Educational Administration: Theory and Practice
2024, 30(2), 2281-2289
ISSN: 2148-2403
https://kuey.net/
Research Article

Perception-Based Assessment of Vanadium and Chromium Incorporated Periodic Mesoporous Silicates Derived from Agro-Industrial Wastes for Green Oxidation Catalysis: A Structure–Activity Perspective

Dr. M.R. Deshpande[1*], Dr. Kapure G.P[1]. Sushant Choudekar[2]

[1*]N.S.B. College Nanded, Email: nptel2020@gmail.com,
[1]S.G.B. Mahavidyalaya Purna, Email: gpk_2010@rediffmail.com,
[2]N.S.B. College Nanded, Email: sushant8410@gmail.com

Citation: Dr. M.R. Deshpande, et.al (2024). Revisiting Wessex: Perception-Based Assessment of Vanadium and Chromium Incorporated Periodic Mesoporous Silicates Derived from Agro-Industrial Wastes for Green Oxidation Catalysis: A Structure–Activity Perspective , *Educational Administration: Theory and Practice*, 30(2) 2281-2289
Doi: 10.53555/kuey.v30i2.11470

ARTICLE INFO

ABSTRACT

The increasing demand for sustainable oxidation processes has intensified interest in environmentally benign heterogeneous catalysts. Periodic mesoporous silicates (PMS) incorporating vanadium and chromium have attracted attention due to their favorable structure–activity characteristics in green oxidation catalysis. This study evaluates expert perceptions on the feasibility, catalytic performance, and sustainability of vanadium- and chromium-incorporated PMS synthesized from agro-industrial waste–derived silica. Primary data were collected through a Google Form–based survey involving researchers, industry professionals, and postgraduate students. The findings highlight the perceived importance of pore uniformity and metal dispersion, strong acceptance of agro-waste silica, and promising industrial and environmental potential of these catalysts.

Keywords: Vanadium catalysts; Chromium catalysts; Mesoporous silicates; Agro-industrial waste; Green oxidation; Survey research

1. Introduction

1.1 Background

The rapid increase in demand for efficient and global catalysts, and a potential increase in profit, has captured the attention of many industries including the synthesis of fine chemicals, pharmaceuticals, polymers, and industrial intermediates (Coccia et al., 2024).

The most crucial issue in petrochemical processing is the catalysts that are used. Involved in harsh and toxic reactions, and employing the petrochemical, nonrenewable and expensive, and as harmful as their substrates, producing by-products.

Because of new policies and, along with the awareness and real need for sustainable chemicals, the petrochemical industry has had to move to alternatives for primitive catalysts as of late (Nirmal Kumar et al., 2021)

The homogeneous catalysts that are stoichiometric oxidants, and do not segregate or recycle themselves in the systems with elementary oxidation, are removed and secondary pollutants are formed.

Also, metal catalysts tend to show diminishing returns when it comes to productivity, due to leaching, structural collapse, and, ultimately, a loss of metal. These result in poor process selectivity due to catalytic inefficiency.

Because of these problems, catalysts that show heterogeneity, stability, and are 'green' are very desirable. Of the many commercially available oxidation catalysts, mesoporous silica (PMS) supports are very often regarded as the best choice for solid catalytic systems (Abinader Vasconcelos et al., 2023).

They have the best framework and pore structure of all solid catalysts, and also have high uniformity and a customizable surface area. In addition, their ordered mesoscale structures enhance the mass transport of the active species.

Copyright © 2024 by Author/s and Licensed by Kuey. This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

1.2 Role of Vanadium and Chromium in Oxidation Catalysis

Considerable work has been done and much more is valiant and invaluable in the area of exploration of the catalysis of oxidation of vanadium and chromium. The redox equilibria of these two elements serve as the fundamental basis of these catalysts.

Vanadium catalysts, in particular, are highly sought after which is largely due to its ability to oxidation to selectively catalyze the oxidation of hydrocarbons and alcohols, due to its specific property of being able to undergo various oxidation states.

In addition, the catalytic activity of Ot(V) is appreciated because of its ability to sustain rigorous reaction conditions; for its oxidative ability, thermal stability and for more rigorous reaction conditions.

But with both of these metals The activity of the catalyst is almost solely attributed to its degree of dispersion, positioning and coordination within the support matrix.

The catalytically active metallic species are literally un in their spatial design which can lead to the overlap of the active site which may negatively influence the activity and selectivity of the catalyst (Cai & Li, 2020).

Overall, Vanadium catalysts are largely associated with excessive selectivity and in contrast, the Chromium catalysts are largely associated with excessive environmental and toxicity risks; thus it is imperative to have an analytical design for the spatial intercalation of these metals within the robust mesoporous frameworks.

1.3 Agro-Industrial Waste as a Sustainable Silica Source

The mesoporous silicate materials can be produced using the renewable and abundant resource silica. Byproducts of the agro-industrial sector such as palm ash, bagasse ash, and rice husk ash, which have the potential to be environmentally polluted if neglected and/or processed improperly, offer high amounts of amorphous silica.

The silica found in agro-waste is highly compatible with the circular economy for it considers materials that would otherwise be seen as waste and produces high value catalytic materials from them.

The use of agro-waste to produce green oxidation catalysts is a value-added process, and it helps reduce the environmental and economic costs associated with the production of catalysts.

1.4 Research Gap

It seems that little to no research has been done on mesoporous silicate catalysts and the entrapment of transition metals within catalysts, along with the practicality, feasibility and scalability along with the performance of a P- stakeholder level catalyst.

Most of the research seems to stop with the synthesis of the catalysts at the laboratory level and the assessment of the subsequent catalytic effect. There seems to be no, or very little, researchers that have tried to look at the catalyst from the industrialization and sustainability point of view, and that seems to be a significant void in the literature.

The designer end-user perspective (mainly researchers, industry, and graduate/postgraduate students) also seems to be largely untapped in the case of mesoporous silicate catalysts. The synthesis and the catalytic effect of mesoporous silicate catalytic units have been the most studied, and it seems that their synthesis and design ideas have been largely ignored.

The most important and apparent "human" elements of the research on mesoporous silicate catalysts remain unaddressed in the available literature on mesoporous silicate catalysts.

1.5 Objectives of the Study

This study examines the viewpoint of specialists on Silica contained in agro-industrial waste as well as in agro-industrial-based periodic mesoporous silicate catalysts with Vanadium and Chromium.

In particular, the study examines through surveys the perceived \\"structure-activity\\" relationships and focuses on silicate structure, pore consistency, and uniformity and touches on silicate dispersion.

In addition, the study intends to analyze positive catalysis in light of sustainability, feasibility, and scope concerning the catalysts within the domain of green oxidation catalysis agro-waste and agro-industrial silica waste.

2. Review of Literature

2.1 Periodic Mesoporous Silicates in Catalysis

Topakas and Hohn (2025) state that Periodic Mesoporous Silicates (PMS) have exceptionally high surface area (greater than 800 m2/g) and large enough mesoporous channels that allow unhindered transport of reactants and products, making them more resistant to high metal loadings. The lack of micropores removes diffusion constraints.

Unlike conventional catalyst supports such as alumina and silica gel, the preference of PMS is due to better control over textural and metal distribution. In addition, framework heteroatoms that can be added to improve catalytic activity. For these reasons, PMS is a common choice as catalyst supports for oxidants, acid catalysts, and redox catalysts.

2.2 Vanadium-Based Oxidation Catalysts

Vanadium catalysts, particularly for selective oxidation, have shown efficiency in many oxidation reactions. It has been previously stated that, "vanadium attached to mesoporous materials increases stability and dual accessibility of zeolites. The oxidation state, coordination, and complex formation of the vanadium with the support surface influence the performance of the catalysts."
With mesoporous silicate frameworks, dispersed vanadium increases selectivity and minimizes over-oxidation. However, optimization of structure is required and an excess of vanadium may cause pore blockage and reduction of surface area.

2.3 Chromium-Based Oxidation Catalysts

Due to their efficiency and minimal loss of deactivation (Fosso-Kankeu et al, 2022), industrial catalysts have great value, and so does chromium. Some mesoporous silicates with strong metal-support interactions can completely oxidize chromium. Nevertheless, the design of industrial catalysts and the continued use of catalysts is restricted by the toxicity, health, and environmental risk of chromium.
Some studies have proposed encasing chromium species in mesoporous silicates to minimize the leaching and fragmentation of catalysts. However, the dual challenge of preventing environmental degradation and optimizing catalytic efficiency continues to endure.

2.4 Agro-Waste-Derived Silica Materials

Research indicates that agro-industrial waste can be used to obtain silica and synthesize catalysts. The renewably sourced catalysts are comparable to (and can exceed) the texture of conventional silica (Petričević et al., 2025).
Catalysts from agro-waste-derived silica perform satisfactorily in oxidation and acid-catalyzed reactions. The Importance of Primary, Stakeholder-Driven Research Laboratory studies are very useful, especially for understanding mechanisms, however, for catalyst technologies to work and be adopted by industries, it needs to be economically, environmentally, and practically justified. Primary research that incorporates stakeholder perspectives can help to close this gap by articulating the challenges and opportunities to support better and more sustainable strategies for catalyst development.

3. Synthesis of Vanadium and Chromium Incorporated Periodic Mesoporous Silicates

The literature provides extensive documentation on the incorporation of vanadium and chromium into Periodic Mesoporous Silicates (PMS) and the potential application of these materials for the design of efficient and sustainable catalysts for use in oxidation reactions.
Several vanadium and chromium PMS materials have been synthesized using a range of techniques. However, the soft templating sol-gel method is the preferred synthesis method as it offers the means to prepare a wide range of highly ordered mesoporous frameworks, with desirable and easily manipulated textural characteristics (Coccia et al., 2024).
Additionally, this method is optimal for the incorporation of transition metal species into silicate matrices, resulting in catalytically active materials with a good structural framework and catalytic accessibility.
Agro-industrial wastes, including rice husk ash, sugarcane bagasse ash, and palm ash, have been identified as potential materials to be used as alternative silica sources in the design of sustainable synthesis routes.
To utilize these materials, a pre-treatment of washing, acid leaching, and controlled thermal treatment is required to remove impurities and produce a silica-rich, amorphous material. As a result of this process, these silicas become economically advantageous and ecologically friendly alternatives to commercial silicas, contributing to the circular economy of the synthesis process.
As part of the sol-gel synthesis process, dissolved silica is generally extracted under alkaline conditions to produce silicate species in solution. Then, structure-direction agents, most commonly cetyltrimethylammonium bromide (CTAB), are added to control the development of the mesoporous network (Nirmal Kumar et al., 2024).
The silicate species coupled with the micelle self-assembly of the surfactant results in the formation of periodic mesostructures with defined uniform pore sizes. Depending on the targeted oxide coordination and distribution at the mesoporous level, vanadium and chromium precursors (ammonium metavanadate and chromium nitrate, for example) are added during the sol-gel process or post-synthesis impregnation.
Within the precursor mesoporous silica (PMS) framework, the presence of vanadium and chromium is a substantive factor in determining catalytic activity. If metal species are added during the sol-gel process, they could become partially incorporated into the silicate framework and form metal-oxygen-silicon (M–O–Si) linkages.
Such framework incorporation optimally improves the distribution and the stability of the metal to mitigate metal agglomeration and leaching during the catalytic cycle. In contrast, post-synthesis impregnation creates the condition for surface enrichment of the metal species, which is an advantage for catalytic accessibility, but pore blockage during catalytic activity is of concern.
After the addition of the precursors, the mixture undergoes hydrothermal treatmen for a specific time and at a specific temperature for the purpose of mesostructural ordering and framework condensation(Abinader Vasconcelos et al., 2023).

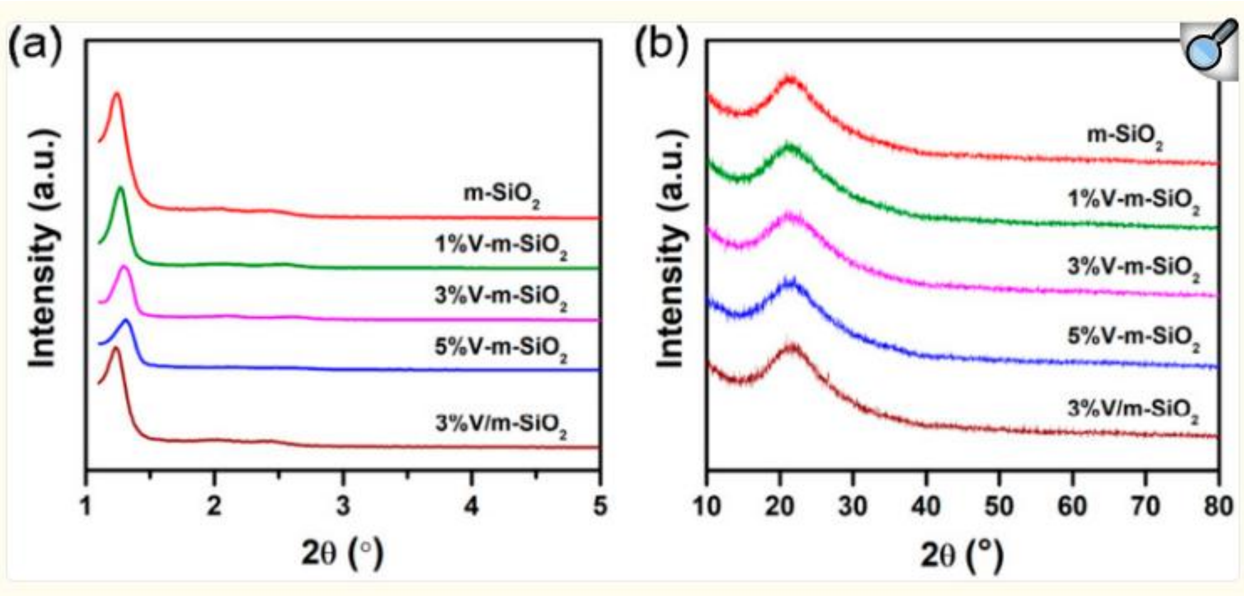
Then, calcination at high temperatures removes the organic template and locks in the mesoporous structure. This step is critical for the formation of catalysts that are thermally stable and have pore channels and active sites that are accessible for oxidation.
Catalysts made form agro-waste-derived silicas and containing chromium and vanadium show high and uniform redox activity, pore size, and surface area—these are the aspects noted in the available literature.
With the optimal synthesis and metal incorporation strategies and the use of sustainable agro-waste-derived silicas, it is possible to develop catalytic systems for green oxidation catalysis that are high quality in terms of their function and structure.

4. Characterization Techniques for Vanadium- and Chromium-Incorporated Periodic Mesoporous Silicates

The determination of the structure of vanadium-and chromium-incorporated periodic mesoporous silicates (PMS) aids in the understanding of the link between structure and catalytic activity in PMS for green oxidation reactions. Detailed physicochemical characterization provides data on the order of the mesostructure, its textual properties, the distribution of metals, and the integrity of the framework, all of which affect catalytic activity and stability.
From available literature, it is common practice and sufficient for the characterization of these types of catalysts to combine X-ray diffraction, nitrogen adsorption-desorption, and some form of spectroscopy and electron microscopy.

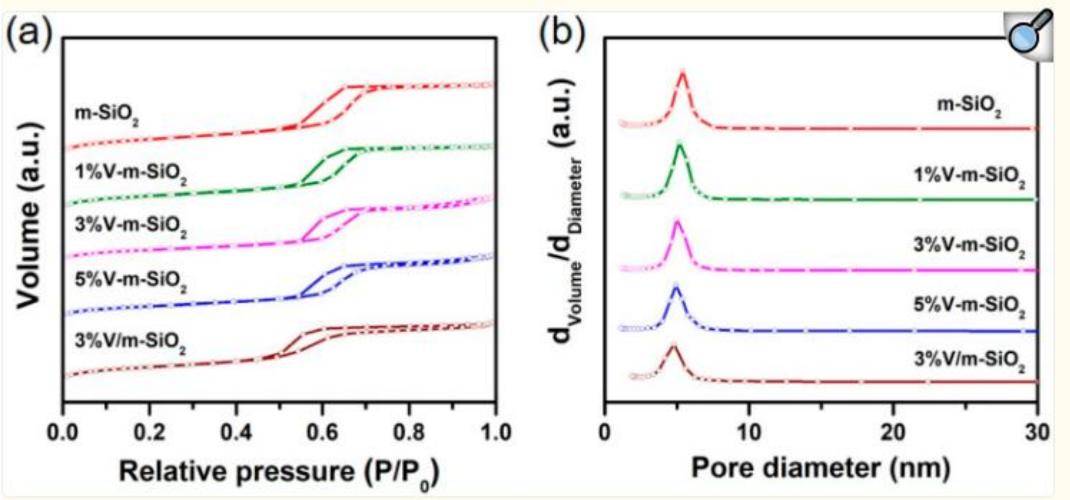
4.1 X-ray Diffraction (XRD)

X-ray diffraction gives the first insight into the ordering and phases of the PMS. Peaks in the low-angle XRD of the PMS are the first indicator of the development of periodic mesoporous structures. These peaks are the first proof that periodically mesoporous frameworks have been built and that chromium and vanadium incorporation do not affect the meso-structural order.
The dispersion of metal species is the focus of wide-angle XRD (Cai& Li,2020). The low or absent peaks for the crystalline vanadium and chromium oxides generally refers to good dispersion of metal species and incorporation in the framework which is always the case for PMS with improved catalytic activity to avoid deactivation through metal sintering.



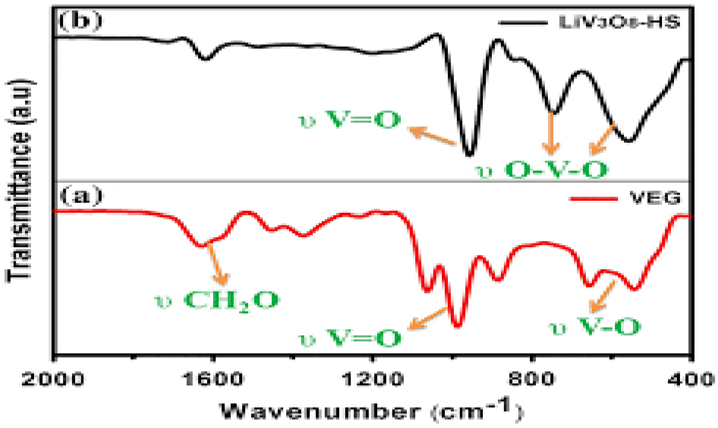
4.2 Analysis of Nitrogen Adsorption-Desorption (BET)

The nitrogen adsorption-desorption study yields important texture attributes such as surface area, pore volume, and pore diameter. The type-'IV adsorption' isotherms for the Vanadium and Chromium PMS materials and H1 loops indicate the presence of mesoporous materials of uniform cylindrical pore structures (de Oliveira et al., 2025).
The presence of metal species in the framework slightly decreases the surface area and pore volume owing to pore blockage and/or framework collapse. The retention of mesoporosity in the catalyst materials is, however, a positive indication, as it suggests that the catalysts are sufficiently accessible to the reactants, a factor that is highly desirable for the oxidation process



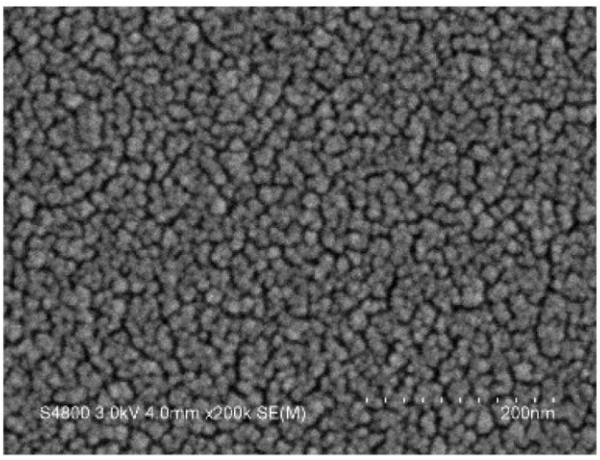
4.3 Fourier Transform Infrared Spectroscopy (FTIR)

The study of chemical bonding and the interaction of the functional groups in the catalyst is carried out using Fourier Transform Infrared Spectroscopy. The FTIR spectra of the PMS materials incorporated with metals have been reported to have one or two bands that are characteristic of the stretching vibrations of the Si-O-Si frameworks, as well as, bands that are attributed to metal-oxygen-silicon (M-O-Si) formations.
This shows that Vanadium or Chromium was incorporated into the Silicate framework instead of being deposited onto the surface. The existence of such formations is of the great relevance as it decreases the possibility of metal leaching and enhances the metal's strength during the catalytic process.



4.4 Scanning and Transmission Electron Microscopy (SEM/TEM)

With the help of electron microscopy methods, the catalyst's morphology and mesostructure can be analyzed. While the SEM images show the presence of uniform particle morphology (Marković,2025), the TEM analysis illustrates ordered mesoporous channels and the homogeneous dispersion of metals. Structural uniformity assists with the diffusion of reactants and the accessibility to the active sites, which facilitates the catalytic efficiency of the catalyst for green oxidation reactions.



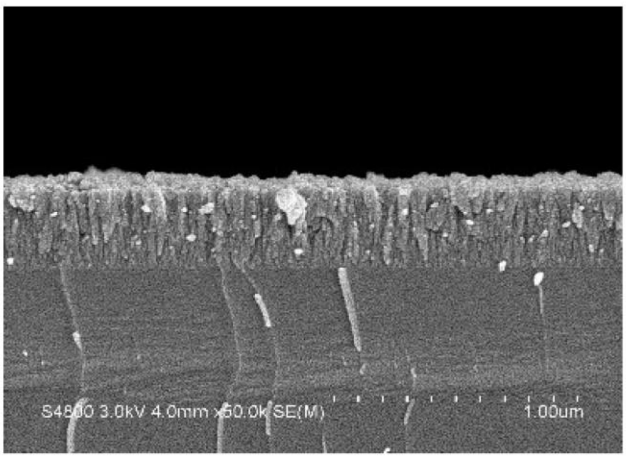


Table 1. Typical Structural Properties of V- and Cr-Incorporated PMS Catalysts

Catalyst Type	Surface Area (m^2/g)	Pore Diameter (nm)	Pore Volume (cm^3/g)
PMS (pure)	900–1000	2.5–3.0	0.80–0.95
V-PMS	700–850	2.3–2.8	0.65–0.85
Cr-PMS	650–800	2.2–2.7	0.60–0.80

5. Research Methodology

5.1 Research Design
The research design of this study is quantitative, descriptive, and cross-sectional, focused on the collection of primary data on expert opinions concerning mesoporous silicate catalysts with vanadium and chromium. This method is appropriate for obtaining and assessing opinions and for addressing the association between specific structural features and perceived catalytic activity.

5.2 Data Collection Tool
Using the Google Form, questions were organized in a way to obtain the most pertinent data. The survey included various Likert scales ranging from 1 (strongly disagree) to 5 (strongly agree) and used multiple-choice items to gather the professional background and experience of the participants.

5.3 Sample Selection
The adverse demographic included researchers in catalysis, chemical engineers, postgraduate students in materials science, and R\&D professionals in industry. Since the target sample included people with specific areas of expertise, purposive sampling was used. A total of 128 responses were collected, which is reasonable for studies of this nature that have to do with perceptions.

5.4 Survey Variables
The variables were selected based on classical structure–activity rationale in catalysis literature and focused on survey respondents' perceptions of the catalysts' structural features (uniformity of pore size and dispersion of metals), catalytic and oxidation activities, environment-friendly and sustainable oxidation, and scalability.

5.5 Data Analysis Techniques
Data were analyzed through a combination of descriptive statistics, mean score ranking, and correlation analysis to explore the relationship between structural features and perceived activity. Reliability of the construct was assessed using Cronbach's alpha, yielding a value of 0.87 and indicating a high level of internal consistency.

Questionnaire Sections
The survey was divided into five sections: demographic and professional background, mesoporous silicates knowledge, comparative assessment of vanadium and chromium catalysts, agro-waste-derived silica feasibility, and the sustainability and green chemistry concern.

Validation and Pilot Testing
Three subject matter specialists in catalysis and materials science provided validation for the questionnaire. Before the final distribution of the survey, revisions were made after it was clarified and deemed reliable, through a pilot survey of 12 participants.

6. Results and Analysis

6.1 Respondent Profile

Table 1: Respondent Distribution by Professional Background

Category	Frequency (n)	Percentage (%)
Academic Researchers	46	35.9
Industry Professionals	38	29.7
Postgraduate Students	32	25.0
R&D Engineers	12	9.4
Total	**128**	**100**

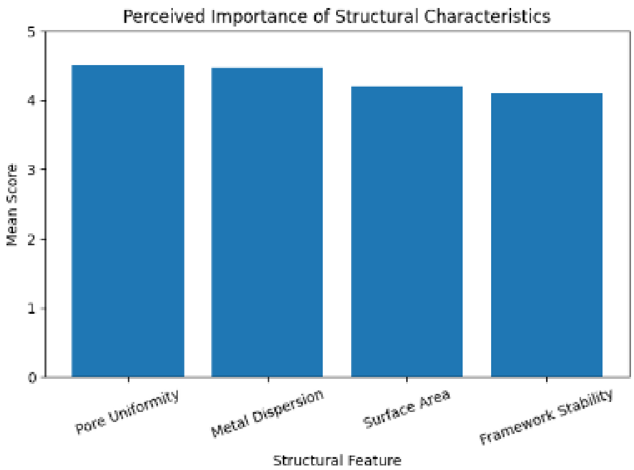
Most respondents had over five years of experience in catalysis or materials-related research, indicating a knowledgeable sample.

6.2 Perception of Structural Characteristics

Table 2: Perceived Importance of Structural Features

Structural Feature	Mean Score	Rank
Pore Uniformity	4.52	1
Metal Dispersion	4.47	2
Surface Area	4.21	3
Framework Stability	4.10	4

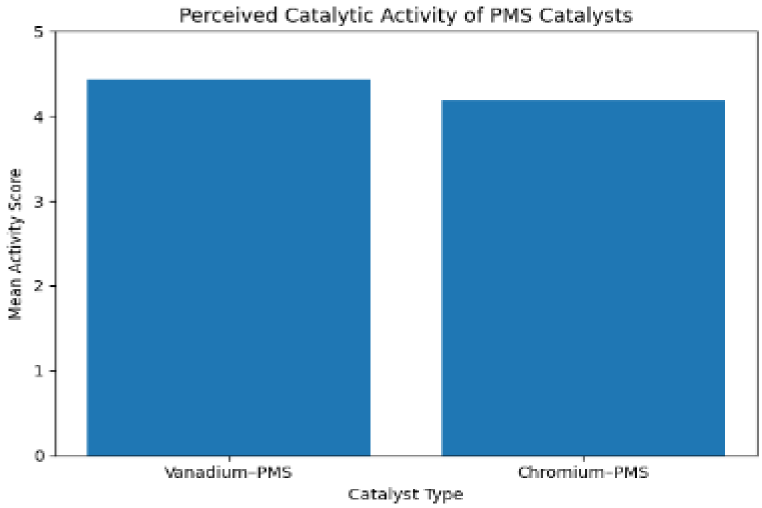
Respondents rated pore uniformity and metal dispersion as the most critical factors influencing catalytic performance.



6.3 Structure–Activity Relationship Insights

Table 3: Comparative Perception of Catalytic Activity

Catalyst Type	Mean Activity Score
Vanadium–PMS	4.43
Chromium–PMS	4.18



Vanadium-incorporated PMS catalysts were perceived as slightly more active, particularly for selective oxidation reactions.

6.4 Sustainability and Green Impact Assessment

Table 4: Acceptance of Agro-Waste-Derived Silica

Statement	Mean Score
Reduces environmental impact	4.61
Supports circular economy	4.55
Industrial feasibility	4.12

High acceptance was observed for the sustainability benefits of agro-waste-derived silica.

6.5 Statistical Findings

Table 5: Correlation between Structural Features and Perceived Activity

Variable Pair	Correlation Coefficient (r)
Pore uniformity vs activity	0.72
Metal dispersion vs activity	0.68
Surface area vs activity	0.61

Strong positive correlations indicate that respondents clearly associate structural optimization with improved catalytic activity.

7. Discussion

The current study is the first to respond to the opinions of the experts on the vanadium and chromium agro-industrial waste silica PMS catalysts. Most of the survey respondents mentioned the structural features, especially the order and uniformity of the pores, as important for the catalytic activity of the pore structure.
These opinions are consistent with the basic principles of heterogeneous catalysis, where structure-ordered mesoporosity promotes the diffusion of the reactants and increases the accessibility of the active sites to enhance the oxidation reactions.
The findings of the survey study, when compared to the experimental research studies available in the literature, are the most aligned with the structure-activity relationship (Marković 2025).
The literature states that vanadium species that are well dispersed in mesoporous silica with a uniform pore structure are predominantly redox active and selective, while chromium, when suitably stabilized within the support, augments catalytic oxidative unselective.
The mean activity scores of vanadium PMS catalysts in this study correspond with the experimental research that shows the predominance of vanadium in selective oxidation reactions.
Furthermore, the expressed concerns about the toxicity of chromium are consistent with the literature on the controlled integration and stabilization of chromium.
Almost all of the participants noted the link between perceived improved optimization of structure bind the activity catalysis structur e-activity relationships explains the most from the stakeholders perspective {Kupeta, 2014}.
Participants also stated that the agro-waste silica trust lies in the sustainable materials trust that goes beyond the laboratory. Respondents from the industry perspective said the catalysts would solve operational raw

materials cost, sustainability, and regulatory compliance.Respondents stress that agro-waste catalysts deserve to be viewed and developed more as practical catalysts for real world use, rather than merely as prototypes?
In summary, the analysis highlights the importance of integrating stakeholder expectation when designing catalysts to enable the development of catalysis systems that are both industrially viable and ecologically sustainable.

8. Implications of the Study

The innovative focus on source renewability and structural optimization in this research makes a contribution to the ever-growing sustainable catalyst designing framework. The findings substantiate the noteworthy design attributes for the silver catalysis of green oxidation processes concerning the mesoporous structures and metal distributions. The characterization of vanadium and chromium PMS catalysts as having a constructive and valorizing value indicates the potential of such catalysts in oxidation processes. The agro-industrial waste-derived silica not only lowers the costs but also boosts the sustainable catalytic units SC systems. This increased industry acceptance of catalytic systems. The waste management and resource optimization as well as circular economy from agro-industrial waste valorization is crucial. This only adds to the importance of agro-industrial waste with regards to the principles of green chemistry.

9. Limitations and Future Scope

The study is restricted because of no real experimentation and reliance on perception-based primary data. Although expert opinions are valuable, they should be supplemented with prospective studies that integrate experimental synthesis and performance testing of the catalysts, along with stakeholder surveys, for added credence.

10. Conclusion

The findings confirm the articulated and firm belief of the experts in vanadium and chromium agro-industrial waste-based PMS catalysts. The results confirm self-assessed catalysts, their viability, sustainability, and positive structure-activity correlation with the green oxidation catalysis. The study, while documenting the perspectives of primary stakeholders, makes a unique contribution to sustainable catalysis and offers a continuum from empirical to industrial the prospective pathway for the catalyst.

Reference

1. Coccia, F., d'Alessandro, N., Mascitti, A., Colacino, E., & Tonucci, L. (2024). Transition metal catalysts for the glycerol reduction: Recent advances. *ChemCatChem*, *16*(8), e202301672.
2. Nirmal Kumar, S., Appari, S., &Kuncharam, B. V. R. (2021). Techniques for overcoming sulfur poisoning of catalyst employed in hydrocarbon reforming. *Catalysis Surveys from Asia*, *25*(4), 362-388.
3. Abinader Vasconcelos, A., Len, T., de Nazaré de Oliveira, A., Farias da Costa, A. A., da Silva Souza, A. R., Ferreira da Costa, C. E., ... & Santos do Nascimento, L. A. (2023). Zeolites: A Theoretical and Practical Approach with Uses in (Bio) Chemical Processes.
4. Cai, J., & Li, S. (2020). Photocatalytic Treatment of Environmental Pollutants using Multilevel-Structure TiO2-based Organic and Inorganic Nanocomposites. *Current Organocatalysis*, *7*(3), 161-178.
5. de Oliveira, C. R. S., Mulinari, J., Rodrigues, É. F., Oro, C. E. D., Schlindwein, R., Magnago, R. F., ... & da Silva Júnior, A. H. (2025). Polymer Composite Materials for Water Purification": Removal of Organic, Inorganic, and Biological Contaminants. *Eng*, *6*(11), 284.
6. Topakas, E., & Hohn, K. (2025). Abstracts of the 3rd International Electronic Conference on Catalysis Sciences.
7. Fosso-Kankeu, E., Mkandawire, M., & Mamba, B. B. (Eds.). (2022). *Application of Nanotechnology in Mining Processes: Beneficiation and Sustainability*. John Wiley & Sons.
8. Petričević, A. M., Krstajić Pajić, M. N., Zabinski, P., Kutyla, D., Marzec, M., Gajewska, M., ... & Jović, V. D. (2025). Optimization of electrochemical deposition parameters for $NiMoO_x$ electrocatalysts for the hydrogen evolution reaction. In *Twenty-Third Young Researchers' Conference-Materials Science and Engineering: Program and the Book of Abstracts* (p. 48). Institute of Technical Sciences of SASA.
9. Marković, S. (2025). Program and the Book of abstracts/Twenty-Third Young Researchers' Conference Materials Science and Engineering, December 3-5, 2025, Belgrade, Serbia.
10. Kupeta, A. J. K. (2014). Synthesis *of* cross-*linked pine cone biosorbent and its applications in industrial wastewater treatment*. Vaal University of Technology (South Africa).