Educational Administration: Theory and Practice
2024, 30(1), 8350-8360
ISSN: 2148-2403
https://kuey.net/
Research Article

Agro-Industrial Waste-Derived Periodic Mesoporous Metallosilicates as Sustainable Multifunctional Materials for Catalysis, Adsorption, and Electrochemical Applications

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

[1*] Department of Physics and Materials Science NSB College, Nanded, India, Email: nptel2020@gmail.com
[2]Department of Physics and Materials Science SGBS College, Purna, India, Email: gpk_2010@rediffmail.com
[3]Department of Physics and Materials Science NSB College, Nanded, India, Email: sushant8410@gmail.com

Citation: Dr. Manish Deshpande, et.al (2024). Agro-Industrial Waste-Derived Periodic Mesoporous Metallosilicates as Sustainable Multifunctional Materials for Catalysis, Adsorption, and Electrochemical Applications, *Educational Administration: Theory and Practice*, 30(1) 8350-8360
Doi: 10.53555/kuey.v30i1.11468

ARTICLE INFO | **ABSTRACT**

With regard restructuring functions in catalysis, environmental remediation, and energy, the multidisciplinary challenges are large. Among the most interesting and evolving areas which are still being developed are Periodic Mesoporous Metallosilicates (PMS). These are still being explored due to their continuous ordering, ease of incorporation of active metal species within the framework of stable silica, and large surface area. PMS from Agro-Industrial waste and Agro-Industrial waste derived PMS build the foundation for this research. Agro-industrial waste derived PMS can be developed as multifunctional sustainable materials for catalysis, adsorption and electrochemical activities. The design objective is to foster integrated sustainable and industrial multifunctional materials for catalysis, adsorption and electrochemical activities. A quantitative, perception-based methodology was designed for this purpose. It incorporates a survey of functional materials researchers, personnel in the industry, and postgraduate students. Descriptive and correlation perception-based methodologies for impact assessment of the structure, function, and environment of the materials and overall impact of the materials, included analysis of the reliability of the framework and structure for the materials. All applications recorded a positive correlation, and most participants pointed to agro-industrial waste as the most functional of the ordered mesoporous silica (OMS) derived silicas. This was attributed to its low cost and functional efficiency as a substitute for industrial silica.The research praises the effectiveness of agro-waste-derived periodic mesoporous metallosilicates as a possible eco-friendly multifunctional material and technology, as well as the importance of stakeholder-informed, design-led approaches in the development of sustainable materials.

Keywords: Agro-industrial waste; Periodic mesoporous metallosilicates; Sustainable multifunctional materials; Catalysis;

1. Introduction

1.1 Need for Sustained Multifunctional Materials Globally

The rush for the environment friendly technologies and the multifunctional sustainable materials that could solve the issues of catalysis, adsorption and various electrochemical applications has intensified. The conventional materials in such areas are often made of non-renewable, energy-intensive and single-use (Malpani et al., 2022).
Such materials also become resource and cost inefficient and pollute the environment. The adoption of such technologies in the industries must address the emerging greener processes and the circular economy. Therefore the need for high performance, sustainable and multifunctional materials is imperative.

1.2 An Overview of Periodic Mesoporous Metallosilicates

Once integrated with metals, silicate frameworks enhance catalysis, adsorption, and electrochemical processes (Rigoletto, 2025). Hence, periodic mesoporous metallosilicates (PMMS) are particularly promising because of their high surface area, tunable pore structure, and ordered mesoporous frameworks.

Metallosilicates are structurally superior to mesoporous silicates and offer greater functional flexibility coupled with improved control over structure and properties for a wide range of applications.

1.3 Sustainability Through Waste Valorization in Agro-Industry

The agricultural and agro-industrial sectors produce high quantities of waste, such as rice husk ash, sugarcane bagasse ash, and palm ash, which, if unaddressed, pose a dire environmental risk (Seaf El-Nasr et al, 2021).

Despite this, such waste materials are rich in amorphous silica, which can be used to create new products.From a silica cost and sustainable resource management perspective, agro-industrial wastes are to be preferred over traditional silicate materials.

1.4 Focus of the Current Study

This research examines sustainable multifunctional materials, particularly the waste from agro-industry periodic mesoporous metallosilicates. It underscores the importance of the structure–property–application paradigm in catalysis, adsorption and electrochemistry, and the corresponding functions (Malpani& Goyal, 2023).

This paradigm is seen as critical to the sustainable green and circular design of materials.

2. Research Gap and Problem Statement

No doubt there has been a lot of progress made over the past few years concerning the development of periodic mesoporous materials. In the majority of these studies, however, the focus has been on the evaluation of their performance in unconnected (and mostly singular) catalytic or electrochemical systems.

The majority of studies, including the ones reported, tend to optimize materials for a single function, ignoring the potential of cross function activating a composite material's synergistic response over a multitude of interconnected applications.

In addition, despite the value of agro-industrial waste as a consistent, renewable source of silica and mesoporous metallosilicates, there has been little to no exploration of the using agro-industrial waste in the synthesis of periodic mesoporous metallosilicates.

Most studies stick to commercially available silica precursors, ignoring the environmental and economic benefits that silica derived from agro-industrial waste provides. Most studies, including the ones reported, emphasize the synthesis and performance evaluation of their materials at the micro-scale or at the laboratory scale. Other than the synthesis and performance evaluation of their materials at the micro-scale, there has been little to no exploration of the sustainability, cost-effectiveness, or scale of their work, leaving their work to only add to the body of academic literature with no practical value.

Most researchers have taken a position that there is a lack of multi-functional performance over a variety of focal application areas, including the studies noted previously, and there is a lean toward subfunction performance evaluation at the focal application areas.

This lack of evaluation over a variety of focal application areas is the cause of the lack of imposition that advanced mesoporous materials have for translating their research from the academic world to the practical world. There exists an identifiable and distinct need for an all-encompassing perspective that merges structure, properties, and performance over multiple functions, while incorporating a research focus that embraces sustainability and the principles of the circular economy.Closing this gap is critical for developing agro-waste-derived periodic mesoporous metallosilicates as sustainable materials for practical applications.

1. Objectives of the Study

1. To examine agro-industrial waste-derived periodic mesoporous metallosilicates as sustainable material platforms
2. To analyze structural features influencing multifunctional performance
3. To evaluate applicability in catalysis, adsorption, and electrochemical systems
4. To assess environmental and industrial relevance within a circular economy framework

4. Review of Literature

4.1 Periodic Mesoporous Materials: Evolution and Design

Since ordered mesostructures with uniform pore dimensions and high surface areas are dispersible mesoporous materials, periodic mesoporous materials have gained a lot of interest. Periodic mesoporous materials' characteristic feature is the periodicity of mesopores, which enhances mass transport and accessibility of active sites (Montini et al., 2023).

The development of frameworks of varying pore architectures, "pore sizes, surface areas, and compositions has been facilitated by advances in sol-gel synthesis and soft-templating methods. The performance of the material in function is determined by rationally designed ordered mesoporosity. The presence of a functional design of the pore size and pore interconnectivity has made them suitable for many advanced applications.

4.2 Metallosilicates: Metal Incorporation Strategies

Incorporation of metal species into mesoporous metallosilicates can be done either within metalosilicate silicate frameworks or at the internal pore surfaces (Morales-Paredes et al., 2023). Different strategies of metal incorporation within the mesoporous metallosilicates alters its physicochemical properties: metal leaching within the frameworks causes changes in the redox activity, conductivity, and acidity of the materials, which impact their function in catalysis, adsorption, and electrochemistry.

4.3 Catalytic Applications of Mesoporous Metallosilicates

Mesoporous metallosilicates have been investigated as heterogeneous catalysts because of their tunable active sites, high surface area, and good thermal stability (Nugraha et al., 2025). Their ordered pore networks promote diffusion of reactants and products, and alleviate mass transfer limitations.

These materials have been effective in oxidation, reduction, and acid–base catalysis. Compared to conventional catalysts, they have provided better selectivity and less formation of by-products. The incorporation of metal species into the mesoporous framework disperses the active sites and increases catalytic efficiency while maintaining structural integrity.
Therefore, mesoporous metallosilicates are being regarded as promising materials for green and sustainable catalysis.

4.4 Adsorption Applications

Other than catalysis, mesoporous metallosilicates have shown potential in adsorption, particularly in environmental remediation and resource recovery. Their extensive surface area and pore volume allow mesoporous metallosilicates to adsorb organic pollutants, heavy metals, and dyes in adsorb liquid and vapor systems (Razak et al., 2022).

Functionalization of the surface and metal integration increases the adsorptive ability of the material by facilitating the formation of new active adsorption sites. The capacity of these adsorbent materials to be regenerated and reused with little or no loss of efficiency is one of the major reasons why they are more aligned than conventional adsorbents with sustainable and economic separation processes.

4.5 Electrochemical Applications

Recent studies show ever growing interest in using mesoporous metallosilicates in electrochemical systems. Their ordered mesostructures provide uninterrupted pathways for charge transport.
When metals are added, redox-active sites are created which enhances electrochemical performance. These materials are being investigated for electrocatalysis, sensing, and energy storage devices including supercapacitors and batteries (Yu & Williams, 2022).

The unique combination of structural integrity, modifiable conductivity, and increased active surface area allows mesoporous metallosilicates to be effective and long-lasting electrochemical materials.

4.6 Agro-Industrial Waste-Derived Silica in Functional Materials

Recent research show that mesoporous materials can now be made using agro-industrial waste silica instead of industrial silica. Agricultural waste silica possesses comparable attributes to industrial silica (Da'na, 2017). In addition, waste silica provides cost savings, greater environmental sustainability, economic and social benefits due to its waste to resource circular economy potential.
Therefore, agro-industrial silica waste is a viable alternative to be utilized in functional materials for mesoporous metallosilicates.

5. Characterization Techniques

Analagously studying the physiochemical characterization will provide a basis for the various agro-industrial waste assimilated into periodic mesoporous metallosilicates, not withstanding the use of diffraction, adsorption, spectroscopic and microscopic methods the cross-analysis of meso-space structure, textural properties, metal gamut, and morphology uniformity as it relates to multi-functional performance in catalysis (Ezzeddine et al., 2025), adsorption, and electrochemistry will provide valuable information.

5.1 XRD Analysis

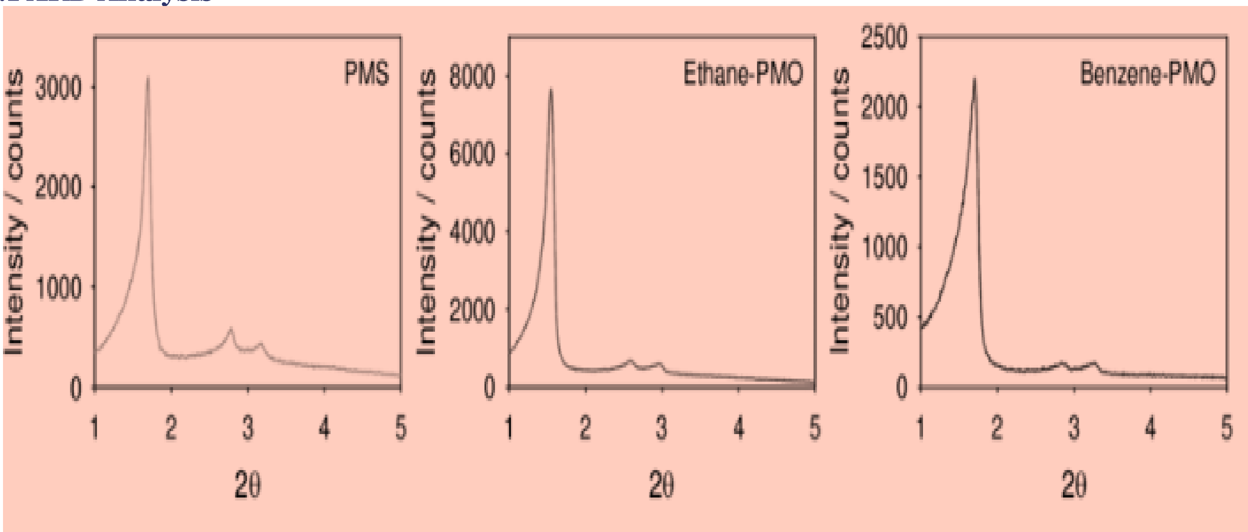

Fig. 1. Low-angle XRD patterns of COK-12

To verify the existence of periodic mesoporous structures and analyze the distribution of embedded metal species, X-ray diffraction (XRD) is one of the main methods utilized. Ordered mesoporous structures can usually be identified by their low-angle XRD patterns **Fig. 1.**, which show distinct diffraction peaks (Grela et al., 2021).
These peaks are usually retained even after metal particles are embedded into the structures, indicating the mesostructural integrity of the material. The nature (crystalline or amorphous) of the metal species embedded in the silicate matrix is described in the broad-angle XRD analysis.
The high catalytic and electrochemical activity attributed to the metal species is often the result of their high dispersion in the silicate matrix (characterized by the absence or low intensity of the metal oxide diffraction peaks) and is seen as a positive trait.

5.2 BET Surface Area and Porosity

Nitrogen adsorption-desorption measurements are conducted to examine the pore distribution, volume, and area of the mesoporous metallosilicates. Type-IV isotherms with well-defined hysteresis loops are characteristic for mesoporous materials with homogeneous pore structures **Fig. 2.**.
Aphane et al. (2024) state that during catalytic processes, the catalyst's surface area and the porosity of the interconnected pore network facilitate access and interaction of the reactants with the active sites.
In electrochemical processes, the structural arrangement of pores and mesoporous materials, which aids in the diffusion of ions, is critical. The fact that a certain level of mesoporosity is retained, even though the inclusion of some metals may result in a slight reduction of surface area due to partial pore filling, illustrates the good structural control.

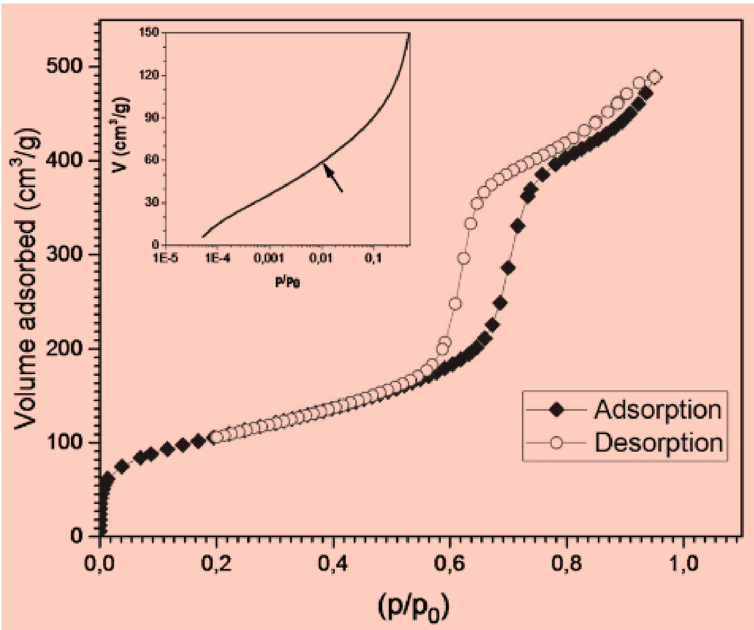

Fig. 2. Nitrogen adsorption-desorption of COK-12

5.3 FTIR and Spectroscopic Evidence

Fourier Transform Infrared (FTIR) Spectroscopy will be used to analyze the integrity of the framework and chemical bonding of the metallosilicates. The absorption bands are due to the vibrations of the silicate framework and the chemical bonding of Si–O–Si and M–O–Si (M is the metal) and confirms that metal species were incorporated into the framework **Fig. 3** (Malpani et al., 2022).

The significance of creating these bonds is that it sequesters the metal, and thus mitigates leaching, which is especially important for the electrochemical and catalytic applications that are to be of long duration. Other, potentially, complementary methods may be used to analyze the metal coordination and surface functional groups.

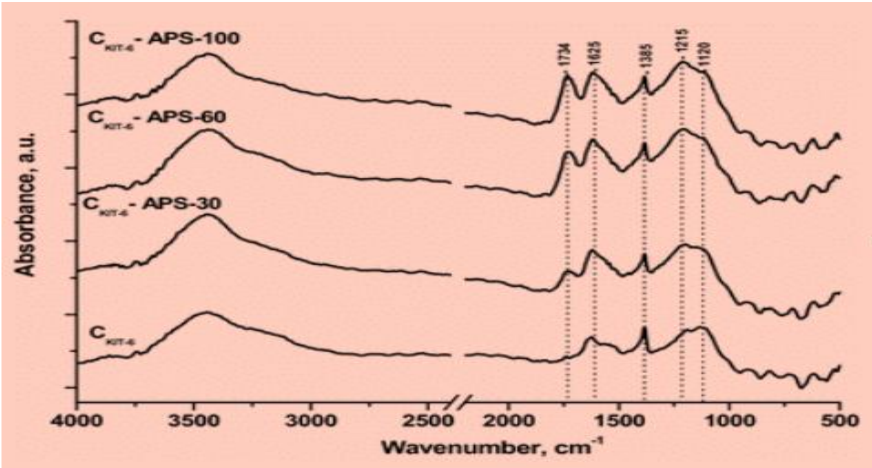

Fig. 3. FTIR and Spectroscopic Evidence of COK-12

5.4 SEM/TEM Analysis

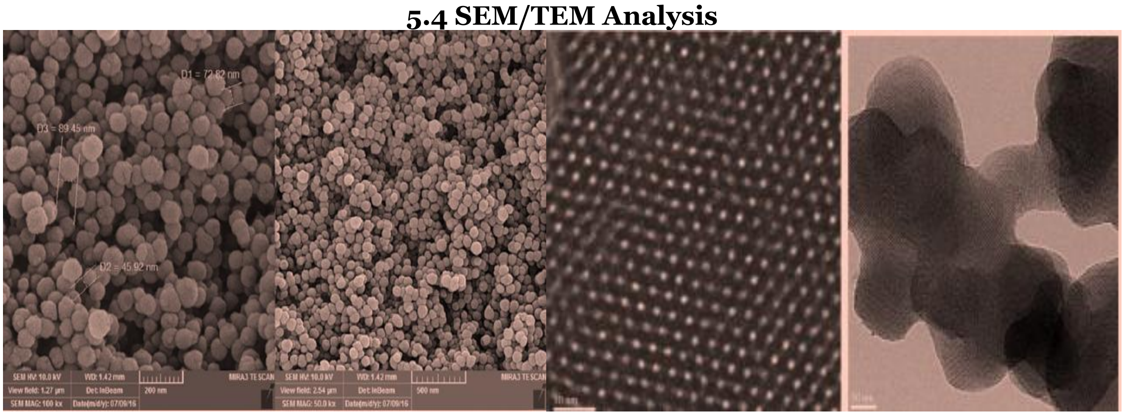

Fig. 4. SEM and TEM images of COK-12

We selected Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) to study the exterior and interior structure of mesoporous metallosilicates **Fig. 4.** Uniformity in the size and shape of the particles and the texture of the surface is displayed in the SEM images.

With TEM, we are able to study the structure and ordered mesoporous channels, and the dispersion of metal within the structure. Considering the uniformity of metal distribution and the ordered arrangement of pores, we postulate there is enhanced multifunctional activity due to improved mass and electronic transport.

Table 1. Typical Structural Characteristics of Agro-Waste-Derived Periodic Mesoporous Metallosilicates

Parameter	Typical Range
Surface area (m^2/g)	600–1000
Pore diameter (nm)	2.0–4.0
Pore volume (cm^3/g)	0.6–1.0
Mesostructural order	High
Metal dispersion	Uniform

6. Research Methodology

6.1 Research Design

A cross-sectional quantitative descriptive study was employed to understand the perceptions of participants regarding the agro-industrial wastes-derived periodic mesoporous metallosilicates as multifunctional sustainable materials.

This methodology was appropriate for the analysis of the opinion structures and perceptions of the stakeholders regarding the materials potential as a catalyst, adsorbent, and in electrochemical applications.
The cross-sectional method analyzes the data regardless of the respondents' education and industry level knowledge of the materials, thus, evaluating the expert level perception of the stakeholders regarding the materials at that particular moment.

6.2 Survey Instrument

The primary data were captured using a structured questionnaire, which was designed and administered using an online survey tool. The various sections of the questionnaire analyzed the respondents' perceptions of the main factors affecting the performance of the materials and their sustainability.
The respondents' perceptions were measured using a Likert scale which assigned the following values: 1 (strongly disagree) to 5 (strongly agree) concerning the surface structure, pore ordering, surface area, and metal dispersion. Other sections analyzed to varying degrees the respondents' perceptions of performance in catalysis, adsorption, and electrochemical activity.
Lastly, environmental, scalability, cost, and industrial sustainability were analyzed for perceptions of sustainability. The questionnaire went through multiple expert reviews to enhance the clarity and content validity before the survey was administered.

6.3 Sampling and Respondents

For this study, the population of interest consisted of the three groups – academia, industry, and postgraduate students, who hold degrees in materials science, chemical engineering, catalysis, or related areas.
To make sure the respondents had enough knowledge on the subject to make valid judgments, a purposive sampling technique was used. This approach is most often used in perception based studies where the opinions of experts are more useful to the study than those of the general public.
Respondents had the freedom to make a choice regarding their participation in the study and bias was reduced as the responses were collected anonymously which also made it easier to be as honest as possible.

6.4 Data Analysis

The certain methods of data analysis used were appropriate given the data collected were quantitative and perception based.
Respondents perceptions were summarized using measures of central tendency and measures of variability, and these descriptive statistics included mean and standard deviation.
Respondents perceptions were summarized using measures of central tendency and measures of variability, and these descriptive statistics included mean and standard deviation.
To determine the possible correlation, or relationship, between perceived structural features and multifunctional performance measures, correlation was applied.
This resulted in a more meaningful explanation of what the study was about. This was in combination with other techniques to provide a systematic approach to analysis.

7. Results and Analysis

7.1 Respondent Demographics

Responses were obtained from 132 participants who possess the necessary academic and professional qualifications in materials science, catalysis, and electrochemical systems. Participants' diverse background provides a comprehensive coverage of both research and practical application perspectives.

Table 2. Distribution of Respondents by Professional Background

Category	Frequency (n)	Percentage (%)
Academic Researchers	48	36.4
Industry Professionals	36	27.3
Postgraduate Students	34	25.8
R&D Engineers	14	10.5
Total	**132**	**100**

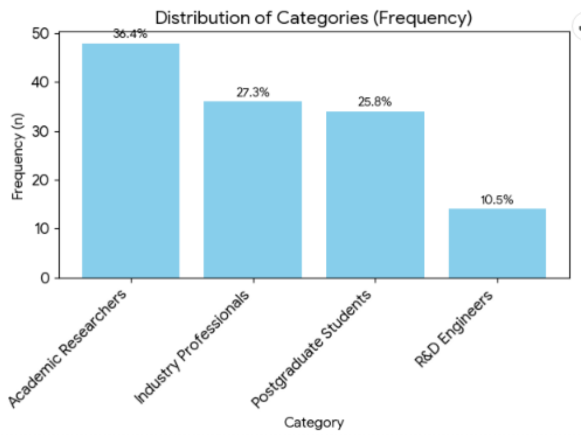

Fig.4 Distribution of Respondents by Professional Background

A majority of participants mentioned having 5+ years of experience in their domain which validates that the sample is sufficiently knowledgeable and informed to undertake perception-based evaluation.

7.2. Perception of Structural Features

Structural characteristics which limit multifunctional performance were noted by most respondents. Based on the respondents' feedback, we conclude that the most appreciated structural characteristic is the uniformity of pores and even distribution of metal. This suggests an acknowledgement of the quality functional design related to constituent materials.

Table 3. Perceived Importance of Structural Features

Structural Feature	Mean Score	Rank
Pore uniformity	4.56	1
Metal distribution	4.49	2
Surface area	4.32	3
Framework stability	4.18	4

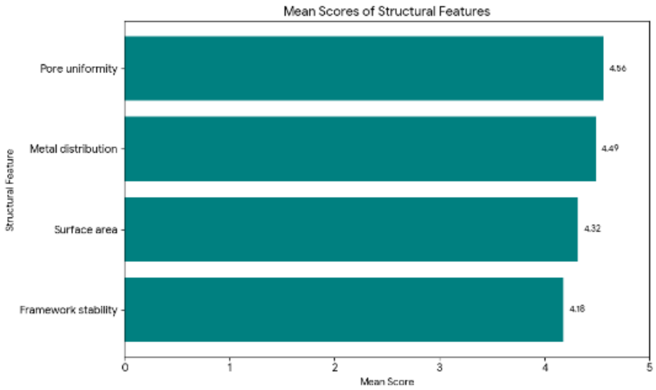

Fig.5. Perceived Importance of Structural Features

The results show that respondents feel most confident structural optimization aligns with functional efficiency across applications.

7.3 Perceptions on Catalytic Performance

Concerning catalysis, agro-waste periodic mesoporous metallosilicates were considered effective as heterogeneous catalysts. Participants noted better site accessibility and mass transport because of the ordered mesoporous structure.

Table 4. Perceived Catalytic Performance

Parameter	Mean Score
Activity efficiency	4.41
Selectivity control	4.29
Stability and reusability	4.24

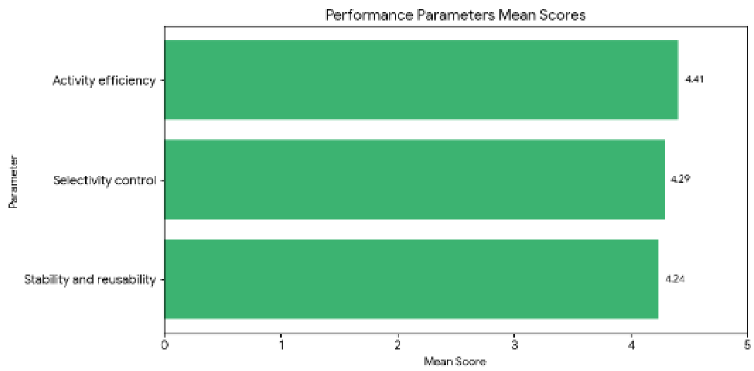

Fig. 6. Perceived Catalytic Performance

7.4 Adsorption Efficiency Perception

The participants assessed the performance of the materials for adsorption based applications, in particular for environmental remediation. The materials were considered suitable due to the high surface area and tunable porosity which could offer greater adsorption and regeneration potential.

Table 5. Perceived Adsorption Performance

Parameter	Mean Score
Adsorption capacity	4.38
Regeneration ability	4.26
Structural durability	4.21

7.5 Electrochemical Application Perception

The respondents highlighted the ordered mesostructures and metal incorporation as advantageous features for charge transport and redox activity in mesostructures for electrochemical applications.

Table 6. Perceived Electrochemical Performance

Parameter	Mean Score
Charge transfer efficiency	4.22
Electrochemical stability	4.19
Application versatility	4.15

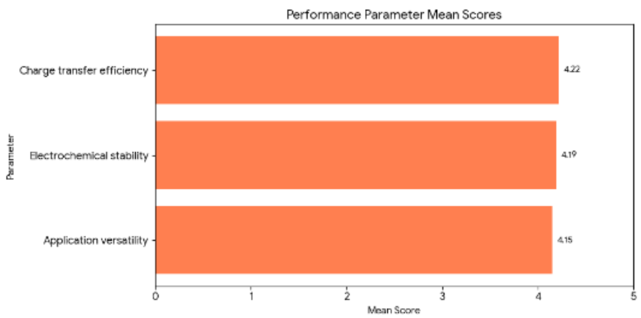

Fig.7. Perceived Electrochemical Performance

7.6 Sustainability and Industrial Acceptance

Respondents articulated the agro-industry waste materials from a sustainability perspective as useful, and these materials may help implement circular economy strategies and improve industrial systems.

Table 7. Sustainability and Industrial Acceptance

Statement	Mean Score
Environmental impact reduction	4.63
Resource valorization	4.58
Industrial feasibility	4.20
Cost effectiveness	4.17

Correlation Analysis

Correlation analysis was performed to assess the relationships between structural traits and perceived multifunctional performance.

Table 8. Correlation Matrix Between Structural Features and Performance

Variable Pair	Correlation Coefficient (r)
Pore uniformity vs catalytic performance	0.74
Pore uniformity vs adsorption efficiency	0.71
Metal distribution vs electrochemical performance	0.69
Surface area vs overall performance	0.65

The respondents explain the strong positive correlations by stating that optimized structural features are linked to better multifunctional performance.

8. Discussion

The results provide additional evidence for the correlation between specific structural characteristics of the agro-industrial waste-derived periodic mesoporous metallosilicates and their possible multifunctional roles as catalysts, adsorbents, and electrodes, (Rigoletto, 2025).

It is interesting that the respondents mentioned ordered mesoporosity, high surface area, and uniform metal distributions, which they attributed to active site accessibility, effective mass transport, and multifunctional stability.

The results of the study change the perspective of mesoporous materials because even when materials have reached the end of their useful life cycle, the pore structure and framework still determine what the materials are capable of accomplishing.

To an extent, there is still experimental literature which, while providing some comparative assessments of the different methodologies for the metal incorporation, elucidates the lesser, albeit still present, trade-offs of metallosilicates containing vanadium and chromium.

Incorporation of vanadium is generally associated with greater catalytic and electrochemical activity because of its multiple oxidation states (Malpani& Goyal, 2023). Chromium-based systems, on the other hand, tend to provide greater structural stability, and stronger metal–oxygen–silicon interactions which makes them more suitable for adsorption and/acido-basic catalytic processes.

The results from perception align with the documented trends for metal selection being application specific rather than general. Because of this, the seeming demand for more flexible synthesis techniques that afford the more specific control over the kind of metal to be used, the quantity, and the position, even within the mesoporous structure is validated.

The consistency between the perception of respondents and the findings of previously conducted experimental research strengthens the proposed concept of multifunctional materials. The literature has repeatedly shown when sufficient structural optimization is achieved and the incorporation of the sufficient metal fills the structure of mesoporous metabolite silicates, the material behaves better than mono functional materials (Montini et al., 2023).

Further, the fact that the silica derived from agro-industrial waste did not compromise functional performance correlates with previous studies which suggested that this waste had comparable or superior textural and chemical properties to commercially available silica.

The fact that this waste has been shown to be functional and that it has also been proven to improve the performance of the materials design is of great importance.

What this report highlights the most is the importance of building resources according to the needs of stakeholders. Most importantly, researchers, representatives of the industry, and postgraduates, describe the need for high performance, scalable, affordable, and sustainable materials (Morales-Paredes et al., 2023).

This, from the practitioner perspective, is feedback for a lab study and helps to bridge the theory-practice divide. The discussion, in general, demonstrates the need to combine the more desirable structure-property relations with the triple bottom line and end-user needs acommpanied to progress agro waste-derived periodic mesoporous metallosilicates to multifunctional materials.

9. Implications of the Study

9.1 Scientific Implications

The various sustainable practices have been summarized to functional tailoring through the design, structure, compositions, and various rational distributions of materials. The specific findings are explained for materials and structural design, performance and certain incorporation of metals.

The study determined that the multifunctional features of catalysis, adsorption and electrochemistry of materials are dependent on optimal design of porous block structures and the ratio of active dispersive metals.

This study further reiterates the agro and agro-industrial waste silica, which until now had been unexplained potential, as a substitute for conventional materials. The performance of sustainable materials should not be compromised.

The existing research scope needs to be widened and expanded to sudden to meet the structure-property-function of multifaceted materials which calls for a more holistic approach in contrast to the current tendency of focusing on materials for specific end use applications.

9.2 Industrial Implications

The study highlights the possible advantages that agro-waste-derived periodic mesoporous metallosilicates can provide in terms material cost reduction while being functional and regulatory compliant. Industry is looking for cost-effective raw materials and resilient supply chains.

Therefore, the use of agro-industrial byproducts as silica sources, which have a low-cost and high-availability, can be economically advantageous. Moreover, the multifunctional attributes of such materials may decrease process efficiency in terms of having to use multiple materials, but will nonetheless improve the overall process by eliminating single-use materials.

The favorable perception regarding the scalability and industrial viability of these materials suggest that the materials will be able to sustain performance to meet the user's needs while keeping the environmental impact low, which will be of great interest in the use of these materials on a large scale for catalysis, adsorption and electrochemistry.

9.3 Environmental Implications

The study examines a facet of 'waste valorization' on strengthening the tenets of the circular economy. The conversion of the agro-industrial byproduct, in this case, of casting, into high value functional materials, alleviates disposal issues, and lessens the dependence on primary materials and the energy cost of extraction, refining, and processing fossil fuel materials.

The derived mesoporous metallosilicates offer considerable perception of low energy, low fossil fuel, and low waste dependency materials which strengthens agro-waste-derived mesoporous metallosilicates.

The reduced fossil fuel dependency, conservation of resources with the less energy provide these materials with a carbon footprint which promotes the use of the agro waste derived mesoporous metallosilicates strengthened by green chemistry and the sustainable development goals oriented worldwide.

10. Limitations and Future Research Directions

The study, however, does have some shortcomings. For instance, reliance on perceptual data entails subjectivity and may not reflect actual performance data under operational conditions.

The design may be empirically verified due to respondent expertise, but the perceptual structure–function links must be experimentally validated. Future studies should perform research in a way that develops integrated catalytic activity, adsorption, and electrochemical performance.

The author suggests hybrid research designs that combine laboratory studies with stakeholder perception studies, as these have the potential to yield a balanced view of the technical and practical aspects of the proposal.

In addition, to bolster the industrial and environmental relevance of the proposal, the author suggests the inclusion of studies on long-term stability and life-cycle assessments.

11. Conclusion

This work represents the first attempt to analyis the catalytic and electrochemical properties of the agro-industrial waste-derived periodic mesoporous metallosilicates. From the integration of stakeholder perspectives and the linkage of structural components to multifunctional capabilities, the study optimistically substantiates the agro waste-derived silica's multifunctional capabilities vis-a-vis the catalytic, electrochemical and adsorption functions, while attaining the desired outcomes of the scientist, the industry and the eco-environment.

From this, the study posits that agro waste-derived silica need not compromise any of the functional silicas to act as a precursor. All in all, the study offers variegated literature for the green chemistry and materials science domains as it creates pathways for sustainable, commercially viable, and empirically supported innovations by advanced functional materials.

12. Reference

1. Malpani, S. K., Meena, R. K., Katara, S., & Goyal, D. (2022). Agro-Industrial Wastes-Derived Carbon Nanomaterials: Synthesis and Multi-faceted Applications. In *Innovations in Green Nanoscience and Nanotechnology* (pp. 227-254). CRC Press.
2. Rigoletto, M. (2025). Recovery and valorisation of agro-industrial waste through the development of hybrid materials for environmental applications.
3. Seaf El-Nasr, T. A., Gomaa, H., Emran, M. Y., Motawea, M. M., & Ismail, A. R. A. (2021). Recycling of nanosilica from agricultural, electronic, and industrial wastes for wastewater treatment. In *Waste*

recycling technologies for nanomaterials manufacturing (pp. 325-362). Cham: Springer International Publishing.

4. Malpani, S. K., & Goyal, D. (2023). Synthesis, analysis, and multi-faceted applications of solid wastes-derived silica nanoparticles: A comprehensive review (2010–2022). *Environmental Science and Pollution Research*, *30*(11), 28321-28343.
5. Montini, D., Cara, C., D'Arienzo, M., Di Credico, B., Mostoni, S., Nisticò, R., ... & Scotti, R. (2023). Recent advances on porous siliceous materials derived from waste. *Materials*, *16*(16), 5578.
6. Morales-Paredes, C. A., Rodríguez-Linzán, I., Saquete, M. D., Luque, R., Osman, S. M., Boluda-Botella, N., & Manuel, R. D. J. (2023). Silica-derived materials from agro-industrial waste biomass": Characterization and comparative studies. *Environmental Research*, *231*, 116002.
7. Nugraha, R. E., Fauziyah, N. A., Nurherdiana, S. D., Sunarti, A. Y., Aziz, A., Sari, N. K., ... &Prasetyoko, D. (2025). Recent strategy on green synthesis of mesoporous silica from waste for A sustainable and circular economy. *Journal of Environmental Chemical Engineering*, 118288.
8. Razak, N. A. A., Othman, N. H., Shayuti, M. S. M., Jumahat, A., Sapiai, N., & Lau, W. J. (2022). Agricultural and industrial waste-derived mesoporous silica nanoparticles: A review on chemical synthesis route. *Journal of Environmental Chemical Engineering*, *10*(2), 107322.
9. Yu, X., & Williams, C. T. (2022). Recent advances in the applications of mesoporous silica in heterogeneous catalysis. *Catalysis science & technology*, *12*(19), 5765-5794.
10. Da'na, E. (2017). Adsorption of heavy metals on functionalized-mesoporous silica: A review. *Microporous and Mesoporous Materials*, *247*, 145-157.
11. Ezzeddine, Z., Batonneau-Gener, I., Ghssein, G., &Pouilloux, Y. (2025). Recent advances in heavy metal adsorption via organically modified mesoporous silica: a review. *Water*, *17*(5), 669.
12. Grela, A., Kuc, J., &Bajda, T. (2021). A review on the application of zeolites and mesoporous silica materials in the removal of non-steroidal anti-inflammatory drugs and antibiotics from water. *Materials*, *14*(17), 4994.
13. Aphane, M. E., Maggott, E. D., Doucet, F. J., Mapolie, S. F., Landman, M., & van der Merwe, E. M. (2024). Synthesis and evaluation of mesoporous silica nanoparticle catalyst supports prepared from South African coal fly Ash. *Waste and Biomass Valorization*, *15*(8), 5053-5068.