JOURNAL OF HEAVY METAL RESEARCH

https://jhmr.hsu.ac.ir Journal of Heavy Metal Research, 2026, vol 1, Issue 1, 41-49

Original Article

Determination of Heavy Metal and Platinum Group Concentrations in Spent Automotive Catalysts from Common Iranian Vehicles

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Abstract

This study provides the first systematic baseline assessment of Platinum Group Metals (PGMs: Pt, Pd, Rh) and associated toxic heavy metals (Pb, Cd, Zn, Ni, Cr) in spent automotive catalytic converters (SACCs) from Iran's most prevalent vehicles. The unique composition of the Iranian fleet, dominated by a mix of older licensed European models and modern domestic and imported cars, creates a distinct SACC waste stream whose characteristics are largely undocumented. Samples from eight common models were systematically collected, prepared, and analyzed using Inductively Coupled Plasma–Mass Spectrometry (ICP–MS) and X-ray Fluorescence (XRF). The results reveal significant inter-model variability, directly linked to vehicle age and technology. A clear technological transition was observed, from older, Pt-dominant catalysts (e.g., Peugeot 405, with total PGMs up to 4,850 mg/kg) to newer, Pd-dominant, and lower-loading designs (e.g., Mazda 3, ~1,255 mg/kg). Critically, SACCs from older, high-volume models were found to be a particularly rich secondary PGM resource. Concurrently, significant concentrations of hazardous metals were quantified, with lead (Pb) reaching up to 750 mg/kg in older models—a legacy of past leaded gasoline use—and zinc (Zn) exceeding 2,000 mg/kg across all samples. These findings underscore the dual nature of SACCs in the Iranian context: a high-value "urban ore" for critical metals and a hazardous waste stream requiring stringent environmental management. This foundational dataset provides the crucial evidence base needed to develop a tailored national SACC recycling strategy, one that can harness the economic opportunity of PGM recovery while mitigating the environmental risks posed by toxic metal contaminants, thereby advancing circular economy principles in the region.

Keywords: Spent automotive catalyst; Heavy metals; Platinum group metals; Iran; Recycling; Urban mining

Received: 21 October 2025
Revised: 5 November 2025
Accepted: 10 November 2025
Published: 1 February 2026

Publisher: Hakim Sabzevari University

Citation: Khan Karani, M.A., & Dongfang, L. (2026). *Determination of Heavy Metal and Platinum Group Concentrations in Spent Automotive Catalysts from Common Iranian Vehicles*. *Journal of Heavy Metal Research*, *1*(1), 41–49.

1. Introduction

1.1. Background on Automotive Catalysts

The internal combustion engine, a pillar of modern transportation, is a major contributor to atmospheric pollution. To combat this, the three-way catalytic converter (TWC) was universally adopted as an essential exhaust after-treatment device. TWCs are engineered to convert toxic emissions simultaneously, carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NOx), into less harmful substances (CO_2, H_2O, and N_2)

via redox reactions. The device's efficacy hinges on a sophisticated material architecture. It typically comprises a ceramic cordierite ($2MgO \cdot 2Al_2O_3 \cdot 5SiO_2$) monolith with a honeycomb structure, which is coated with a high-surface-area γ-Al_2O_3 'washcoat'. This washcoat is stabilized by rare-earth oxides, such as CeO_2 and ZrO_2, to enhance thermal durability and oxygen storage capacity (Heck and Farrauto, 2001). The catalytically active components are the Platinum Group Metals (PGMs), platinum (Pt), palladium (Pd), and rhodium (Rh), finely dispersed on the washcoat. Pt and Pd are primary oxidation catalysts for CO and HCs, while Rh is the key reduction catalyst for NOx (Morita et al., 2014).

1.2. The Dual Role of SACCs: Resource and Hazard

With time, catalytic converters degrade due to thermal stress and chemical poisoning, becoming spent automotive catalytic converters (SACCs). The escalating number of end-of-life (EOL) vehicles globally has transformed SACCs into a rapidly growing waste stream (IEA, 2025). This waste, however, is also a significant secondary resource. The concentration of PGMs in SACCs is orders of magnitude higher than in their primary ores, making "urban mining" an economically compelling and environmentally preferable alternative to traditional mining (Sun et al., 2022). The high and often volatile prices of PGMs, particularly rhodium, further underscore the financial incentive for efficient recovery (Chidunchi et al., 2024). Despite this, global PGM recycling rates from SACCs remain suboptimal, indicating a vast untapped potential.

This economic opportunity is shadowed by a significant environmental threat. Beyond the valuable PGMs, SACCs contain a cocktail of heavy metals accumulated from fuel, lubricants, and engine wear, including lead (Pb), zinc (Zn), cadmium (Cd), and nickel (Ni) (Tang et al., 2021). If improperly disposed of in landfills, these toxic metals can leach into soil and groundwater, posing risks to ecosystems and human health. Leaching studies have confirmed that, based on the mobility of these metals, SACCs should be classified as hazardous waste, necessitating specialized management to prevent environmental contamination (Bahaloo-Horeh and Mousavi, 2020). This duality—a valuable resource that is also a hazardous material—defines the central challenge of SACC management.

1.3. The Iranian Context and Research Gap

Iran provides a unique and understudied landscape for SACC management. Its automotive market is characterized by a distinctive fleet, heavily dominated by domestically produced vehicles (e.g., Saipa Pride, IKCO Samand) and long-running licensed production of older European models, notably the Peugeot 405 (bestsellingcarsblog.com, 2010). This fleet composition differs markedly from those in North America, Europe, or East Asia, where most existing SACC characterization studies have been conducted. Consequently, the catalyst technology, PGM loading, and contaminant profiles within the Iranian SACC stream are likely to be different.

Furthermore, Iran's history of leaded gasoline use, which persisted for many years, may have resulted in a legacy of lead contamination in older vehicles' exhaust systems (Roydel et al., 2025). This, combined with severe urban air pollution issues linked to traffic emissions (Mehdipour et al., 2020), creates a pressing need for effective waste management solutions. While the potential for SACC recycling is recognized locally (Tahamipour Zarandi and Moghise, 2022), there is a critical knowledge gap: a lack of published, peer-reviewed data on the elemental composition of SACCs from Iran's most common vehicles. This absence of foundational data severely hampers the ability to design efficient recovery processes, assess economic viability, and formulate evidence-based environmental policies.

1.4. Study Objectives

This research aims to fill the aforementioned knowledge gap by conducting the first comprehensive analysis of the metallic content of SACCs from Iran's most common vehicles. The specific objectives are:

1. To quantitatively determine the concentrations of Pt, Pd, and Rh in SACCs from eight prevalent vehicle models in Iran.
2. To quantify the concentrations of toxic and other heavy metals, including Pb, Zn, Ni, Cr, and Cd.
3. To analyze and compare the metallic content and PGM ratios across different vehicle models, correlating findings with vehicle age, origin, and technology.
4. To provide a foundational dataset to evaluate the dual nature of the Iranian SACC stream—its economic potential for PGM recovery and its environmental hazard profile—to inform the development of a sustainable national management strategy.

2. Methodology and Data

2.1. Sample Collection and Preparation

2.1.1. Sampling Strategy

A total of 40 SACC samples were collected from automotive scrapyards and exhaust repair workshops in Tehran and Isfahan, Iran. To ensure a representative cross-section of the national fleet, five independent samples (n=5) were obtained for each of eight target vehicle models. These models, detailed in Table 1, include high-volume domestic products, older licensed models, and more modern vehicles. Only original equipment manufacturer (OEM) converters were selected. For each sample, vehicle model, manufacturing year, and estimated mileage were recorded.

Table 1. Overview of Vehicle Models Selected for the Study.

Vehicle Model	Manufacturer	Typical Production Era in Iran	Origin / Technology Base
Saipa Pride	Saipa	1993–2020	Korean (Kia Pride, 1980s)
Peugeot 405	IKCO	1992–2020s	French (Peugeot, 1980s-90s)
Peugeot 206	IKCO	2001–2020s	French (Peugeot, late 1990s)
IKCO Samand	IKCO	2001–2020s	Domestic (based on Peugeot 405 platform)
IKCO Dena	IKCO	2015–Present	Domestic (modernized platform)
Renault Logan (Tondar 90)	IKCO / Pars Khodro	2007–2019	French/Romanian (Dacia/Renault, 2000s)
Mazda 3	Bahman Group	2006–2019	Japanese (Mazda, 2000s)
Suzuki Grand Vitara	IKCO	2007–2018	Japanese (Suzuki, 2000s)

2.1.2. Standard Operating Procedure (SOP) for Pre-treatment

A rigorous SOP, adapted from established protocols (CPCB, 2021), was followed. The process is illustrated in Fig. 1. First, the stainless-steel casing of each SACC was cut open (decanning) to extract the internal ceramic monolith. The entire monolith was then crushed into coarse fragments (~1-2 cm) using a jaw crusher. Subsequently, the fragments from each monolith were individually milled in a planetary ball mill (PM 100, Retsch) with zirconia media to prevent metal contamination. The material was milled to a fine powder and sieved to ensure a particle size of <100 µm, as confirmed by SEM imaging (Fig. 2). This fine powder was then homogenized in a V-blender for 30 minutes. Finally, a ~100 g representative sample of the dried (105°C for 4 hours) powder was stored in a sealed HDPE container for analysis.

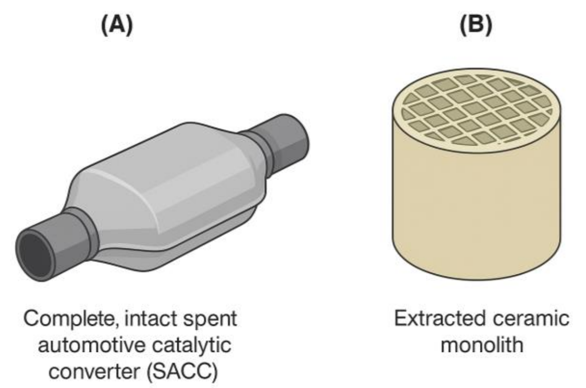

Fig. 1. A schematic image showing the Visual representation of SACC components. (A) A complete, intact SACC unit. (B) The extracted ceramic monolith shows its honeycomb structure.

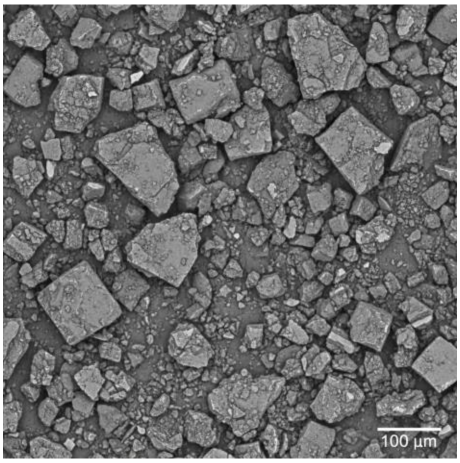

Fig. 2. SEM micrograph of the final homogenized SACC powder, confirming particle size <100 µm. (Note: Representative image).

2.2. Chemical Analysis

2.2.1. Sample Digestion: Microwave-Assisted Acid Digestion

A CEM MARS 6 Microwave Digestion System was used for sample digestion. Approximately 0.25 g of dried powder was weighed into a TFM-lined vessel. A 3:1 mixture of high-purity HCl (9 mL) and HNO_3 (3 mL) (aqua regia) was added. The vessels were sealed and subjected to a microwave program (15-min ramp to 180°C, 30-min hold at 180°C). After cooling, the digestate was quantitatively transferred and diluted to 100 mL with deionized water.

2.2.2. Instrumentation and Elemental Quantification

A dual-technique approach was employed for comprehensive characterization.

X-ray Fluorescence (XRF) Spectroscopy: A benchtop EDXRF spectrometer (Bruker S1 Titan) was used for rapid, semi-quantitative screening of the bulk matrix composition of the homogenized powders. XRF determines elemental concentrations (e.g., Al, Si, Ce, Zr). For reporting and by convention in geological and ceramic analysis, these elemental results were stoichiometrically converted to their most common stable oxide forms (e.g., Al_2O_3, SiO_2). It is important to note that this method provides an estimate of the chemical composition, while definitive phase identification would require techniques like X-ray Diffraction (XRD).

Inductively Coupled Plasma-Mass Spectrometry (ICP-MS): Primary quantitative analysis of PGMs and other trace heavy metals was performed using an Agilent 8900 Triple Quadrupole ICP-MS (ICP-QQQ). This technique was chosen for its exceptional sensitivity, wide dynamic range, and its ability to mitigate polyatomic interferences. Operating in MS/MS mode with a collision/reaction cell, the system provides highly accurate, interference-free measurements of Pt, Pd, and Rh, which is crucial for complex matrices like SACCs (Kolbadinejad and Ghaemi, 2023).

2.3. Quality Assurance and Quality Control (QA/QC)

A comprehensive QA/QC protocol was implemented. The ICP-MS was calibrated daily with a five-point curve ($r^2 > 0.999$). A Certified Reference Material (NIST SRM 2556, Used Auto Catalyst) was analyzed with each batch, with recoveries required to be within ±10% of certified values. Procedural blanks, sample replicates (RSD < 15%), and matrix spikes (recovery 75-125%) were processed with each batch. A multi-element internal standard solution was used online to correct for instrument drift and matrix effects, with recoveries monitored to be within 80-120%.

2.4. Statistical Analysis and Data Reporting

All experiments were conducted on five independent SACC samples for each of the eight vehicle models (n=5). The data are presented as the mean ± standard deviation (SD). The SD reflects the real-world inter-sample variability among catalysts from different vehicles of the same model, which is a result of their diverse operational histories, and not merely analytical uncertainty. This variability is a key parameter considered in our discussion.

3. Results and Discussion

3.1. Physicochemical Characterization of SACC Powder

Preliminary XRF analysis confirmed the expected bulk composition of the SACC powders (Table 2). The dominant components were alumina (Al_2O_3, 30-50 wt.%) and silica (SiO_2, 30-45 wt.%), constituents of the cordierite substrate and alumina washcoat. Significant levels of washcoat promoters, cerium oxide (CeO_2, 1.5-5.2%) and zirconium oxide (ZrO_2, 1.3-3.0%), were also detected, consistent with their role in enhancing thermal stability and oxygen storage capacity (Robles-Lorite et al., 2023). These findings align with global reports (Bahaloo-Horeh and Mousavi, 2020), confirming the fundamental material similarity of the Iranian SACC stream, though variations in promoter packages were noted across models.

Table 2. Major Elemental Composition (wt.%) of SACC Powders as Determined by XRF Analysis (Mean ± SD, n=5 per model). Results are reported as weight percent (wt.%) of the most common oxides, calculated from elemental concentrations. This is a conventional reporting method and does not represent direct phase analysis.

Vehicle Model	Al_2O_3 (%)	SiO_2 (%)	CeO_2 (%)	ZrO_2 (%)	Fe_2O_3 (%)	Other Oxides (%)
Saipa Pride	42.5 ± 3.1	38.2 ± 2.5	2.1 ± 0.4	1.3 ± 0.3	1.8 ± 0.5	14.1
Peugeot 405	45.1 ± 2.8	35.5 ± 3.0	3.5 ± 0.6	1.9 ± 0.4	2.1 ± 0.6	11.9
Peugeot 206	46.3 ± 2.5	33.8 ± 2.2	4.0 ± 0.5	2.2 ± 0.3	1.5 ± 0.4	12.2
IKCO Samand	44.8 ± 3.0	36.1 ± 2.8	3.3 ± 0.7	1.8 ± 0.5	2.0 ± 0.5	12.0
IKCO Dena	47.2 ± 2.1	32.5 ± 2.4	4.5 ± 0.4	2.5 ± 0.3	1.3 ± 0.3	12.0
Renault Logan	48.0 ± 1.9	31.9 ± 2.0	4.8 ± 0.5	2.8 ± 0.4	1.1 ± 0.2	11.4
Mazda 3	49.5 ± 1.5	30.1 ± 1.8	5.2 ± 0.3	3.0 ± 0.2	0.9 ± 0.2	11.3
Suzuki Grand Vitara	46.8 ± 2.3	33.0 ± 2.5	4.2 ± 0.6	2.4 ± 0.4	1.4 ± 0.3	12.2

3.2. Platinum Group Metal (PGM) Concentrations

The ICP-MS analysis revealed substantial PGM concentrations, confirming Iranian SACCs as a high-grade secondary resource. The results, detailed in Table 3 and visualized in Fig. 3, show wide variations linked to vehicle technology and age.

Table 3. Mean Concentrations (mg/kg ± SD, n=5) of Platinum, Palladium, and Rhodium in Spent Catalysts as Determined by ICP-MS.

Vehicle Model	Platinum (Pt) (mg/kg)	Palladium (Pd) (mg/kg)	Rhodium (Rh) (mg/kg)	Total PGM (mg/kg)	Pt/Pd Ratio
Saipa Pride	1150 ± 210	1450 ± 250	280 ± 55	2880 ± 160	0.79
Peugeot 405	2800 ± 450	1600 ± 300	450 ± 80	4850 ± 290	1.75
Peugeot 206	1500 ± 280	2200 ± 350	380 ± 70	4080 ± 240	0.68
IKCO Samand	2450 ± 380	1750 ± 290	420 ± 75	4620 ± 230	1.40
IKCO Dena	950 ± 180	2500 ± 400	350 ± 60	3800 ± 220	0.38
Renault Logan	850 ± 150	2850 ± 450	320 ± 50	4020 ± 210	0.30
Mazda 3	250 ± 50	850 ± 120	155 ± 30	1255 ± 110	0.29
Suzuki Grand Vitara	650 ± 110	2100 ± 330	290 ± 45	3040 ± 175	0.31

The most striking finding is the exceptionally high PGM content in SACCs from the Peugeot 405 and the related IKCO Samand, averaging 4,850 mg/kg and 4,620 mg/kg, respectively. These older-generation vehicles feature a high Pt/Pd ratio (1.75 and 1.40), characteristic of 1990s catalyst technology that favored platinum before palladium became more cost-competitive. This high loading reflects a less optimized use of precious metals (Sun et al., 2022). Given the vast number of these models in Iran, their SACCs represent a prime feedstock for PGM recycling.

In stark contrast, newer models demonstrate a clear technological shift. The Renault Logan, IKCO Dena, and Suzuki Grand Vitara all show Pd-dominant formulations (Pt/Pd ratios of 0.30-0.38), a trend consistent with modern global catalyst design (Tang et al., 2021). This is most pronounced in the Mazda 3, which has both the lowest total PGM loading (1,255 mg/kg) and a very low Pt/Pd ratio (0.29). This aligns with Mazda's development of single-nanocatalyst technology aimed at drastically reducing precious metal use (Mazda Newsroom, 2009). Rhodium content remained a relatively consistent fraction (8-12%) of total PGMs across most models, reflecting its indispensable role in NOx reduction (Jeong et al., 2024).

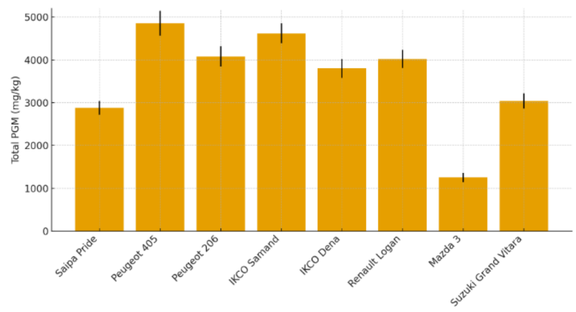

Fig. 3. Comparison of average total PGM concentration (mg/kg) across the eight vehicle models. Error bars represent the standard deviation (n=5). Data derived from ICP-MS analysis.

3.3. Other Heavy Metal Concentrations

The analysis also quantified a range of environmentally significant heavy metals (Table 4), which accumulate from fuel, lubricants, and engine wear. These results highlight the hazardous nature of SACC waste.

Table 4. Mean Concentrations (mg/kg ± SD, n=5) of Selected Heavy Metals in Spent Catalysts as Determined by ICP-MS.

Vehicle Model	Lead (Pb)	Zinc (Zn)	Nickel (Ni)	Chromium (Cr)	Cadmium (Cd)	Manganese (Mn)
Saipa Pride	750 ± 150	2100 ± 300	180 ± 40	95 ± 20	15 ± 4	450 ± 90
Peugeot 405	680 ± 130	2500 ± 350	220 ± 50	110 ± 25	18 ± 5	510 ± 100
Peugeot 206	350 ± 80	2350 ± 320	190 ± 45	100 ± 22	12 ± 3	480 ± 95
IKCO Samand	650 ± 120	2450 ± 340	210 ± 48	105 ± 24	16 ± 4	500 ± 98
IKCO Dena	150 ± 40	2800 ± 400	150 ± 35	80 ± 18	8 ± 2	550 ± 110

Vehicle Model	Lead (Pb)	Zinc (Zn)	Nickel (Ni)	Chromium (Cr)	Cadmium (Cd)	Manganese (Mn)
Renault Logan	120 ± 30	2950 ± 420	140 ± 30	75 ± 15	7 ± 2	580 ± 120
Mazda 3	80 ± 25	3100 ± 450	120 ± 28	65 ± 14	5 ± 1.5	620 ± 130
Suzuki Grand Vitara	210 ± 50	2700 ± 380	160 ± 38	85 ± 19	10 ± 2.5	530 ± 105

A critical finding is the high concentration of lead (Pb) in older models like the Saipa Pride (750 mg/kg) and Peugeot 405 (680 mg/kg). This is a clear legacy of historical leaded gasoline use in Iran. Even after the phase-out, Pb deposited in engines continues to accumulate on the catalyst surface (Tahamipour Zarandi and Moghise, 2022), corroborating studies that identified vehicles as a major source of Pb in Iranian roadside soils (Saeedi et al., 2009). Zinc (Zn) was found at high levels (2100-3100 mg/kg) across all models, originating from the common anti-wear lubricant additive ZDDP. The presence of these metals, along with Ni, Cr, and Cd, confirms that SACCs must be treated as hazardous waste, as their components can be mobilized under environmental conditions (Bahaloo-Horeh and Mousavi, 2020). Figure 4 provides a comparative visualization of these contaminant loads for key models.

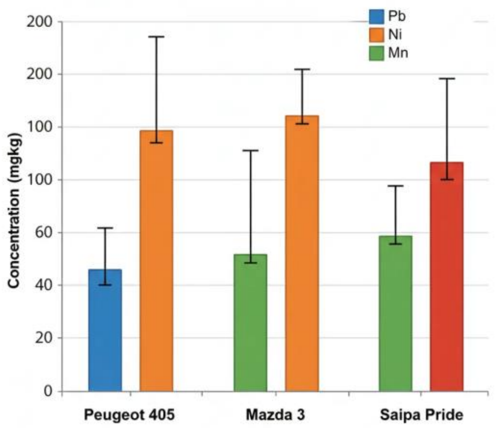

Fig. 4. Comparison of selected heavy metal concentrations (mg/kg) for key vehicle models, showing differing contaminant profiles. Error bars represent the standard deviation (n=5).

3.4. Implications for Recycling and Environmental Management in Iran

The results carry profound implications for industrial policy and environmental protection in Iran. The high PGM concentrations, especially in the vast fleet of older vehicles, present a compelling economic driver for establishing a domestic SACC recycling industry. Developing indigenous processing capabilities could capture significant value, create jobs, and reduce reliance on imported PGMs.

3.4.1. A Quantitative Perspective on Economic Potential

The economic incentive can be quantified. For instance, a single SACC from a Peugeot 405 (approx. 1.2 kg monolith) with an average total PGM content of 4,850 mg/kg contains approximately 5.8 grams of PGMs. Based on early 2024 prices, with rhodium alone valued at ~€150/g (Chidunchi et al., 2024), the ~0.54 grams of rhodium in one unit could be worth over €80. Extrapolated across millions of such vehicles at their end-of-life, this illustrates a multi-million-euro national resource waiting to be tapped.

3.4.2. Challenges and Strategic Considerations

However, realizing this potential is challenging. This characterization data is a critical first step, providing the knowledge base for designing extraction processes tailored to the Iranian SACC stream. For example, the high Pt content in older catalysts may favor specific hydrometallurgical routes, while the high concentrations of contaminants like Pb and Zn must be managed. These contaminants can interfere with PGM recovery and require separate, costly treatment of waste streams from the recycling process. From an environmental standpoint, our data provides quantitative evidence to support the formal classification of SACCs as hazardous waste under Iranian national regulations (Mohammadi et al., 2023), mandating a regulated collection system and precluding landfilling.

3.5. Data Variability and Implications for Sampling

A crucial observation from our data (Tables 3 and 4) is the high standard deviation for many elemental concentrations. This variability is not an artifact of the analytical measurement but a reflection of the inherent heterogeneity of the SACC waste stream. Catalysts from vehicles of the same model have experienced different operational lives, including variations in mileage, fuel quality, oil consumption, and driving conditions. This leads to real differences in PGM loading and contaminant accumulation. For a commercial recycling operation, this highlights a critical challenge: a single SACC is not representative of the whole stream. Therefore, industrial-scale processing will require robust sampling and homogenization protocols for large batches (e.g., several tons of crushed monoliths) to obtain an accurate assessment of the feedstock's composition before committing to a specific metallurgical process.

4. Conclusion and Policy Implications

4.1. Summary of Findings

This study delivered the first systematic analysis of PGM and heavy metal content in SACCs from Iran's most common vehicles. We found that this waste stream is a heterogeneous but highly valuable secondary resource. Total PGM concentrations ranged from 1,255 mg/kg in modern, low-loading catalysts to as high as 4,850 mg/kg in older, Pt-dominant models like the Peugeot 405. Concurrently, we confirmed the presence of significant levels of toxic metals, including lead (up to 750 mg/kg) and zinc (up to 3,100 mg/kg), which solidifies the classification of SACCs as hazardous waste.

4.2. Significance and Implications and Proposed Framework

The significance of this research extends beyond data reporting. It provides an actionable foundation for policy and industry. We propose a classification framework to guide SACC processing strategies in Iran:

Class A (High-Value, High-Risk): e.g., Peugeot 405, IKCO Samand. Characterized by high PGM content (>4,000 mg/kg, Pt-dominant) and high lead contamination (>600 mg/kg). Processing requires a flowsheet that maximizes PGM recovery while incorporating a dedicated step for managing a hazardous lead-containing residue.

Class B (Modern, Pd-Dominant): e.g., Renault Logan, IKCO Dena, Peugeot 206. Characterized by moderate-to-high PGM content (3,800-4,100 mg/kg, Pd-dominant), low Pb, but high Zn. The process should be optimized for palladium recovery and must address zinc removal, as zinc can interfere with leaching processes.

Class C (Low-Loading, Modern Tech): e.g., Mazda 3. Characterized by low PGM content (<1,500 mg/kg) and low Pb. Economic viability depends on highly efficient, low-cost recovery methods and economies of scale.

This framework highlights the crucial conflict: the highest-value SACCs (Class A) also carry the highest environmental risk and processing complexity due to lead. A sustainable national strategy must therefore integrate the economic incentive of PGM recovery with the environmental imperative of hazardous waste management, creating a circular economy that is both profitable and responsible.

4.3. Future Work

While this study provides a crucial baseline, it opens the door for targeted, hypothesis-driven research. Future work should focus on:

1. Environmental Risk Assessment: Answering the question: What is the differential leachability of Pb and other toxic metals from Class A versus Class B and C catalysts under simulated Iranian environmental conditions (e.g., using TCLP/SPLP tests)? This would quantify the specific environmental risk posed by each class.
2. Tailored Process Optimization: Investigating the hypothesis that a selective leaching process (e.g., using specific halide concentrations or redox potentials) can be developed to preferentially extract PGMs from Class A feedstock while simultaneously passivating lead into a stable, non-leachable phase like $PbSO_4$ or $PbCl_2$.
3. Techno-Economic and Life-Cycle Assessment (LCA): Developing a detailed techno-economic model for a domestic recycling facility that can flexibly process batches of Class A, B, and C materials. This model should be coupled with a full LCA to compare the environmental and economic footprint of this strategy against the current practice of exportation or landfilling.
4. Expanded Fleet Inventory: Broadening the analysis to include SACCs from heavy-duty vehicles (trucks, buses) and a wider range of passenger cars to create a comprehensive national inventory of this secondary resource, refining the proposed classification framework.

Acknowledgements

The chemical analyses in this study were conducted at the State Key Laboratory of Complex Nonferrous Metal Resources Clean Utilization, Kunming University of Science and Technology, China. We would like to thank the laboratory staff for their assistance with these analyses. We also thank the anonymous reviewers for their constructive comments, which helped improve the manuscript.

Declarations

Data and code availability

All data generated or analyzed during this study are available from the corresponding author upon reasonable request. No computational code was used in this study.

Conflicts of interest

The authors announced that they have no known conflicts of interest or personal relationships that could have appeared to influence the work reported in this manuscript.

Ethical approval

The authors declare no ethical issues; the research was carried out in full agreement with ethical standards. Also, this paper is neither under Review nor published elsewhere.

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