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Recent Advancements of Core-Shell Zeolites: Fabrication and Catalytic Performance

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ABSTRACT

Core-shell zeolites offer superior performance in numerous catalytic reactions. Core-shell zeolites are fabricated with various methods, in terms of achieving a desired core structure that is encapsulated with an outstanding shell. This review paper comprehensively discusses various methods of core-shell zeolite fabrication, not limited to zeolite@zeolite core-shell and zeolite@metal core-shell. In addition, we present each catalytic performance, in which the core-shell zeolites demonstrated improved catalytic activity compared to its substituent.

ABSTRAK

Zeolit cangkang-inti mampu menawarkan kinerja yang unggul dalam berbagai reaksi katalitik. Zeolit cangkang-inti dapat dibuat dengan berbagai metode untuk mendapatkan struktur inti yang diinginkan yang dienkapsulasi dengan cangkang berperforma baik. Kajian ini membahas secara komprehensif berbagai metode pembuatan zeolit cangkang-inti, tidak terbatas hanya pada zeolit@zeolit cangkang-inti dan zeolit@logam cangkang-inti. Selain itu, tinjauan ini menyajikan setiap kinerja katalitik, yang dapat menunjukkan bahwa zeolit cangkang-inti mampu menghasilkan aktivitas katalitik yang lebih baik dibandingkan dengan substituennya.

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KEYWORDS
Core-shell, Zeolites, Fabrication, Catalyst

INTRODUCTION

Zeolites' framework has 256 types that the International Zeolite Association has determined to date. Zeolites are widely regarded as effective catalysts owing to their exceptional characteristics (Qin et al., 2025; Rafiani et al., 2025; Sun et al., 2025; Wu et al., 2024). In particular, zeolite has a large specific surface area, adjustable acidity, and superior adsorption capacity, which make zeolite highly suitable for various industrial applications (Aulia et al., 2024; Qin et al., 2025; Rafiani et al., 2025; Rafiani, Aulia, et al., 2024; Rafiani, Culsum, et al., 2024; Sun et al., 2025). ZSM-5 zeolite, in particular, is frequently used for producing BTX compounds due to its features, specifically the pore structures, which closely match the pore sizes of aromatic compounds (Cui et al., 2024; Wang et al., 2024; Wu et al., 2024) Nevertheless, its microporous structure is susceptible to amorphous silica blockage, which reduces both its surface area and micropore volume, ultimately decreasing its catalytic efficiency and lifetime. Moreover, it remains a challenge to achieve simultaneously high stability and selectivity for aromatics using the substituent ZSM- 5 (Wang et al., 2024; Wu et al., 2024). On the other hand, Y zeolite possesses several notable advantages, such as large three-dimensional micropores, extensive surface area, and rich acid sites (Qin et al., 2025). Despite these strengths, zeolites generally are prone to coke formation during reactions. To that, tuning the zeolite's acidity is considered an effective strategy to mitigate this issue (Jia et al., 2025). One of the ways to modulate zeolite acidity is by incorporating other materials to form a core-shell zeolite (Rafiani et al., 2025).

Zeolite catalysts with a core-shell structure have demonstrated outstanding catalytic performance (Rafiani, Aulia, et al., 2024). In particular, zeolite@zeolite core–shell structures have shown significantly enhanced catalytic performances (Cui et al., 2024; Rafiani et al., 2025; Rafiani, Aulia, et al., 2024; Wu et al., 2024). This improvement is attributed to the ideal lattice compatibility between the Silicalite-1 shell and the zeolite core, which ensures a uniform, smooth, and stable coating layer (Jia et al., 2025). On the other hand, fabricated core-shell zeolite offers diverse advantages, such as improved pore selectivity, enhanced product selectivity, and extended catalyst lifetime (Cui et al., 2024). Notably, the catalytic performances of zeolite@zeolite core-shell showed higher para-xylene production compared to its substituent zeolite (Xu & Zhu, 2022). In addition, metal@zeolite core-shell also exhibited improved physicochemical properties and superior catalytic activity (Jia et al., 2025; Sun et al., 2025; Tian et al., 2025; Wang et al., 2024) The fabrication of ZSM-5 core with low SiO_2/Al_2O_3 ratio, combined with a Zn/ZSM-5 shell, introduces additional acid sites that facilitate methanol aromatization and promote dealkylation of aromatic products, thereby contributing to an extended catalytic lifetime (Wang et al., 2024).

The current number of published papers related to the core-shell zeolites has risen over the past decade, as depicted in Figure 1a. In addition, Figure 1b highlights the most frequently occurring keywords associated with core–shell zeolites. This review specifically emphasizes core–shell structures of the zeolite@zeolite and metal@zeolite, focusing on their catalytic performance across a range of chemical reactions. This review begins by outlining the fabrication techniques for zeolite@zeolite and metal@zeolite core-shell structures. Particular attention is given to their catalytic performance in aromatization reactions. The proposed methods for core-shell fabrication are intended to address industrial requirements of catalysts. Apart from that, the core-shell zeolite catalyst is expected to deliver improved catalytic performances, thereby supporting industrial advancement and promoting long-term sustainability.

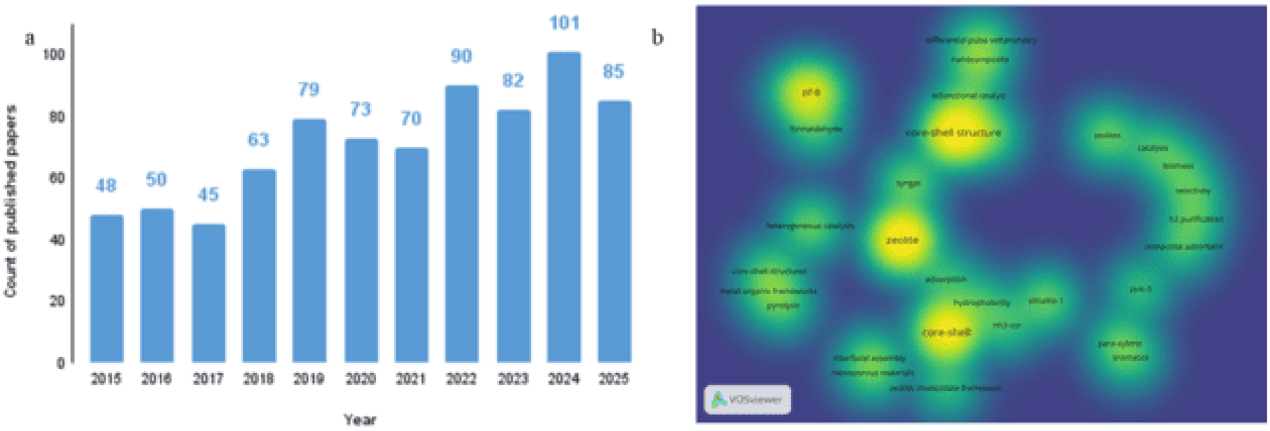

Figure 1. (a) The core-shell zeolite-related papers from 2015 to 2025 indexed by Scopus as of July 28, 2025. (b) Core-shell zeolite publications text-based analysis using VOSviewer software.

METHODS

To conduct this review paper, a comprehensive literature search was performed in electronic databases including Scopus and ScienceDirect. The search terms included combinations of keywords such as “core-shell”, “zeolite”, “catalysis”, “metal catalyst”, “aromatization”, and “nanoparticles”. We conducted the search to cover articles published between 2015 to 2025.

RESULTS AND DISCUSSION

Core-shell zeolite fabrication

Core-shell structure describes a composite system where the core and shell play distinct catalytic roles. The core acts as the primary site of catalytic activity, whereas the shell serves as a protective barrier, controlling molecular diffusion and improving selectivity. This combination material not only broadens its potential applications but also improves the reaction efficiency and long-term stability (as depicted in Figure 2) (Cui et al., 2024; D. He et al., 2019; T. Li et al., 2022; Rafiani, Aulia, et al., 2024; Sun et al., 2025; Wang et al., 2024). In addition, core-shell zeolites are carefully engineered at the microscopic scale to introduce novel desirable properties while preserving the essential characteristics of their individual components (Q. Li et al., 2023). Core-shell zeolite structures have garnered significant attention due to their well-developed pore networks and tunable acidity (Wu et al., 2024). Coating the outer surface with a dense aluminum-containing shell is a key strategy for enhancing catalytic performance as it helps suppress undesired side reactions (Wang et al., 2024).

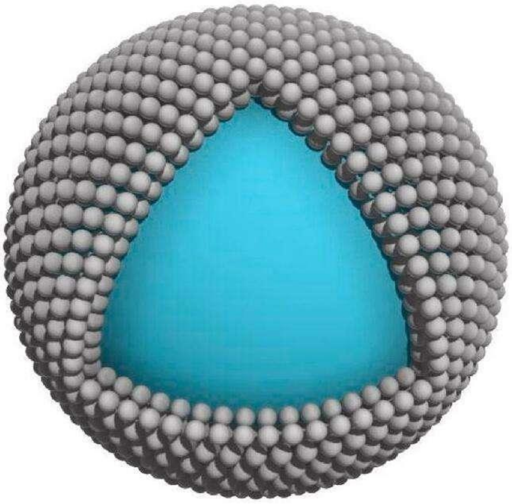

Figure 2. Core-shell structure. Adapted with permission from (Qin et al., 2025)

In comparison to the individual components or their physical mixtures, core-shell zeolites show great potential for applications in catalysis (Jia et al., 2025; Ma et al., 2021; Qin et al., 2025; Wang et al., 2024; Zou et al., 2023). The fabrication of core-shell zeolite has been widely explored, with hydrothermal as a primary synthesis method (Cho et al., 2020; Q. Li et al., 2023; Rafiani, Aulia, et al., 2024; Zou et al., 2023) Zeolite@zeolite core-shell structure composed of different zeolite components that act as core and shell. On the other hand, a metal@zeolite core- shell structure is composed of metal as a core, and zeolite as a shell, or vice versa. Following are several reported works of zeolite@zeolite and metal@zeolite core-shell structure as catalysts in broad applications (Table 1).

Table 1. Publications of core-shell zeolite catalysts through an assorted core and shell

Catalysts	**Core**	**Shell**	**Applications**	**Ref**
S-1@ZSM-5	Silicalite-1	ZSM-5	Methanol aromatization	(Wu et al., 2024)
USY-xTT@NiMo	Y zeolite	NiMo	Dibenzothiophene hydrodesulfurization	(X. Li et al., 2025)
Y@NY	Y zeolite	Nano sized Y zeolite	Hydrocracking of VCO	(Qin et al., 2025)
TS-1@TiO_2	TS-1	TiO_2	Xylene degradation	(Sun et al., 2025)
MCM-41@ZSM-5	ZSM-5	MCM-41	Pyrolysis of wheat straw	(Tian et al., 2025)
MCM-22/ZSM-5	MCM-22	ZSM-5	Cracking of polyethylene	(Ge et al., 2025)
W-Z5@S-1	W-ZSM-5	Silicalite-1	Dehydro-aromatization of methane	(Jia et al., 2025)
Silicalite-1@ZSM-5	ZSM-5	Silicalite-1	Aromatization of 1-hexene	(Cui et al., 2024)
ZSM-5@Zn/ZSM-5	ZSM-5	Zn/ZSM-5	Methanol aromatization	(Wang et al., 2024)
ZSM-11@Silicalite-2	ZSM-11	Silicalite-2	Methanol to hydrocarbon reaction	(Le et al., 2022)
ZSM-5@Na-Y	ZSM-5	Na-Y zeolite	-	(Advani et al., 2024)
PZ@NS	ZSM-5	Nanosheet Silicalite-1	Dehydrogenation of n-pentane	(Advani et al., 2024)
ZSM-5@SSZ-13	ZSM-5	SSZ-13	Methanol to olefin reaction	(Q. Li et al., 2023)
BEA@NanoZSM-5	BEA zeolite	Nanocrystalline ZSM-5	Cracking reaction of 1,3,5-triisopropylbenzene and n-hexadecane	(Mensah et al., 2021)

Pd@Silicalite-1	Pd	Silicalite-1	Oxidation of methane	(Feng et al., 2022)
Pd@S-1	Pd	Silicalite-1	Hydrogenation of p-chloronitrobenzene	(T. Li et al., 2022)
Ni@S2	Ni nanoparticles	Silicalite-2	Dry reforming of methane	(Lu et al., 2021)
sPd@meso-ZSM-5	Pd nanoparticles	ZSM-5	Biofuels production	(Deng et al., 2023)
Pt@Sn-Beta	Pt	Sn-Beta	Propane dehydrogenation	(Ma et al., 2021)
Cuo@Fe-MFI	CuO	Fe-MFI	Tetracycline degradation	(Zou et al., 2023)
Pt@H-BEA	Pt nanoparticles	H-BEA	Catalytic upgrading of cyclopentanone	(Cho et al., 2020)

Zeolite@zeolite core–shell

Reported works of zeolite@zeolite core-shell catalysts are widely developed (X. He et al., 2023; Le et al., 2022; Qin et al., 2025; Sun et al., 2025; Wu et al., 2024). The fabrication of zeolites core-shell structures mostly reported with the similar topology, which MFI topology be the preferable zeolite utilized (Cui et al., 2024; Le et al., 2022; Wang et al., 2024; Wu et al., 2024). MFI zeolite has multiple frameworks that has primary characteristics which is high acid cites that beneficial for catalytic reaction (Rafiani et al., 2025) In addition, MFI zeolite broadly used in the catalytic cracking reaction due to its unique porosity and outstanding stability (Aulia et al., 2024).

Wu and colleagues (Wu et al., 2024) reported that the fabrication of zeolite@zeolite core-shell catalyst that is S-1@ZSM-5 synthesized by seed-induced method, specifically by adjusting the crystallization situation. The seed- induced method is initially done by preparing the S-1 (core) seeds then mixed to ZSM-5 precursor liquid (Figure 3a). The crystallization time and temperature of the core-shell played important roles in the catalyst produced. It is shown that crystallization at a low temperature (115 ℃) attained worm-like framework which the ZSM-5 shell is slowly growth on the S-1 core, induced the enhanced surface acidity and micropore structure with adjustable ZSM-5 shell thickness of 30 nm, depicted on Figure 3b. This thin shell accelerated the coke removal of precursors and led to prolonged catalyst lifetime. Additionally, the low temperature crystallization at a short time caused the insufficient growth of shell materials on the core surface. By extending the crystallization time to 24 h at the same temperature, the relative crystallinity raised to 66,7%. Thereby demonstrate better shell growth on the core surface. Additionally, prolong the crystallization time or increase crystallization temperature, the gradual incorporation of aluminum species into the framework happened. This incorporation encourages the development of acid sites, resulting in a higher Brønsted acid site (BAS) density and a lower bulk SiO_2/Al_2O_3 ratio in the ZSM-5 zeolite (Figure 3c).

Wang and co-workers (Wang et al., 2024) developed the zeolite@zeolite core-shell structure over an identical framework, namely ZSM-5. At first, the ZSM-5 core is synthesized using the hydrothermal method with a high SiO_2/Al_2O_3 ratio. Subsequently, the fabrication of Zn/ZSM-5 shell around the core was carried out by the dry-gel method, employing a lower SiO_2/Al_2O_3 ratio. The coating process was solvent-free and assisted with steam, by varying the coating ratio. The study revealed that both the shell thickness and the core acid density play a crucial role in determining the core-shell catalytic performances. Still, the resulting core–shell structures maintained crystallinity levels comparable to the parent ZSM-5, indicating that the MFI topology remained intact across different coating ratios, as shown in Figure 3d. Moreover, the increase in the coating exhibited the enhancement of weak acid sites of the core-shell. Transmission electron microscopy (TEM) analysis further demonstrated the morphological characteristics of the core–shell particles. The parent ZSM-5 exhibited uniform nanoparticle morphology, while the application of Zn/ZSM-5 coatings resulted in increased grain sizes. This growth became more pronounced with higher coating ratios (Figure 3e). However, at these higher ratios, the grain surfaces became irregular, likely due to competitive crystallization of excess dry gel in the presence of water vapour.

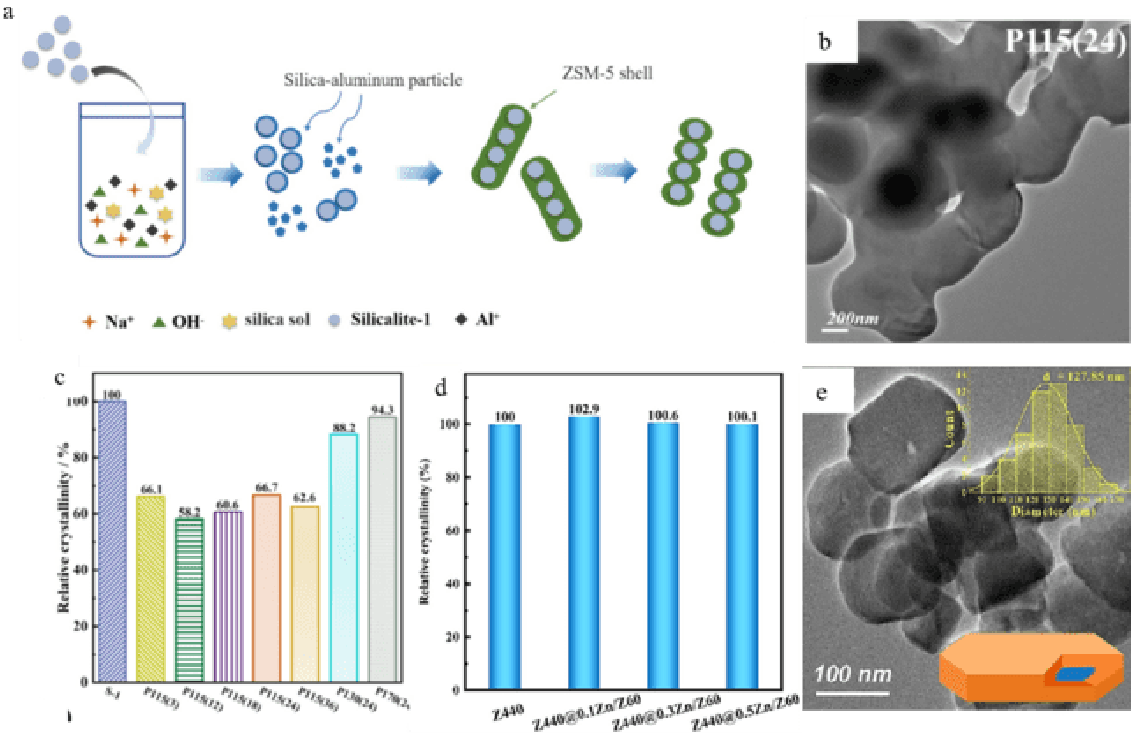

Figure 3. (a) Schematic illustration of synthesis S-1@ZSM-5 zeolite. (b) TEM image of synthesized S-1@ZSM-5 zeolite. (c) Relative crystallinity. Adapted with permission from (Wu et al., 2024), (d) Relative crystallinity. (e) TEM image and particle size distribution. Adapted with permission from (Wang et al., 2024)

Fabrication of core-shell zeolites widely reported with a similar topology. Still, the different topologies of zeolite@zeolite core-shell limitedly reported due to the tendency of interzeolite transformation was found difficult (Advani et al., 2024; Q. Li et al., 2023). Furthermore, it is challenging to achieve adequate shell coverage for the shell material, and to maintain the pore network connectivity within the core-shell structure, which significantly influences the characteristics of core-shell zeolite (Q. Li et al., 2023). Thereby, the versatile fabrication methods need to explore more.

Work reported by Li and colleagues (Q. Li et al., 2023) successfully synthesized the different topologies of core- shell zeolite, that is ZSM-5@SSZ-13, through the hydrothermal method assisted with surfactant, which solved the chemical compatibility and charge matching issues between ZSM-5 and SSZ-13 zeolites. The fabrication of ZSM- 5@SSZ-13 starts with synthesizing the SSZ-13 shell modified with various TPAOH solutions. The synthesized SSZ-13 crystal was then mixed with ZSM-5 synthetic gel and prepared using a hydrothermal method. The produced crystal was obtained as H-ZSM-5@SSZ-13 core-shell. Comparing other methods for core-shell zeolite fabrication, which mostly happen under harsh conditions, it was considered that this surfactant-assisted method was the solution. The XRD characteristic showed that the primary peaks of ZSM-5 and SSZ-13 appeared in ZSM-5@SSZ- 13 core-shell, indicating the successful core-shell fabrication. Under the conventional synthesis method, the stacking of ZSM-5 and SSZ-13, and the stacking of most of SSZ-13 that caused an uncoated ZSM-5 surface, were found, indicating the unsuccessful core-shell fabrication. On the other hand, the modified method, which was done by surfactant treatment of the SSZ-13 crystal, showed that small SSZ-13 particles covered the outer surface of ZSM-5. This exhibits successful core-shell fabrication in which SSZ-13 played as the shell and ZSM-5 as the core. Additionally, TPAOH played as a surfactant and growth template for SSZ-13 and ZSM-5, subsequently. The schematic illustration of the modified method is displayed in Figure 4.

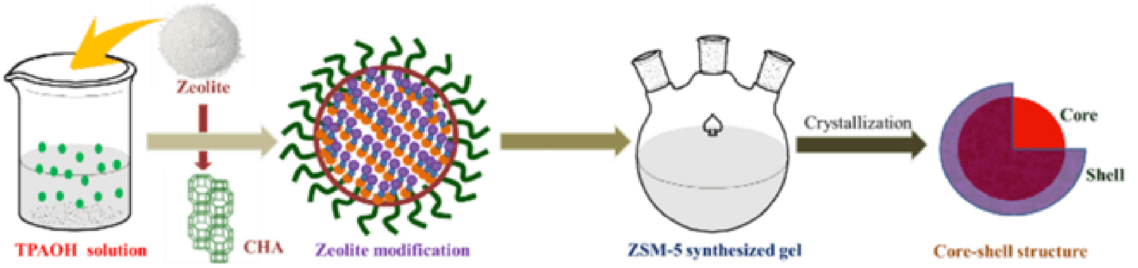

Figure 4. Schematic illustration of core-shell synthesis. Adapted with permission from (Q. Li et al., 2023)

The variation of the TPAOH amount affects the core-shell fabrication. The high concentration of TPAOH treated to the SSZ-13 resulted in more SSZ-13 being attached to the ZSM-5 surface, and also decreased the ZSM- 5 crystal size. This result demonstrated that the increased TPAOH concentration is beneficial for the core-shell fabrication (Q. Li et al., 2023).

The conventional hydrothermal method is still preferable in terms of core-shell fabrication. Hence, the hydrothermal method needs to have slight modification to improve the chemical compatibility problem, a packed aluminium on the shell, and the thickness of shell regulation, in order to provide a better catalytic performance.

Metal@zeolite core–shell

Pd@meso-ZSM-5 was fabricated through a dry-gel method, which transforms amorphous aluminosilicalite shell on Pd@aluminosilicalite to ZSM-5, and finally obtained the Pd@meso-ZSM-5 core-shell. The characterizations of Pd@meso-ZSM-5 showed the successful core-shell fabrication. From the TEM image, it is displayed that Pd nanoparticles are fully encapsulated by meso-ZSM-5 with no aggregates shown on the shell surface (Figure 5b). Moreover, the section tomography image further confirms that the Pd nanoparticles were located within the meso-ZSM-5 (Figure 5c). Thus, this one-pot transformation offers a simple and industrial applicable method to form core-shell zeolite. Likewise, the mesoporous ZSM-5 shell provides the enhancement of catalytic activity. The schematic illustration of this method is shown in Figure 5d.

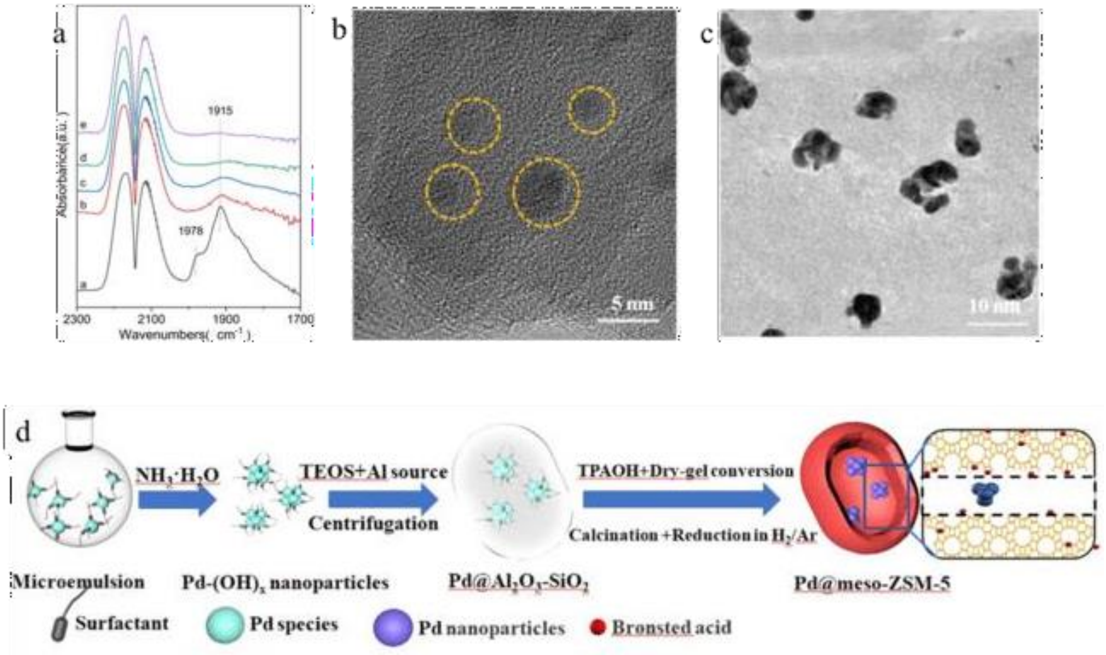

Figure 5. (a) CO-FTIR Spectra. Adapted with permission from(Feng et al., 2022), (b) TEM image of Pd@meso-ZSM-5. Section tomography image. (d) Schematic illustration of core-shell synthesis. Adapted with permission from (Deng et al., 2023).

The noble metals are well known, highly active catalysts towards numerous reactions. Thus, noble metals are invaluable due to their high cost (Ma et al., 2021)(Cho et al., 2020)(T. Li et al., 2022). Transition metals are widely utilized as catalysts owing to their considerable catalytic activity (Zhang et al., 2025). Transition metal encapsulated by zeolite is reported by Lu's group (Lu et al., 2021). Nickel nanoparticles are chosen because of their activity that is similar to noble metal-based catalysts, and also because they are economically friendly. Still, the deactivation of nickel-based catalysts is inevitable due to easy agglomeration over at high temperatures. Therein, the metal-based core-shell structure could overcome those issues through the confinement effect. In addition, the use of zeolites as a shell of a metal core is beneficial due to their outstanding properties.

The fabrication of Ni@Silicalite-2 core-shell is carried out under a two-step procedure. At first, Ni-SiO$_2$ was obtained through a micro emulsion method, then the product produced subsequently crystallized under a solvent- free crystallization method. Thereby, the Ni@Silicalite-2 (abbreviation by Ni@S2-T) was obtained (Figure 6a). This two-step core-shell fabrication method demonstrates a homogeneous Ni particle dispersion within the Silicalite-2 shell. Before the crystallization process, Ni-SiO$_2$ initially has a spherical morphology; however, after the crystallization, the sample changed to an irregular columnar form. That result indicated the effective core-shell fabrication (Figure 6b-c). The resulting Ni@S2-T core-shell gives the elevated catalytic performance over dry reforming of methane. Ni nanoparticles act as active catalytic sites, while the zeolite improves their stability through a confinement effect (Lu et al., 2021).

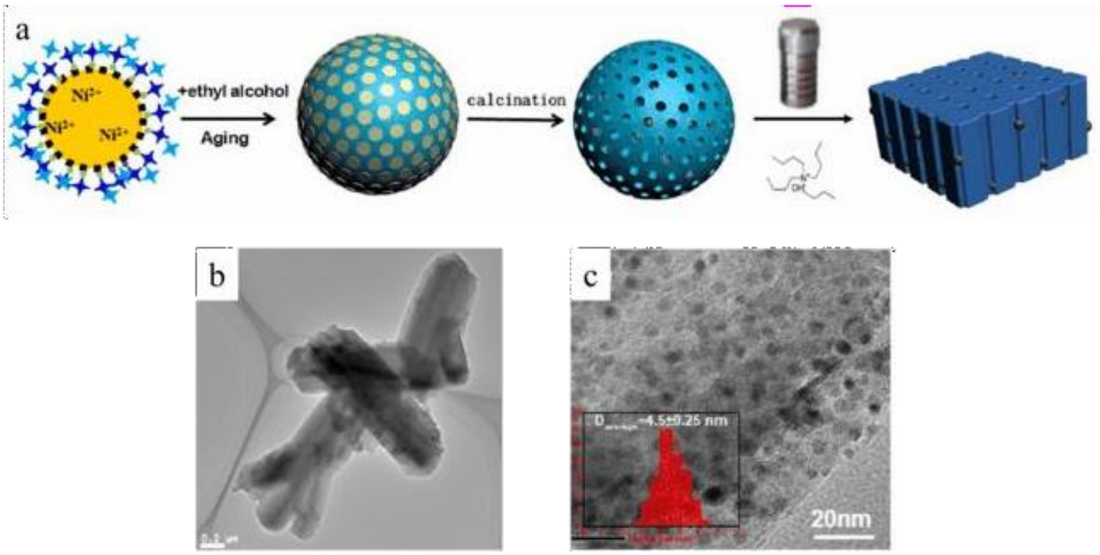

Figure 6 (a) Synthesis process of core-shell structure. SEM image. TEM image. Adapted with permission from (Lu et al., 2021)

The fabrication of metal@zeolite core-shell could be carried out under one-pot and two-step synthesis methods. The utilization of noble metal over metal@zeolite core-shell offers desirable catalyst properties. Nevertheless, the high cost of noble metal remains the primary problem. Furthermore, transition metal encapsulated with zeolite provides comparable catalyst properties to noble metal. So, the core-shell structure of transition metal and zeolite is feasible for industrial-scale development.

Core-Shell Zeolite Catalytic Performances

Zeolite is known to have various applications for aromatization reactions (Rafiani, Culsum, et al., 2024). Latest works have utilized zeolite-based core-shell to enhance selectivity and enable the productivity of targeted products. The excellent properties of zeolite-based core-shell make it a preferable choice in aromatization reaction. Zeolite@zeolite core-shell possibly to add more pores to the catalyst, which is beneficial for the reaction. On the other hand, metal@zeolite core-shell delivers a confinement effect that ensures the metal is still active and homogenous distributed inside the zeolite (Rafiani, Aulia, et al., 2024).

Aromatization reaction over zeolite-based core-shell

Aromatization is a chemical process in which non-aromatic compounds transform into aromatic compounds. Aromatic compounds mostly hydrocarbons such as benzene, toluene, and xylene. Aromatics originated from petroleum and coal (Rafiani, Culsum, et al., 2024). Currently, research on produced bio-aromatic products is being favored in terms of environmental sustainability.

Wu and colleagues (Wu et al., 2024) prepared the core-shell structure of S-1@ZSM-5 to be performed as a catalyst on methanol to aromatic (MTA) reaction. The S-1@ZSM-5 core-shell synthesized by seed-induced method, under controlled crystallization temperature and time. It resulted that the core-shell S-1@ZSM-5 catalyst with crystallization temperature of 115 ℃ and crystallization time of 24 h (abbreviated as P115(24)) revealed the increase of surface area and Brønsted acid site (BAS) thus the liquid hydrocarbon yield and the catalytic lifetime also increased. Moreover, the escalation of surface area and BAS density strongly influenced the aromatic selectivity. The catalytic performance showed that the aromatics and para-xylene selectivity were increased under P115(24) condition (Figure 7a). In addition, the thin ZSM-5 shell formed is beneficial owing to the fast coke precursors removal, as well as prolonging the catalyst lifetime. The thin ZSM-5 shell also provides good diffusion capability that make S-1@ZSM-5 core-shell catalysts have a high catalytic activity over MTA reaction (Wu et al., 2024).

The MTA reaction over zeolite-based core-shell structure was also evaluated by Wang, et al. (Wang et al., 2024) using the ZSM-5@Zn/ZSM-5 catalyst with different coating ratio. It is found that the coating ratio of 0.3 indicates the better catalytic activity over MTA reaction. The ZSM-5@0.3Zn/ZSM-5 showed the enhanced acid amount that reinforced the aromatization ability and also the liquid hydrocarbon yield. Simultaneously, the catalyst exhibited greatly enhanced stability, maintaining a 100% methanol conversion rate for up to 215 hours. The inclusion of ZSM-5 as the core catalyst introduces a higher density of acid sites and facilitates more complex reaction pathways, thereby enhancing the aromatization of methanol and its intermediate products. Additionally, the presence of ZSM-5 aids in dealkylation of larger aromatic molecules originating from the upper catalyst bed, which in turn increases the selectivity toward lighter aromatics.

This is why ZSM-5@0.3Zn/ZSM-5 demonstrates significantly higher selectivity for both total and light aromatics. Furthermore, the in-situ reaction confirms that integrating a ZSM-5 core with the Zn/ZSM-5 catalyst enhances methanol adsorption and the subsequent formation of aromatic compounds. Importantly, optimizing molecular diffusion within the catalyst bed facilitates the release of aromatic products from catalyst surfaces, effectively limiting their undesired secondary conversions between particles. These findings also suggest that while the core catalysts supply additional acid sites that enhance the aromatization of methanol and its intermediates, an excessive number of acid sites may lead to increased generation of coke precursors, thereby speeding up catalyst deactivation (Figure 7b).

Other aromatization reactions also reported by Cui and colleagues using 1-hexene feedstock (Cui et al., 2024). Core-shell zeolite applied over this reaction is membrane-restricted Silicalite-1@ZSM-5 with different crystallization time and hydrothermal cycles. The overly thick shell in S-1@ZSM-5(48)-3 was detrimental to its aromatization capability. The formation of the Silicalite-1 shell effectively neutralized the external acid sites of ZSM-5, leading to decreased acid strength and overall acidity. This not only reduced the catalyst's cracking function but also limited oligomerization, cyclization, and aromatization reactions. Consequently, small hydrocarbons formed within the zeolite could no longer convert into longer-chain hydrocarbons and aromatics on the external surface. The BTX selectivity in hydrocarbons for S-1@ZSM-5(48)-3 was lower than for S-1@ZSM-5(48)-2, possibly due to the lower aromatic yield caused by the deactivation of outer acid sites (as shown in Figure 7c). This suggests that it’s possible to achieve higher BTX selectivity without significantly compromising aromatization activity. Furthermore, the ethylbenzene proportion in the aromatic products remained unchanged, indicating that the shell coverage had little influence on ethylbenzene formation.

As the shell thickness increased, PX (para-xylene) selectivity improved markedly from 24.2% to 83.85%. This enhancement is attributed to the reduced number of acid sites on the zeolite's exterior, which lowered the chances of xylene isomerization occurring there. Additionally, the shell encapsulation extended the pore channels, increasing the diffusion resistance for MX (meta-xylene) and OX (ortho-xylene), thereby favoring PX formation. However, the zeolite framework is not entirely rigid; its pore dimensions can fluctuate due to thermal vibrations, which, together with molecular vibrations, may allow slightly larger molecules like MX to diffuse in and out of the zeolite pores (Cui et al., 2024).

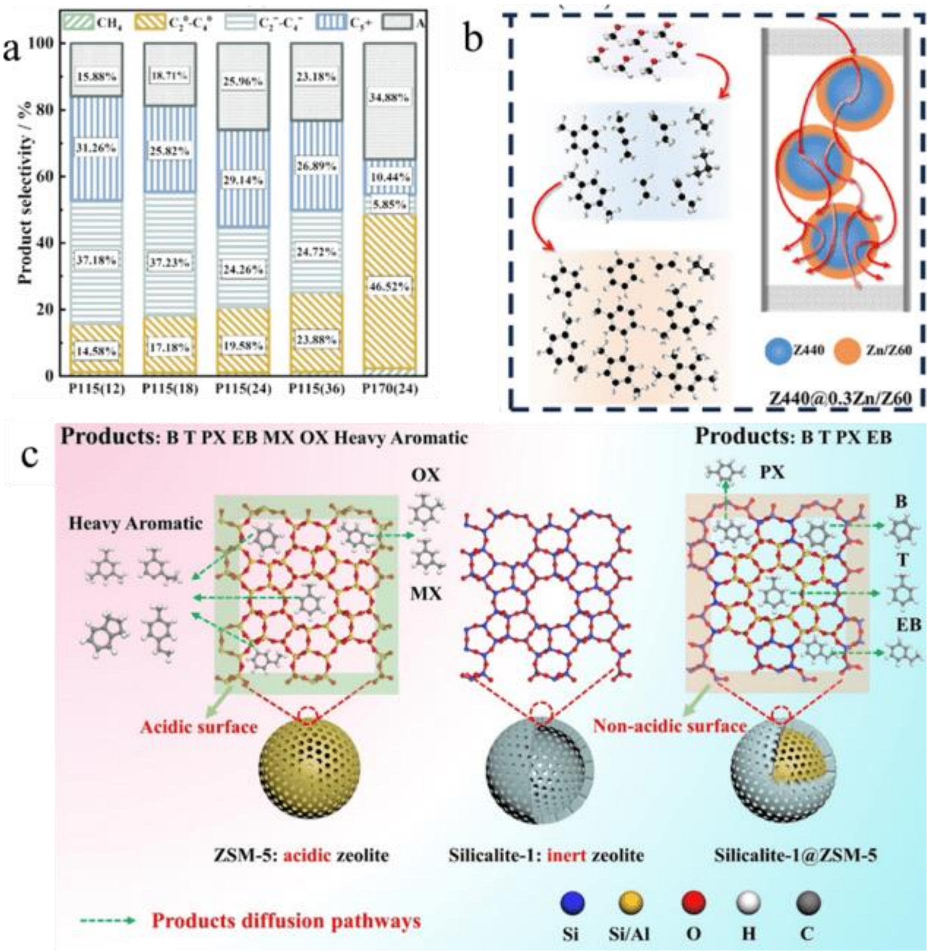

Figure 7. (a) Product distribution. Adapted with permission from (Wu et al., 2024). (b) Reaction pathway for MTA. Adapted with permission from (Wang et al., 2024). (c) Mechanism for BTX and PX selectivity. Adapted with permission from (Cui et al., 2024)

CONCLUSIONS

The highest number of journal article publications occurred in 2024, with a total of 101 articles. The conventional hydrothermal method is still preferable in terms of core-shell fabrication. Hence, the hydrothermal method needs to have slight modifications to improve the chemical compatibility problem, and the thickness of the shell to provide a better catalytic performance.

The fabrication of metal@zeolite core-shell could be carried out under one-pot or two-step synthesis methods. The utilization of noble metal over metal@zeolite core-shell offers desirable catalyst properties. Nevertheless, the high cost of noble metals remains the primary problem. Furthermore, transition metal encapsulated with zeolite provides comparable catalyst properties to noble metal. So, the core-shell structure of transition metal and zeolite is feasible for industrial-scale development.

Zeolite-based core-shell catalyst showed an excellent catalytic performance for the aromatization reaction. Zeolite@zeolite core-shell is possible to add more pores to the catalyst, which is beneficial for the reaction. On the other hand, metal@zeolite core-shell delivers a confinement effect that ensures the metal is still active and homogenous distributed inside the zeolite.

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REFERENCES

Advani, J. H., Manal, A. K., Kanna, N., Kumar, P., Bal, R., & Srivastava, R. (2024). Synthesis of core–shell structured zeolite nanocomposite comprising ZSM-5 core and zeolite Y shell. *Materials Letters*, *360*, 135994. https://doi.org/10.1016/j.matlet.2024.135994

Aulia, D., Maghfirah, A., & Kadja, G. T. M. (2024). Green synthesis of hierarchical ZSM-5 using cellulose nanocrystal-mesoporogen at low temperature for catalytic cracking of palm oil into aromatic-rich gasoline. *Results in Engineering*, *24*, 102954. https://doi.org/10.1016/j.rineng.2024.102954

Cho, H. J., Kim, D., & Xu, B. (2020). Pore Size Engineering Enabled Selectivity Control in Tandem Catalytic Upgrading of Cyclopentanone on Zeolite-Encapsulated Pt Nanoparticles. *ACS Catalysis*, *10*(15), 8850–8859. https://doi.org/10.1021/acscatal.0c01542

Choi, M., Wu, Z., & Iglesia, E. (2010). Mercaptosilane-Assisted Synthesis of Metal Clusters within Zeolites and Catalytic Consequences of Encapsulation. *Journal of the American Chemical Society*, *132*(26), 9129–9137. https://doi.org/10.1021/ja102778e

Cui, X., Lyu, H., Chai, Y., Liu, B., Zhao, D., & Liu, C. (2024). Selective aromatization of 1-hexene to BTX over core-shell structured Silicalite-1@ZSM-5 catalyst. *Separation and Purification Technology*, *349*, 127881. https://doi.org/10.1016/j.seppur.2024.127881

Deng, Q., Peng, H., Yang, Z., Wang, T., Wang, J., Zeng, Z., & Dai, S. (2023). A one-pot synthesis of high-density biofuels through bifunctional mesoporous zeolite-encapsulated Pd catalysts. *Applied Catalysis B: Environmental*, *337*, 122982. https://doi.org/10.1016/j.apcatb.2023.122982

Feng, X., Wang, T., Mu, L., Chen, Z., Liang, J., & Xiao, C. (2022). Excellent stability for catalytic oxidation of methane over core–shell Pd@silicalite-1 with complete zeolite shell in wet conditions. *Catalysis Today*, *400– 401*, 66–72. https://doi.org/10.1016/j.cattod.2021.11.013

Ge, H., Gu, Y., Liu, F., Huang, Y., Liu, Y., Wu, S., Hu, Y., Li, Z., & Lin, H. (2025). Preparation of MCM-22/ZSM- 5 core–shell structured zeolite for catalytic cracking of polyethylene to selectively produce paraxylene. *Fuel*, *398*, 135550. https://doi.org/10.1016/j.fuel.2025.135550

He, D., Zhang, C., Zeng, G., Yang, Y., Huang, D., Wang, L., & Wang, H. (2019). A multifunctional platform by controlling of carbon nitride in the core-shell structure: From design to construction, and catalysis applications. *Applied Catalysis B: Environmental*, *258*, 117957. https://doi.org/10.1016/j.apcatb.2019.117957

He, X., Tian, Y., Qiao, C., Diao, Z., & Liu, G. (2023). Dehydrogenation–cracking synergistic pathway of n–pentane by core–shell MFI zeolite to produce light olefins. *Microporous and Mesoporous Materials*, *362*, 112790. https://doi.org/10.1016/j.micromeso.2023.112790

Jia, Y., Li, S., Peng, L., Xie, Z., Yu, F., Huang, C., Wang, W., Liu, R., Wang, Z., Liu, C., Zhao, L., & Wang, L. (2025). Rational design of silicalite-1-encapsulated W-ZSM-5 core-shell catalysts for optimizing selectivity and stability in methane dehydro-aromatization reaction. *Molecular Catalysis*, *584*, 115314. https://doi.org/10.1016/j.mcat.2025.115314

Le, T. T., Shilpa, K., Lee, C., Han, S., Weiland, C., Bare, S. R., Dauenhauer, P. J., & Rimer, J. D. (2022). Core-shell and egg-shell zeolite catalysts for enhanced hydrocarbon processing. *Journal of Catalysis*, *405*, 664–675. https://doi.org/10.1016/j.jcat.2021.11.004

Li, Q., Wen, Z., Zhang, Z., Wei, P., Wang, X., & Yang, C. (2023). Surfactant-assisted hydrothermal synthesis of core-shell ZSM-5@SSZ-13 zeolite for methanol to olefins reaction. *Molecular Catalysis*, *547*, 113321. https://doi.org/10.1016/j.mcat.2023.113321

Li, T., Wang, S., Yu, H., Yuan, L., Zhang, D., & Yin, H. (2022). Encapsulation of Noble Metal Nanoclusters into Zeolites for Highly Efficient Catalytic Hydrogenation of Nitroaromatics. *Industrial & Engineering Chemistry Research*, *61*(51), 18762–18771. https://doi.org/10.1021/acs.iecr.2c02038

Li, X., Ren, S., Liu, L., & Yang, C. (2025). Controllable assembly of NiMo nano-wool shell on zeolite Y and its advanced behavior of hydrodesulfurization toward dibenzothiophene. *Microporous and Mesoporous Materials*, *381*, 113368. https://doi.org/10.1016/j.micromeso.2024.113368

Lu, Y., Guo, D., Zhao, Y., Moyo, P. S., Zhao, Y., Wang, S., & Ma, X. (2021). Confined high dispersion of Ni nanoparticles derived from nickel phyllosilicate structure in silicalite-2 shell for dry reforming of methane with enhanced performance. *Microporous and Mesoporous Materials*, *313*, 110842. https://doi.org/10.1016/j.micromeso.2020.110842

Ma, Y., Chen, X., Guan, Y., Xu, H., Zhang, J., Jiang, J., Chen, L., Xue, T., Xue, Q., Wei, F., & Wu, P. (2021). Skeleton-Sn anchoring isolated Pt site to confine subnanometric clusters within *BEA topology. *Journal of Catalysis*, *397*, 44–57. https://doi.org/10.1016/j.jcat.2021.03.022

Mensah, J., Yan, P., Kennedy, E., Drewery, M., & Stockenhuber, M. (2021). Novel hierarchical core-shell BEA@NanoZSM-5 zeolite for improved cracking performance for 1,3,5-triisopropylbenzene and n-hexadecane. *Microporous and Mesoporous Materials*, *328*, 111399. https://doi.org/10.1016/j.micromeso.2021.111399

Qin, B., Zhang, T., Liu, Y., Chen, Z., Gao, H., Du, Y., Hou, S., & Zheng, J. (2025). Design and synthesis of core- shell Y zeolite: A tandem microreactor facilitating efficient and targeted conversion of heavy oil macromolecules. *Materials Today Sustainability*, *31*, 101165. https://doi.org/10.1016/j.mtsust.2025.101165

Rafiani, A., Aulia, D., & Kadja, G. T. M. (2024). Zeolite-encapsulated catalyst for the biomass conversion: Recent and upcoming advancements. *Case Studies in Chemical and Environmental Engineering*, *9*. https://doi.org/10.1016/j.cscee.2024.100717

Rafiani, A., Culsum, N. T. U., & Kadja, G. T. M. (2024). State-of-the-art and the future directions of glycerol transformation to bio-based aromatics via catalytic pyrolysis over zeolite catalysts. In *Bioresource Technology Reports* (Vol. 25). Elsevier Ltd. https://doi.org/10.1016/j.biteb.2024.101785

Rafiani, A., Maghfirah, A., & Kadja, G. T. M. (2025). Enhanced Catalytic Pyrolysis of Glycerol into Gasoline Over TS-1/ZSM-5 Hybrid Catalysts. *Waste and Biomass Valorization*. https://doi.org/10.1007/s12649-025-03122- 5

Sun, S., Li, Y., Chen, Y., Chen, D., Yang, Y., Liu, M., Li, S., Li, B., Sun, X., Turabdjanov, S., Donaev, S., Wang, L., & Li, B. (2025). Enhancing xylene degradation by core-shell TS-1@TiO2 in a bubble reactor with ultraviolet/H2O2. *Journal of Colloid and Interface Science*, *695*, 137803. https://doi.org/10.1016/j.jcis.2025.137803

Tian, H., Mao, H., Wang, J., & Cheng, Y. (2025). Ga-Ni modified MCM-41@HZSM-5 core-shell zeolite for catalytic fast pyrolysis of wheat straw to produce monocyclic aromatics. *Chemical Engineering Journal*, *510*, 161707. https://doi.org/10.1016/j.cej.2025.161707

Wang, Z., Zheng, H., Meng, F., Fu, T., & Li, Z. (2024). ZSM-5@Zn/ZSM-5 core@shell nanocrystals as integrated catalysts for efficient methanol conversion into aromatics. *Fuel*, *369*, 131728. https://doi.org/10.1016/j.fuel.2024.131728

Wu, X., Cao, C., Yao, R., Fu, T., & Li, Z. (2024). A core-shell structured S-1@ZSM-5 catalyst with thin shell and weak surface acidity for stable methanol aromatization to para-xylene. *Fuel*, *375*, 132647.

https://doi.org/10.1016/j.fuel.2024.132647

Xu, G., & Zhu, X. (2022). A core-shell structured Zn/ZSM-5@MCM-41 catalyst: Preparation and enhanced catalytic properties in propane aromatization. *Fuel*, *317*. https://doi.org/10.1016/j.fuel.2022.123546

Zhang, L., Li, Z., Gao, Y., Li, Q., Deng, Z., Miao, B., He, H., Poh, C. K., Zhang, L., & Chan, S. H. (2025). Recent advances in supported metal catalysts for CO2 methanation: mechanisms, materials design, and the promise of perovskite-based supports. *Energy Conversion and Management: X*, *27*, 101066. https://doi.org/10.1016/j.ecmx.2025.101066

Zou, X., Wang, J., Lv, G., Wang, T., Zhou, C., Chen, Y., Shen, J., Su, S., & Liu, Z. (2023). Fe-MFI zeolite-encapsulated copper oxide with excellent re-usability for efficient tetracycline degradation. *Microporous and Mesoporous Materials*, *360*, 112735. https://doi.org/10.1016/j.micromeso.2023.112735