-country

67. Yousefinejad, M., Khalife Soltani, S. M., & Rajabi, M. (2015). Analysis of energy consumption, economic welfare in developing countries 1995-2011. *National Energy Conferences.*

68. Zereini, F., Wiseman, C., & Püttmann, W. (2007). Changes in palladium, platinum, and rhodium concentrations, and their spatial distribution in soils along a major highway in Germany from 1994 to 2004. *Environmental Science & Technology*, *41*(2), 451-456.

69. Zereini, F., Wiseman, C. L., & Puttmann, W. (2012). In vitro investigations of platinum, palladium, and rhodium mobility in urban airborne particulate matter (PM_{10}, $PM_{2.5}$, and PM_1) using simulated lung fluids. *Environmental Science & Technology*, *46*(18), 10326-10333.