

Harnessing the potential of manufactured zeolites for a sustainable circular economy

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ABSTRACT

Manufactured zeolites are widely recognized for their high purity, cation exchange capacity, molecular sieve structure, and environmental stability, enabling applications across diverse industries. Unlike existing studies that primarily investigate the material properties or interdisciplinary applications of manufactured zeolites, this work uniquely positions them within a circular economy (CE) framework. This study pioneers the concept of zeolite synthesis from waste-derived feedstocks as a direct driver of CE, linking this transformation to concrete pathways for achieving multiple UN sustainable development goals (SDGs), highlights their untapped role in resource recovery, pollution reduction, and climate change mitigation. In addition, this work advances novelty by not only mapping opportunities but also identifying systemic barriers – economic, technical, and governance-related – that hinder large-scale adoption. This dual focus on value creation from waste and barrier resolution establishes a new research direction that previous studies have not addressed, thereby extending the role of manufactured zeolites from industrial materials to strategic enablers of sustainable policy and practice.

Keywords: circular economy, climate change, manufactured zeolites, sustainable development goals.

INTRODUCTION

Unprecedented global population growth, rapid industrialization, urbanisation, and economic development are putting pressure on land resources, threatening global food security, and exposing sustainability issues. By the year 2100, the global population is projected to rise about 11 billion (Babu et al., 2022). Along with population growth, waste generation will increase accordingly putting pressure on existing landfills and thereby posing several key challenges for future generations (Nguyen et al., 2023). It is estimated that by 2050, global waste will increase to 3.4 billion metric tons (Kaza et al., 2018). Accordingly, various national and international initiatives have been launched to mitigate waste pollution.

Effective waste management is key to the circular economy (CE), minimizing pollution,

maximizing resource efficiency, and supporting sustainable production. Utilizing waste end-products enhances circularity, reducing disposal issues while aligning with UN sustainability goals. Addressing waste management and sustainability in tandem is crucial for achieving the UN SDGs by 2030 (Uday et al., 2022). For example, to attain the UN SDG of ‘Net Zero Emissions’, transitioning to new materials and implementing low-impact production methods are critical. This involves adopting CE principles centred around the ‘Rs’ (i.e. Recovery, Reuse, Remanufacture, and Recycling) which are vital for promoting sustainability and achieving carbon neutrality by 2050 (Schwanke et al., 2022; Yang et al., 2023). Industry by-products – commonly categorised as waste materials – offer great opportunity for valorisation, contributing to effective waste management and CE outcomes.

Of particular interest here is zeolite, which is an aluminosilicate mineral that can be produced from various stock sources. Manufactured zeolites have a pivotal role in waste management by enabling the recovery, recycling, and reuse of materials from various waste streams. Recent studies showcase their expanding applications in agriculture, environmental remediation, catalysis, animal feed, and pharmaceuticals (Kordala and Wyszowski, 2024; Ma et al., 2024; Nguyen et al., 2023). Due to its prominent physiochemical properties such as molecular sieve properties, microporous structure, high cation exchange capacity (CEC), large surface area, and high adsorption capacity, manufactured zeolite has been pursued across various ranges of uses (Szerement et al., 2021). These properties enable zeolites to effectively adsorb pollutants from soil and water, thereby aiding in the reduction of environmental contamination (Hermassi et al., 2020; Khandaker et al., 2020).

Manufactured zeolites enhance soil productivity and stability, serving as eco-friendly slow-release fertilizers (Lateef et al., 2016). They also support greenhouse gas reduction, aligning with the UN SDG (climate action) (Gao et al., 2023). Research shows that manufactured zeolites lower CO₂ and NO_x emissions from vehicle and industrial sources (Parvulescu and Maurer, 2022) and could reduce atmospheric CH₄ concentrations from 1860 ppb to about 750 ppb (Jackson et al., 2019). Zeolites enhance the cement strength, with a 20% cement substitution reducing global warming potential by 69.7% (Valipour et al., 2014). As phosphate-free detergent builders, they pose minimal environmental risk (Koohsaryan et al., 2020). Consequently, their application contributes significantly to advance multiple UN SDGs, particularly the (climate action) goal.

Unlike existing studies that mainly examine the material properties or catalytic performance of manufactured zeolites, this work uniquely positions them within the wider context of the circular economy (CE). It pioneers the concept of synthesising zeolite from waste-derived feedstocks as a direct driver of CE, linking this transformation to concrete pathways for achieving multiple UN sustainable development goals (SDGs). Beyond identifying opportunities, the study also highlights key knowledge gaps – where research is limited, inconclusive, or contradictory – and uncovers systemic barriers, including economic, technical, and

governance-related challenges, that hinder large-scale adoption. By combining value creation from waste with strategies to overcome these barriers, this work establishes a new research trajectory, reframing manufactured zeolites not only as industrial materials but also as strategic levers for sustainable policy and practice.

ZEOLITE BACKGROUND

Zeolites were discovered by Swedish mineralogist Alex Fredrick Cronste in 1758, with their first industrial use in 1905. The first manufactured zeolite was produced in 1948 (de Magalhães et al., 2022). Nowadays, the International Zeolite Association (IZA) recognizes around 230 types within 133 crystalline structures. These microporous aluminosilicate minerals feature a 3D framework of SiO₄⁴⁻ and AlO₄⁵⁻ tetrahedra, forming channels and cages that house water molecules and alkaline ions (K⁺, Na⁺, Ca²⁺, etc.) (Tauanov et al., 2022). New variations, such as titanosilicates, continue to emerge (Přech, 2018). Zeolites assemble like Lego bricks, forming secondary building units as shown in Figure 1.

Few countries worldwide however have exploitable zeolite deposits, accessible only through open-pit mining. In 2021, global natural zeolites production was estimated at 1.6 M-tons, Figure 2 for instance shows the production data for multiple countries. However, only a limited supply meets industrial demand (Khaleque et al., 2020). Natural zeolites vary widely in composition and structure, often containing impurities like metals, quartz, or different types of zeolite (Jarosz et al., 2022), affecting purity and consistency. Additionally, their diverse pore sizes and structures can limit applications requiring uniformity, impacting adsorption and catalytic performance, necessitating refinement for specific uses (de Magalhães et al., 2022). For instance, the presence of impurities and structure irregularities can adversely affect adsorption capacity and catalytic activity, necessitating thorough characterization and potential modification for specific applications (Hartati et al., 2020). Unlike natural zeolites, manufactured zeolites are formed quicker ranging from a few hours to several days under controllable laboratory conditions, allowing precise management over crystal size, shape, and pore structure (Khaleque et al., 2020).

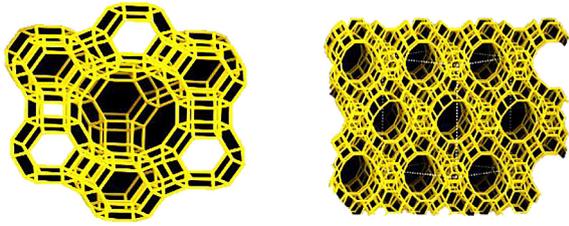
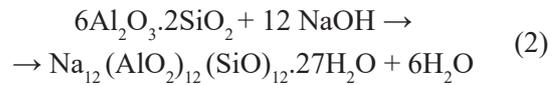


Figure 1. Zeolite framework type FAU (adopted from <http://www.iza-structure.org/>)

Further, manufactured zeolites can be produced with desirable physiochemical properties such as high purity structure, high CEC, high porosity, uniform size, and high surface area (Szerepent et al., 2021). This uniformity enhances performance in catalytic and adsorption processes by optimizing surface area and pore volume distribution, thereby facilitating more consistent and reliable process outcome.

There has been a growing trend in producing manufactured zeolites from various Si- and Al-rich waste by-products such as rice husk, kaolin, and fly ash, resulting in high yields. For instance, different zeolite frameworks, including Y, P, N, X, and A, have been manufactured using various processing methods and various sources, each exhibiting distinct physiochemical properties and chemical compositions. Collins et al. (2020) noted that the predominant technique for transforming kaolin into zeolite LTA involves heating the clay minerals at 550 °C to transform them into the more reactive meta-kaolin, as shown in Equation

1. This is followed by a reaction with alkali to formulate of zeolite LTA (Equation 2):



Abdelrahman et al. (2021) reused waste aluminium cans and rice husk as Si and Al sources to produce nanosized zeolite, a cost-effective and eco-friendly method for removing Co, Zn, and Cu from water. Converting waste into zeolite supports the circular economy and conserves natural resources (Jarosz et al., 2022). Mallapur and Oubagaranadin (2017) found that zeolites from natural clays, fly ash, rice husk ash, and porcelain waste have versatile industrial uses. By-products like spent fluid cracking catalysts and cupola slag have also been used to synthesize ZSM-5, NaA, and NaX zeolites, proving waste-derived zeolite production is viable and reduces environmental pollution (Gao et al., 2023). Waste-derived zeolites further support SDG 12 (Responsible Consumption and Production) by reducing utilization of non-renewable resources and supporting sustainable waste management aligned with global clean and green initiatives.

MANUFACTURED ZEOLITES PROPERTIES

Zeolites stand out from other porous materials due to their structured micropores, typically under

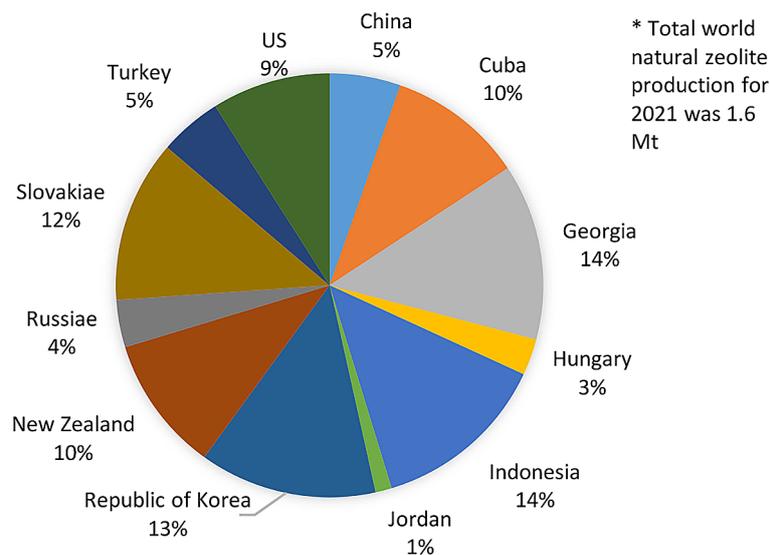


Figure 2. Estimated world natural zeolite production for 2021* (Data are extracted from: https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-zeolites_bef3.10.22.pdf)

2 nm (Jarosz et al., 2022). Table 1 compares the physiochemical characteristics of manufactured and natural zeolites, showing that manufactured types have significantly higher surface area and CEC. Zeolite A, commonly used in detergents, excels in ion exchange, replacing Na ion with Mg and Ca ions from hard water (Collins et al., 2020). CEC varies based on factors like structure, Si/Al content, pH, and ionic strength (Khaleque et al., 2020; Szerement et al., 2021). Khaleque et al. (2020) found that higher Al and Na content enhances ion exchange in manufactured zeolites.

Another special characteristic of zeolites is their adsorption capability, which involves the uptake of chemical components from gases or liquids onto the surface of zeolite minerals. Zeolite adsorption characteristics are significantly affected by the ratio of Si/Al (Flores et al., 2021). For instance, zeolites with high concentration of silica (i.e. Si/Al > several thousands) are useful for removing organic micro pollutants, whereas zeolites with low silica concentration (i.e. Si/Al below 2) show high ion-exchange capacities and are highly effective in heavy metals and ammonium adsorption (Jiang et al., 2018). As seen later in Table 3, manufactured zeolites generally exhibit substantial adsorption capacities for heavy metals removal compared to those obtained naturally (Kozera-Sucharda et al., 2020). This enhanced performance is related to the materials' high porosity, high CEC, and

extensive surface area of manufactured zeolites (Gaidoumi et al., 2018; Szerement et al., 2021).

ZEOLITE APPLICATION AS TOOL FOR ENVIRONMENTAL SUSTAINABILITY

Because of their unique physiochemical characteristics, manufactured zeolites are employed in different applications including pollutants removal, agricultural applications, detergent applications, catalysis, aquaculture, animal feed, medical applications, and for mitigating climate change (see Table 2). These applications highlight the versatility of manufactured zeolites across various industries, demonstrating their potential for commercialization in improving efficiency, sustainability, and functionality in engineering and technological applications. The upcoming sections will examine these applications in depth.

Agricultural applications

The growing need for food has led to increased chemical fertilizer use, disrupting nutrient cycles and causing nitrate, ammonium, and phosphate runoff into water bodies. Ammonia volatilization further contributes to nitrogen loss in agriculture (Cataldo et al., 2021). To address this, zeolite-based slow-release fertilizers have been explored to reduce nutrient leaching and

Table 1. Manufactured zeolite physicochemical properties in comparison with natural zeolites

Zeolite type	Origin	pH	Pore size (nm)	Surface area (m ² /g)	Si/Al ratio	CEC (meq/g)	Pore volume (cm ³ /g)	References
Natural zeolite	Germany	-	0.4	30–60	4.80–5.40	1.2–1.5	-	(Eberle et al., 2022)
Natural zeolite Linde type A-zeolite Zeolite X Coal fly ash-zeolite Na-P1	Japan	-	-	-	4.88–5.04 1.0–1.2	2.11 6.15 5.56 3.25	-	(Johan et al., 2015)
Clay-zeolite 13x Kaolin-zeolite 13x Bentonite-zeolite 13x	Iran	-	-	588 591 505	2.5–4.5	-	0.240 0.250 0.140	(Garshasbi et al., 2017)
Fly ash-zeolite ZCET40	Romania	-	14.16	52.44	1.48	-	0.003	(Visa, 2016)
Zeolite-geopolymer composite (Z/G)	Egypt	-	4.2	106	2	-	0.058	(Salam et al., 2021)
Chitosan/zeolite A Zeolite A	Egypt	-	23.6 11.6	446.7 423.0	-	-	0.412 0.382	(Mostafa et al., 2021)
Fly ash-NaA zeolite	China	-	-	43.185	2	2.123	0.0364	(Wang et al., 2023)
Bentonite-zeolite 13x	China	-	2.2	688	-	-	0.3	(Chen et al., 2014)
Fly ash-slag Zeolite 13x Fly ash-slag Zeolite 4A Clinoptilolite	NA	-	24.18 4.535 7.960	388.372 295.464 239.313	-	-	0.8375 0.6032 0.4614	(Lu et al., 2023)

Note: NA – unknown sources.

Table 2. Manufactured zeolites and their applications to different sectors

Type of zeolite	Feedstock	Application	Sources
Zn-LTA zeolites	Kaolin mining wastes	Antibacterial application	(Schwanke et al., 2022)
Zeolite P	Red mud	NH ₄ removal	(Zhao et al., 2016)
Na-PI zeolite	Brazilian coal-fly ashes	Wastewater treatment	(Cardoso et al., 2015)
Fly ash-based zeolite	Fly ash	Mercury capture	(Kunecki et al., 2023)
Zeolites- FAU type	Coal fly ash	Cd, Co, Cu, Pb, and Zn removal	(Joseph et al., 2020)
Zeolite FA-Z	Coal fly ash	Ni and Cd ions removal	(Sireesha et al., 2022)
Zeolite Na-A	Fluid catalytic wastes	CO ₂ adsorption from a gas mixture of CO ₂ /CH ₄	(Ferella et al., 2020)
Zeolite A Zeolite 13x	Fly ash	Ion-exchange CO ₂ capture	(Soe et al., 2016)
Zeolite 13x	Fly ash	CO ₂ capture	(Zhang et al., 2017)
Nano-sized Zeolite 4A	Kaolin	CH ₄ removal	(Wang et al., 2020)
Zeolite 13x	Clay Kaolin Bentonite	CO ₂ and CH ₄ adsorption	(Garshasbi et al., 2017)
Zeolite A	Coal fly ash	Slow urea release	(Fan et al., 2023)
Zeolite 5A	Kaolin	As and Pb removal	Mayta-Armas et al., 2023)

enhance crop yields (Soltys et al., 2020). While natural zeolites are extensively employed as soil amendments (Mondal et al., 2021), their non-renewable nature and environmental impact make sustainable alternatives essential. Developing manufactured zeolites offers an affordable, eco-friendly substitute to preserve natural reserves.

Research shows that manufactured zeolite amendments improve soil fertility, nutrient retention, pH, water infiltration, and hydraulic conductivity (Fan et al., 2023; Szerement et al., 2021) (Figure 3). Their high surface area enhances soil structure and cation exchange, aiding nutrient availability (Szerement et al., 2021). Combining zeolite with potassium (K) increased rice yield by 6.4%, offering a 6.6% economic advantage over conventional K application (Li et al., 2022). Noori et al. (2007) stated that while both natural and manufactured zeolites improved soil salinity and radish yield, manufactured zeolites had greater benefits caused by the highly surface area as well as enhanced ion-exchange properties. This supports UN SDG 2 (Zero Hunger) by supporting sustainable agricultural practises.

Zeolites also boost nutrient retention, water-holding capacity, and aeration (de Carvalho Izidoro et al., 2024). Lateef et al. (2016) synthesized nano-zeolites from sodium silicate and aluminium sulphate, demonstrating their effectiveness as slow-releasing fertilizers. They enhanced water absorption, retained moisture, and reduced nutrient leaching compared to

chemical fertilizers, aligning with UN SDG 6 (Clean Water and Sanitation). Zeolites adsorb nutrients like phosphorus from runoff, preventing pollution and algal blooms (Warahena and Warahena, 2023). When applied to soil, zeolite capture NH₄⁺, releasing it for plant uptake, boosting yield and reducing ammonia loss (Zheng et al., 2019). Hermassi et al. (2020) used coal fly ash to synthesis zeolites, which demonstrated high PO₄³⁻ adsorption, making them ideal for soil remediation and slow-release fertilization. This reduces nutrient leaching, protecting water supplies and ecosystems, and contributes to UN SDGs, including SDG 14 (life below water) and SDG 15 (life on land).

Zeolite soil amendment increases plant water availability by 50% (Sangeetha and Baskar, 2016), aiding drought resilience. Ca-type zeolite reduced deep water percolation and improved nitrogen balance in sandy soils (Al-Busaidi et al., 2008). Zeolites also enhance microbial activity, supporting soil carbon composition (Ferretti et al., 2018). Their porous structure fosters beneficial microbes while suppressing pathogens like nematodes, fungi, and viruses. Schwanke et al. (2022) demonstrated that LTA, sodalite, and Zn-exchanged LTA zeolites from kaolin mining waste exhibited antibacterial effects against *Listeria monocytogenes*, *E. coli*, *Salmonella enterica*, and *Staphylococcus aureus*.

Unlike conventional soil amendments like gypsum or lime, zeolitic minerals do not degrade

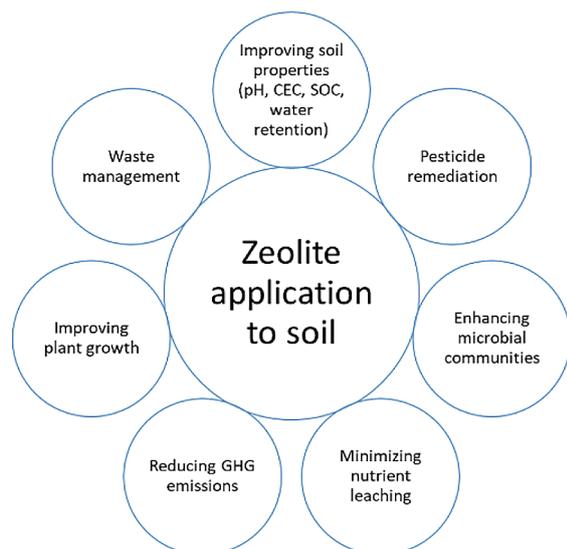


Figure 3. Positive effects of zeolite application to soil

over time, which can help gradual building up of soil organic carbon (SOC) (Nakhli et al., 2017). This durability allows zeolites to support the gradual accumulation and stabilization of soil organic carbon (SOC), a critical element of nutrients cycling in the CE. Research shows the capacity of zeolites to retain organic carbon in soils (Doni et al., 2021). Pal et al. (2015) demonstrated that Ca-zeolite, when employed as a soil conditioner, enhances water retention, creating favourable conditions for SOC sequestration in the face of global climate challenges. Complementary findings Doni et al. (2021) show that zeolite application fosters soil microbial activity, enzyme synthesis, and organic matter transformation – processes central to regenerative soil health. By improving soil carbon storage while mitigating greenhouse gas emissions (Chatterjee et al., 2021), zeolites exemplify a circular solution as they close resource loops, regenerate soil ecosystems, and contribute directly to climate resilience. As SOC underpins the carbon cycle, its restoration through zeolite uses lines-up with the CE concepts and advances progress toward UN SDG 13 (climate action).

Pollutant decontamination

Clean drinking water is a worldwide challenge. Industrial growth and unsustainable farming generate wastewater containing heavy metals, organics, pesticides, and nitrogen compounds. Contamination harms ecosystems and human health (de Magalhães et al., 2022). For instance, excess nitrogen runoff leads to eutrophication,

causing harmful algal blooms and suffocates marine life in dead zones, threatening water supplies. This hinders progress toward SDG 14 (Life Below Water) and SDG 6 (Clean Water and Sanitation). Adsorption is an efficient, low-cost water treatment method with minimal energy use (Gouran-Orimi et al., 2018). Among the various adsorbents, activated carbon (AC) is highly effective because of its high surface area; however, it is expensive, exhibits low selectivity, and limited regenerate (Tran et al., 2021). Alternatives like clay minerals, biomaterials, biochar, and zeolites are also used for contaminant removal. While AC and biochar originate from organic matter calcination, their properties vary by precursor (de Magalhães et al., 2022). Additionally, these adsorbents often need modification – such as thermal, acidic, or surfactant treatments – to enhance adsorption but increase costs and environmental impact.

Zeolites, known for their multifunctionality, have been widely applied as efficient adsorbents for removing various contaminants (de Magalhães et al., 2022; Hermassi et al., 2020) as seen in Table 3. Naturally occurring zeolites have been widely investigated, with Eberle et al. (2022) demonstrating their high selectivity and capacity for NH_4^+ adsorption due to the electrostatic interactions between their negatively charged surfaces and the cationic NH_4^+ . Nevertheless, several studies have demonstrated that manufactured zeolites generally surpass natural counterparts in terms of performance. For example, under the same conditions, You et al. (2017) found that NH_4^+ removal using Na-zeolite synthesised from coal fly ash reached 109 mg/g, which is ten times greater than the 10.72 mg/g achieved by natural zeolite. Canellas et al. (2019) compared natural zeolites (clinoptilolite, mordenite, chabazite) to a synthetic zeolite (MesoLite) for NH_4^+ removal from both synthetic and real wastewaters. They found that the synthetic zeolite achieved a capacity of 4.6 meq g^{-1} , while natural zeolites ranged between 1.1 to 2.1 meq g^{-1} under the same pre-treatment with Na ions. Comparable results have been observed in radionuclide remediation, where synthetic zeolites outperformed natural forms in the removal of Cs and Sr (Król, 2020).

Manufactured zeolites remove heavy metal ions like Zn^{2+} , Pb^{2+} , Cr^{3+} , Ni^{2+} , Cd^{2+} , and Cu^{2+} more efficiently than natural zeolites (Kozera-Sucharda et al., 2020). Na-X zeolite exhibits exceptionally high adsorption capacities, ranging from 75–212 mg g^{-1} for individual heavy metals and reaching

Table 3. Adsorption performance of manufactured zeolite compared to natural zeolites

Type	Adsorbate	q_{\max} (mg/g)*	References
Nutrients			
Natural zeolite	NH ₄	0.02–20.29	(Eberle et al., 2022)
Natural zeolite	NH ₄	6.3012	(Widiastuti et al., 2011)
Na-zeolite from coal fly ash	NH ₄	109	(You et al., 2017)
Zeolite-geopolymer composite	PO ₄	206	(Salam et al., 2021)
	NH ₄	140	
NaA zeolite from fly ash	NH ₄	37.81	(Wang et al., 2023)
Heavy metals			
Natural zeolite	Cr	0.0267–0.0223	(Álvarez et al., 2021)
Modified zeolite with 2 M HCl and HCl NH ₄ Cl solution	Pb	27.7	(Sprynskyy et al., 2006)
	Cu	25.76	
	Ni	13.03	
	Cd	4.22	
ZCET40 zeolite	Pb	88.31	(Visa, 2016)
	Cu	20.921	
	Cd	26.881	
	Ni	5.911	
	Zn	7.898	
Natural zeolite	Ni	153.846	(Al-Abbad and Al Dwairi, 2021)
Fly ash zeolite (FA24)	Hg	23.1–30.8	(Kobayashi et al., 2020)
	Pb	31.7–40.5	
Radioactive substances			
Natural zeolite	Cs	39.0	(Hong and Um, 2021)
NaPI zeolite		35.3	
Natural zeolite		4.9	
NaPI zeolite	Sr	27.9	
Dyes			
Natural zeolite	Basic Blue 41	192.31	(Humelnicu et al., 2017)
Zeolite X	Methylene blue	1.93	(Mulushewa et al., 2021)
Pesticides and herbicides			
Natural zeolite	Clomazone	0.5	(Shikuku et al., 2015)
Chitosan/zeolite A	Acephate Omthosate Methyl parathion	650	(Mostafa et al., 2021)
		506	
		560	
Zeolite Y	2,4-dichlorophenoxyacetic acid	82.64–92.59	Pukcothanung et al. (2018)
Composite of chitosan and zeolite A	Methyl parathion Omthosate Acephate	560.8	(Mostafa et al., 2021)
		506.5	
		650.7	

Note: * Maximum adsorption capacity.

322–333 mg g⁻¹ in mixed-metal systems. These values are significantly higher than those typically observed for natural zeolites under comparable experimental conditions (Medykowska et al., 2024). Na-PI and FAU-type zeolites achieve 98% Pb²⁺ removal, compared to 24% for natural zeolites (Lee et al., 2000). Fly ash zeolite (FA-Z) removes Ni²⁺ and Cu²⁺ with 60–99% efficiency (Sireesha et al., 2022). Hong and Um (2021) found NaP zeolite removed Sr (27.9 mg/g) far better than natural zeolite (4.9 mg/g), though Cs removal was slightly lower (35.3 mg/g vs. 39.0 mg/g). These findings highlight NaP zeolite's

effectiveness in radionuclide removal from waste solutions. Manufactured zeolites outperform natural ones in adsorption due to lower density, higher crystalline ordering, and greater surface area (de Magalhães et al., 2022). Their larger pores enable adsorption of bigger molecules, including oil, with twice the removal capacity of natural zeolites like clinoptilolite (Bandura et al., 2015), making them effective for petroleum spill cleanup. They are also highly effective in pesticide removal (Andrunik and Bajda, 2021), thanks to their high surface area, structured pores (Bajuk-Bogdanović et al., 2017; Janićijević et al., 2020),

and surface-active functional groups (Mousavi et al., 2023). Bajuk-Bogdanović et al. (2017) found BEA zeolite adsorbed nicosulfuron 400 times better than activated carbon. Pukcothanung et al. (2018) reported strong herbicide adsorption onto zeolite Y, attributed to its large surface area and 7.4 Å channels.

Manufactured zeolites when synthesized from industrial residues such as fly ash, blast furnace slag, or other aluminosilicate-rich by-products, these zeolites embody the principles of the CE. By transforming industrial waste into high-value adsorbent materials, they reduce dependency on virgin raw materials, mitigate waste disposal challenges, and close resource loops. Such waste-to-resource pathways not only advance sustainable waste management but also contribute directly to multiple UN SDGs such as 6 (clean water and sanitation), 9 (industry, innovation, and infrastructure), 11 (sustainable cities and communities), 12 (responsible consumption and production) as well as 13 (climate action). The integration of CE strategies with zeolite synthesis and application underscores their potential as transformative materials in sustainable environmental management and pollution mitigation.

Climate change abatement

Climate change poses significant challenges that underscore the importance of carbon capture and methane removal for achieving carbon neutrality and mitigating climate-related impacts. Key challenges include increasing global temperatures, more frequent severe weather events, increased CO₂ absorption by oceans leading to ocean acidification, loss of biodiversity, disruption of ecosystems, and adverse effects on agricultural productivity (Reddy and Reddy, 2015). Thus, tackling these challenges through carbon capture and methane removal, using high surface minerals (Pratt et al., 2024) such as zeolites, is an important link to protect our ecosystems and ensure a stable climate for future generations.

As the 2030 carbon neutrality target approaches, climate mitigation measures aligned with the Paris Agreement have become increasingly urgent (Lin et al., 2022). Within this context, adsorption-based technologies for CH₄, NO_x, and CO₂ removal have gained prominence, particularly through the development of manufactured zeolites synthesized from industrial

wastes and by-products (Cheng et al., 2020; Lin et al., 2022). Such approaches integrate CE principles by converting low-value residues into high-performance materials, thereby reducing environmental burdens. Empirical evidence demonstrates the strong potential of manufactured zeolites: Garshasbi et al. (2017) synthesized zeolite 13X using clay minerals with a CO₂ adsorption capacity of 286.06 mg/g, surpassing activated carbon (161.95 mg/g) (He et al., 2021) and metal-organic frameworks such as M808 (12.76–60.73 mg/g) (Park et al., 2020). Similarly, zeolite 13X derived from fly ash exhibited high adsorption capacity (223 mg/g), attributed to its microporous volume (0.35 cm³/g) and high surface area (643 m²/g) (Zhang et al., 2017). These zeolites also maintained stable adsorption–desorption cycles underscoring their suitability for regeneration and reuse – an essential feature within circular economy frameworks (Soe et al., 2016).

Beyond CO₂, both natural and manufactured zeolites exhibit adsorption capabilities for gases such as H₂S, SO₂, Ar, CO, H₂, O₂, He, Kr, and N₂ (Cataldo et al., 2021). However, synthetic zeolites generally achieve higher efficiencies in removing SO_x, NO_x, CO_x, and H₂S (Khaleque et al., 2020). Aydani et al. (2021) demonstrated that SSZ-13 zeolite effectively adsorbed CO₂ from mixtures containing CH₄, N₂, and H₂, reinforcing the versatility of zeolites in mitigating diverse emissions. Their role in CH₄ removal is particularly critical, as methane is a potent greenhouse gas. Arefi Pour et al. (2016) reported that NaA zeolite adsorbed 5.2 mmol CO₂ and 2.6 mmol CH₄ per g, while (Jackson et al., 2019) suggested such technologies could reduce atmospheric CH₄ concentrations from 1860 ppb to ~750 ppb.

Incorporating zeolite synthesis into CE systems strengthens climate strategies by transforming industrial by-products into functional materials for carbon and methane mitigation. Such innovations not only support carbon neutrality targets for 2030 and 2050 (El Bojaddayni et al., 2023) but also advance several UN SDGs, in particular SDG 7 (affordable and clean energy), SDG 12 (responsible consumption and production) as well as SDG 13 (climate action). By linking waste valorisation with climate action, zeolite-based carbon capture technologies exemplify how CE pathways can deliver environmental, economic, and societal benefits simultaneously.

Aquaculture application

Aquaculture, which has a critical role in meeting the demand for food, represents one of the world's most highest-growth food production sector (Ghasemi et al., 2018), with an annual growth rate of nearly 4.6% over the past decade (FAO, 2022). While it helps alleviate poverty, hunger, and malnutrition, concerns arise about its environmental impacts, especially wastewater discharge (FAO, 2022). Ammonia nitrogen ($\text{NH}_3\text{-N}$), primarily excreted by fish through their gills due to protein deamination, is a significant nitrogenous waste from aquaculture (Cataldo et al., 2021). Ghasemi et al. (2018) noted that at lethal levels of NH_3 (<0.02 ppm), fish experience reduced growth, poor feed conversion, and lower disease resistance. Concentrations above 0.02 ppm can be toxic, leading to fish mortality. To mitigate these impacts, sustainable water treatment methods, including adsorption, are increasingly investigated.

In aquaculture systems, various adsorbents, such as zeolites, are used for the NH_3 removal from contaminated water. Since zeolitic minerals selective adsorbents for NH_4^+ compared to a wide range of other cations (Ghasemi et al., 2018; Paul and Hall, 2021). While natural zeolites are commonly used due to their availability, some types, such as fibrous erionite, pose health hazards, having been linked to peritoneal mesothelioma (Ghasemi et al., 2018). Manufactured zeolites, although more costly, present safer alternatives with tailored physicochemical properties for targeted pollutant removal (Koohsaryan et al., 2020). Beyond water treatment, zeolites can be integrated into aquaculture feed to enhance nutrient utilization, reduce ammonia toxicity, improve immune response, and promote overall fish health and productivity (Abbas et al., 2021; Eya et al., 2008).

Manufactured zeolite's ion-exchange capacity, governed by charge density and cation size within the aluminosilicate framework, underpins their effectiveness in selectively removing diverse cations (Ghasemi et al., 2018). Zeolites application in aquaculture can align with the CE framework as waste-derived zeolites valorise industrial by-products while enhancing sustainability in food systems. This approach advances multiple UN SDGs, including SDG 14 (life below water), by reducing aquatic pollution as well as SDG 3 (good health and well-being)

via improving animal welfare and food safety. Nevertheless, the circularity of zeolite use in aquaculture requires attention to end-of-life management. Spent zeolites, if improperly disposed of, may release accumulated pollutants, with risks of persistence, bioaccumulation, and ecological harm (Bansal and Tiwari, 2022). Thus, efficient regeneration, recycling, or pollutant recovery strategies are critical to closing resource loops and preventing secondary contamination. Addressing these challenges through innovative waste recovery and zeolite regeneration systems will be essential to fully embed aquaculture practices within a circular economy paradigm.

Detergent industry application

Traditional detergents containing phosphates such as tetra sodium pyrophosphate ($\text{Na}_4\text{P}_2\text{O}_7$) as well as sodium tripolyphosphate ($\text{Na}_5\text{P}_3\text{O}_{10}$) are the most widely used detergent builders. However, their excessive accumulation in water bodies has raised significant environmental concerns due to their contribution to eutrophication and algal blooms, rendering them potentially harmful to aquatic ecosystems (Akinawo, 2023). In a CE framework, detergent formulations must achieve high cleaning performance while ensuring environmental safety and human health throughout their production, use, and end-of-life stages (Koohsaryan et al., 2020). Consequently, phosphate-free alternatives such as zeolite-based builders are being increasingly developed to close material loops and reduce ecological burdens.

Zeolite detergents, including types A, P, and 13X, exhibit strong ion-exchange properties that enable efficient water softening while lowering nutrient loading in aquatic systems (Koohsaryan et al., 2020; Koohsaryan et al., 2021; Yusriadi et al., 2020). Importantly, sustainable synthesis routes – such as producing zeolite A from rice husk ash – demonstrate the potential for upcycling agricultural waste into high-value detergent additives, aligning with circular principles of waste valorisation Yusriadi et al. (2020). Toxicological assessments further suggest that manufactured zeolites, unlike fibrous natural counterparts such as erionite, present minimal risks to humans and ecosystems, though precautionary measures are recommended for handling powdered forms (Samantha et al., 2022). Their stability under normal conditions and capacity to support compact detergent formulations make zeolites a promising

substitute for phosphate-based builders. As demand for detergents continues to rise globally (Insights, 2023), the transition to zeolite-based formulations supports responsible production and consumption patterns, contributing to achieve both SDG 9 (industry, innovation, and infrastructure) alongside with SDG 12 (responsible consumption and production).

Catalytic industry

The application of zeolites as catalysts constitutes a major industrial pathway that supports the circular economy by enabling resource efficiency, waste valorisation, and emission reduction. About 99% of the world's petroleum refining relies on zeolite-based catalysts (Mgbemere et al., 2017), highlighting their central role in energy and materials production. In the transportation sector, zeolite catalysts help mitigate the environmental impacts of fossil fuel combustion, which remains a critical challenge given rising vehicle numbers and associated emissions of particulate matter, nitrogen oxides (NO_x), hydrocarbons, and carbon monoxide (CO) (Wang and Olsson, 2019). By extending catalyst lifespans, enhancing regeneration, and lowering energy demand, zeolites provide circular solutions that reduce environmental footprints while maintaining industrial productivity. Therefore, a substantial reduction in fuel combustion emissions from the transportation sector is essential to address the UN SDG 6 (Clean Air, Water, and Land).

Nowadays, there is an increasing emphasis on reducing fossil fuel consumption by substituting with hybridization, electrification, fuel cells, and alternative fuels to meet lower emissions standards (Wang & Olsson, 2019). For instance, throughout the coming decades, there will probably be a major growth in the manufacture of hybrid vehicles. However, the high hybridization level necessitates intermittent use of the engine, which can result in cold-start issues (Rahman et al., 2022). Lee et al. (2019) reported that during the cold-start phase (1–3 min), emissions can reach as high as 80% until the after-treatment catalysts attain their light-off temperatures. Additionally, exhaust temperature is likely to be considerably cooler, which will enhance opportunities for waste heat recovery and further optimise energy use (Wang and Olsson, 2019). Consequently, catalysts development capable of

capturing emissions at low temperature is among the most important obstacles facing automotive exhaust catalyst converters in the coming years.

Practical CH_4 mitigation using materials such as zeolites for catalytic oxidation is feasible, even in the absence of noble metals (Pratt and Tate, 2018). Palladium (Pd) and platinum (Pt) supported on alumina are commonly used catalysts for CH_4 oxidation (Chetyrin et al., 2020); however, water and sulphur are very effective at deactivating these catalysts. Recent advancements have shown that zeolites incorporated with Pd, where acidic sites are blocked by sodium ions (Petrov et al., 2018) and highly siliceous zeolites (Friberg et al., 2019) exhibit stable catalytic activity due to their hydrophobic properties in the presence of water vapor (Wang and Olsson, 2019). Additionally, the regeneration of Pd-supported siliceous zeolites from sulphur contamination is relatively straightforward (Friberg et al., 2019). Effective oxidation of CH_4 was observed using Cu-rich manufactured zeolite at a temperature below 125 °C that is exceptionally low for CH_4 oxidation (Narsimhan et al., 2016). Thus, zeolite can be engineered into robust, stable, and low-temperature oxidation catalysts of CH_4 (Mortensen et al., 2022).

An effective strategy for managing NO_x emissions during the phase of cold-start is the use of passive adsorbents that can capture NO_x emissions at ambient temperatures and subsequently release them under suitable conditions (Wang and Olsson, 2019). Pd-supported zeolites have demonstrated strong potential as adsorbents for NO_x removal (Chen et al., 2016). High-framework silica zeolite A (Cu/LTA) was effectively synthesised (Ryu et al., 2017). The authors found that Cu/LTA zeolite proved to be a strong selective catalyst for catalytic reduction, maintaining significant NO_x reduction activity even after undergoing extreme hydrothermal ageing at 900 °C. A growing body of research demonstrates the potential for circular resource flows through zeolite catalyst design. For instance, Pavlović et al. (2020) produced CaO-zeolite catalysts using waste streams such as fly ash and chicken eggshells for biodiesel synthesis, achieving 97.8% methyl ester content in just 30 minutes at 60 °C with a 6% catalyst concentration and a 6:1 methanol-to-oil ratio. Similarly, Argaw Shiferaw et al. (2023) used sodium methoxide-doped zeolite Y to effectively transesterify waste cooking oils into biodiesel. Likewise, Miandad et al. (2017) explored zeolite-assisted catalytic

cracking of plastic waste into high-value liquid oils, creating energy recovery pathways for otherwise persistent wastes. Such examples highlight how zeolites can transform waste materials into secondary resources, advancing closed-loop energy systems.

Zeolites also demonstrate environmental applications beyond energy systems. For example, iron zeolite-4A (O₃/Fe-Z4A) has been successfully applied in catalytic ozonation for heavy metals and pathogens removal from milk, achieving near-complete purification within minutes (Ikhlaq et al., 2023). These multifunctional applications underscore the versatility of zeolites in creating circular systems across food, energy, and environmental sectors. Compared to conventional catalysts, zeolites deliver higher stability, lower energy requirements, and enhanced recyclability, reducing dependency on critical raw materials such as vanadium or cerium (Sun et al., 2021; Sunil Kumar et al., 2023). Their integration into industrial processes supports multiple UN SDGs, including SDG 7 (affordable and clean energy), SDG 9 (industry, innovation, and infrastructure), SDG 11 (sustainable cities and communities), and SDG 13 (climate action), while also addressing SDG 14 (life below water) and SDG 15 (life on land) through pollution reduction. By fostering waste-to-resource pathways, extending catalyst lifetimes, and reducing emissions, zeolite catalysts represent a cornerstone for embedding circular economy principles into industrial and environmental systems.

Medical applications

Currently, Zeolites show considerable promise for a variety of medical uses. Zeolites are widely used in wound healing, drug delivery systems, tissue engineering scaffolds, implants coating, antibacterial agents, dental application, and detection of cancer cells (Bacakova et al., 2018; Derakhshankhah et al., 2020). With medical devices like umbilical tubes, there is a noticeable decrease in the frequency of bloodstream infections connected to catheter use when silver-zeolite LTA is used (Bertini et al., 2013). Zeolite A was utilised as an antimicrobial dressing for wound-healing (Neidrauer et al., 2014). Guo et al. (2014) used MFI zeolite (ZSM-5) for drug delivery such as *Gentamycin* as well as bone implants. Certain manufactured zeolites are cytotoxic and can be employed in the treatment of tumours (Bacakova et al., 2018). Hao et al.

(2021) reported positive outcomes in the zeolite's application as well as zeolitic imidazolate frameworks as a nano-platforms for drug delivery, enhancing the effectiveness and specificity of conventional anti-cancer medicines. Zeolites and ZIFs have intrinsic pH-sensitive characteristics and are porous, which allows them to selectively release anticancer medications into the acidic tumour microenvironment. Nanoparticles zeolites were shown to be the most efficient antibacterial agent delivery platform because of their long-lasting effects in the oral environment, even after extended contact with saliva (Derakhshankhah et al., 2020). Additionally, adding zeolite to the cement dental composite ingredients improved the material's resistance to both the alkali-aggregate expansion brought on by thermal treatment and the acidic environments bred by inflamed dental tissues (Derakhshankhah et al., 2020). With respect to nanozeolite toxicity, Thomassen et al. (2012) evaluated the in vitro cytotoxicity of synthetic nanozeolites A and Y of particle sizes ranging from 25 to 100 nm. Their findings showed that after 24 hours of exposure, no significant cytotoxic effects were observed at concentrations up to 500 µg/ml. These results support the safe application of nanozeolites in fields such as medical imaging and molecular separation processes.

From a CE perspective, zeolite-based medical technologies offer sustainability advantages by reducing dependence on resource-intensive pharmaceuticals, minimizing medical waste, and promoting the reuse of materials where feasible. Manufactured zeolites, due to their multifunctionality, can provide cost-effective alternatives to conventional treatments, lowering both economic and environmental burdens associated with healthcare delivery. Even though manufactured zeolites have exhibited notable potential across a variety of medical uses, research in this space is still developmental and the full potential of zeolites in the medical field is not yet established. While research is still evolving, integrating zeolites into medical applications exemplifies how advanced materials can support both healthcare innovation and sustainable resource management within a circular economy framework.

Animal feed additives

Zeolites are increasingly incorporated into animal feed to enhance livestock health, growth, and

environmental performance. Their use has been observed across different animals such as broiler chickens, goats, pigs, and lambs, improving overall productivity while reducing odour emissions, including broiler chickens (Pavlak et al., 2022), goats (El-Nile et al., 2023), and pigs (Šperanda et al., 2021). Clinoptilolite, a natural zeolite, is widely utilized as a feed supplement for swine, cattle, rabbits, poultry, turkeys, dairy cows, and sheep (Papaioannou et al., 2005). The Food and Drug Administration of the United States (FDA) approves its use as an antibacterial agent, aiding in toxic metal excretion without disrupting essential electrolytes (Papaioannou et al., 2005). However, natural zeolites cannot trap mycotoxins like aflatoxins despite their similar molecular size range from 5.18 Å to 6.50 Å (Colella, 2007).

Manufactured zeolites, with enhanced adsorption and molecular sieve properties, can selectively capture nitrosamines, heavy metals, dichlorobenzene, and mycotoxins, mitigating health risks in livestock and preventing contamination of animal-derived products like milk (Ghasemi et al., 2018; Sungsinchai et al., 2023). For instance, Sungsinchai et al. (2023) synthesized zeolite from sugarcane bagasse fly ash, demonstrating effective removal of aflatoxin B-1 via its negatively charged surface, optimized pore structure, and acid site intensity. Figure 4 shows a few possible ways that zeolite minerals could improve livestock husbandry performance through their diet.

The inclusion of synthetic zeolites as animal feed additives not only improves nutrient absorption and animal health but also reduces nutrient excretion, thereby lowering the environmental burden associated with livestock waste. By enhancing feed efficiency, zeolites indirectly contribute to reducing greenhouse gas emissions from livestock production, aligning with global environmental sustainability goals. From a circular economy perspective, incorporating waste-derived manufactured zeolites into animal diets exemplifies resource valorisation by transforming agricultural and industrial by-products into high-value feed additives. This approach supports sustainable livestock production by improving animal health, enhancing growth, and reducing odour and environmental pollution. Such applications align with UN SDG 6 (clean water and sanitation) and SDG 15 (life on land), promoting sustainable agriculture while closing material loops in food production systems.

MANUFACTURED ZEOLITE TO PROMOTE A CIRCULAR ECONOMY MODEL

A transition from the linear model of “take-make-dispose” to a circular economy (CE) is essential for resource conservation and sustainability. The CE promotes minimizing waste, reusing resources, and waste recycling to develop sustainable products and resilient business models (Kurniawan et al., 2023). At present, inadequate waste

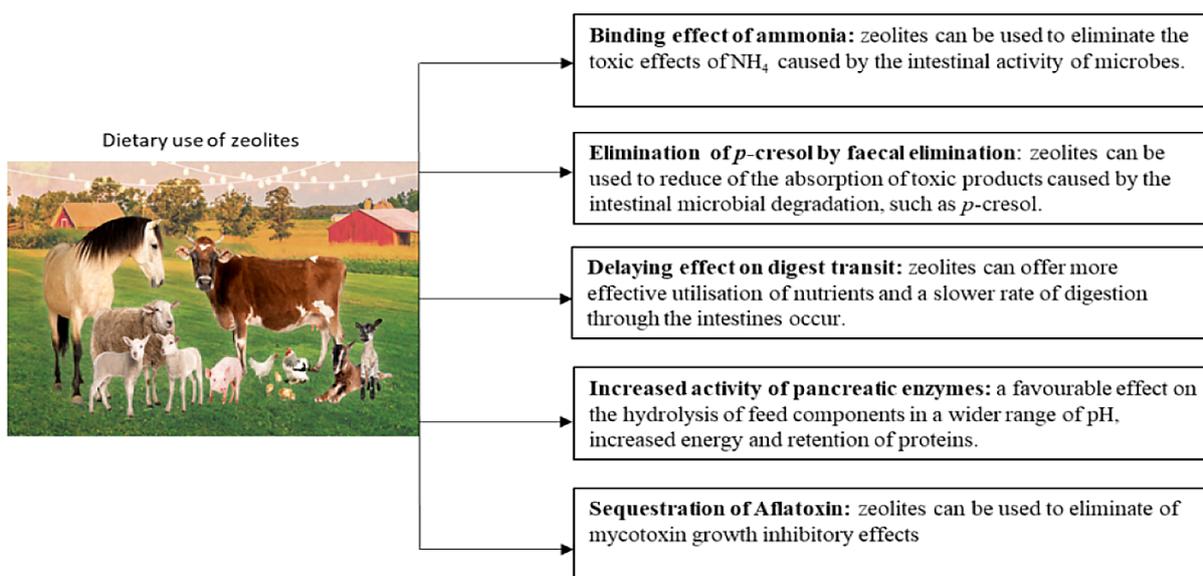


Figure 4. A few possible ways that zeolite minerals could improve animal husbandry performance through their diet (Adapted from Papaioannou et al., 2005)

management practices – particularly open dumping, which accounts for about 33% of global waste disposal – continue to pollute air, water, and soil (Nimita Jebaranjitham et al., 2022). Despite growing awareness, only 13.5% of global waste is recycled, while incineration and composting account for 11.1% and 5.5%, respectively (Sharma et al., 2021). This underscores the strong necessity to strengthen 3Rs strategies – reduce, reuse, and recycle – within global production and consumption systems.

Manufactured zeolites are instrumental in advancing the CE concept by transforming industrial by-products and waste streams into value-added products through closed-loop recycling systems (Singh et al., 2022). This process reduces reliance on primary resources, prolongs the life-cycle of materials, and generates new economic opportunities, all while mitigating environmental impacts (Morseletto, 2020). Zeolite derived from secondary raw materials has wide applications in agriculture, pollution control, industry, medicine, and animal feed – each contributing to sustainable growth. For instance, zeolite-based fertilizers provide an environmentally friendly alternative to synthetic chemicals, supporting regenerative farming practices (Fan et al., 2023). Similarly, zeolite synthesized from coal fly ash has been proven effective in capturing mercury from gas streams Kunecki et al. (2023), showcasing how hazardous waste can be repurposed into functional materials that align with the CE framework and support the achievements of the UN sustainable development goals (SDGs) achievements.

Looking ahead to 2050 and the UN SDG targets, the shift from a depletive linear system toward a restorative CE model – based on reuse, recycle, redesign, and remake – is strongly recommended (Figure 5). By integrating manufactured zeolite

into waste management approaches, industries can lower greenhouse gas emissions, minimize environmental pollution, and optimize production costs and labour (Yang et al., 2023). Furthermore, large volumes of silica- and alumina-rich wastes – including kaolin, lithium slag, paper sludge, rice husk, fly ash, cupola slag, metallic residues, porcelain scraps, and windshield waste – can serve as precursors for zeolite synthesis. Instead of accumulating in landfills or waterways, where they pose ecological risks (Mallapur and Oubagaradin, 2017), these wastes can be valorised into high-value materials, thereby revolutionizing the manufacturing sector and reinforcing the principles of the circular economy.

Manufactured zeolites contribute to the circular economy at multiple scales (Figure 6). Globally, they support climate action by enhancing carbon capture and storage, aligning with the goals of the Paris Agreement. Nationally, they stimulate innovation, economic development, and green job creation, reinforcing sustainable industrial transitions. Locally, zeolites improve air and water quality, directly benefiting public health and ecosystems while reducing waste-related pollution. However, despite entering a new era of CE adoption, several technical, technological, and socioeconomic obstacles hinder large-scale implementation (Singh et al., 2022). These include high start-up costs, limited stakeholder coordination, shortage in the technical and labour skills, and insufficient knowledge related to waste sorting, processing, recycling, and reuse. Furthermore, the rapidity of technology advancements and new business models development as well as people’s eagerness to adopt sustainable lifestyles will ultimately determine how effectively manufactured zeolites can drive circularity across different sectors (Kurniawan et al., 2023).

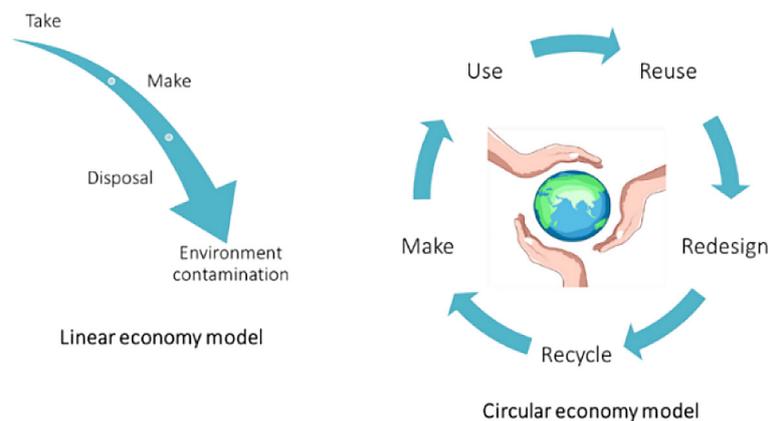


Figure 5. Differences between a linear economy and a CE model

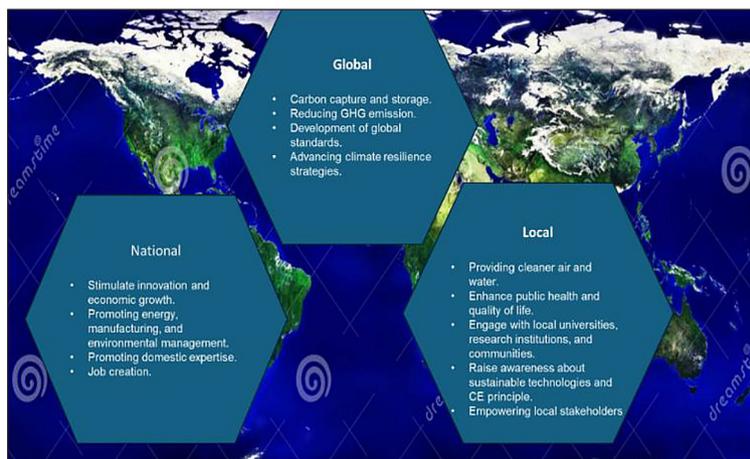


Figure 6. The impacts of using manufactured zeolites across global, national, and local scales

ECONOMIC OUTLOOK OF MANUFACTURED ZEOLITES IN A CIRCULAR ECONOMY

In 2021, the global zeolite market was reached of \$4.12 billion and is expected to rise to \$5.71 billion USD by 2029 (Insights, 2023). This growth is strongly linked to their highly cation exchange capacity as well as water retention properties, which make zeolites valuable for soil amendments and fertilizers – positioning agriculture as a key sector between 2023 and 2028 (Intelligence, 2023). However, studies predict that rising costs will slow the natural zeolite market by 2030, while demand for manufactured zeolites will accelerate, particularly in industrial applications (Szerecent et al., 2021). The production economics of zeolites are evolving. For example, Chi et al. (2021) estimated that synthesizing 1 kg of zeolite from furnace slag and fly ash costs \$27.85 – cheaper than premium-grade zeolite X (\$243.42 per 10 g), though higher than some commercial grades (\$25–\$80 per 10 g). Similarly, Cavallo et al. (2023) showed that natural clinoptilolite costs around \$300 per ton for CO₂ capture, significantly less than manufactured Ca-LTA at \$1,300 per ton. Despite these differences, economic comparisons between natural and manufactured zeolites remain limited and require further research (Szerecent et al., 2021).

The CE lens reveals that costs are not just monetary but also tied to resource efficiency and waste valorisation. Manufacturing costs depend on the availability of raw materials, energy inputs, recycling potential, labour, and

marketing. For instance, Sapawe et al. (2013) demonstrated that NaA zeolite prepared using microwave-assisted synthesis requires just 100 W at \$0.003 for 5 g, compared to 2000 W at \$1.16 for conventional methods – cutting time by 16-fold and energy use by 20-fold. Similarly, Mukherjee et al. (2018) reported that producing 100 g of NaA zeolite from rice husk costs \$26.09, compared to \$97.03 for the same amount purchased commercially. These examples illustrate how upcycling agricultural and industrial waste into zeolites can deliver both environmental and economic benefits, even though many studies remain at lab-scale.

With growing demand, especially in construction, where zeolites are used for lightweight concrete (El Bojaddayni et al., 2023), the zeolite market is set to expand. Beyond direct market growth, manufactured zeolites advance the CE model by recovering resources, reducing landfill disposal, and lowering greenhouse gas emissions. Companies that integrate zeolites into their processes not only enhance industrial efficiency but also gain a competitive advantage through sustainability, improving brand reputation and attracting eco-conscious consumers and investors. Looking ahead, the expanding portfolio of zeolitic frameworks highlights their versatility across sectors such as construction, agriculture, medicine, and energy. By coupling waste-derived feedstocks with advanced synthesis techniques, zeolites serve as both a technological enabler and a material platform for CE strategies – closing resource loops, reducing dependency on virgin materials, and driving sustainable industrial growth.

POTENTIAL LIMITATION AND FUTURE NEEDS

Manufactured zeolites improve soil properties, crop yields, and aid climate mitigation, but challenges remain with key research areas include:

1. Cost-effective synthesis – optimizing zeolite production, regenerating spent zeolites, and offering subsidies to reduce costs and being financially viable. Industrial-scale cost reduction remains underexplored.
2. Long-term soil impact – field studies are needed to assess prolonged effects on soil and crops.
3. Sodium ion exchange – high Na content in synthesized zeolites may harm plant growth. Research should explore replacing Na with ions such as K, Mg or Ca (Szerement et al., 2021).
4. Cost-benefit analysis – the economic viability of zeolite use in greenhouse gas mitigation needs further investigation.
5. Life cycle analysis (LCA) – assessing energy use, production impact, and sustainability is essential.
6. Circular economy (CE) promotion – many countries lack policies to integrate zeolites into the CE. Thus, stakeholder collaboration is crucial.
7. Waste management – new laws and funding mechanisms are needed to support zeolite production from waste and educate the public.
8. Commercialization challenges – Scaling up production from lab to industry faces hurdles in reagent selection, scalability, and meeting high demand (Willis and Benin, 2007; Zones, 2011).
9. Stability issues – some zeolites degrade in acidic or high-temperature conditions. Research should focus on coatings, modifications, and operational parameter control to improve durability.
10. Sustainable aquaculture – Zeolites enhance water quality and fish health, but proper disposal is needed to prevent environmental harm. Further research can support sustainable practices.
11. Developing standards and certification schemes is crucial to guarantee the quality, safety, and sustainability of regenerated zeolites, especially for sensitive applications in medicine and agriculture.
12. Introducing regulatory incentives – such as tax credits – for industries that recover and reuse zeolites.
13. Supporting public-private partnerships to foster industrial symbiosis, where spent

zeolites from one sector (e.g., wastewater treatment) are safely repurposed in another (e.g., construction), thereby promoting a shift from single-use materials toward a sustainable, circular model.

14. A comprehensive and direct toxicological assessment for nanosized forms of zeolites before large-scale applications can be recommended.

CONCLUSIONS

Converting waste materials into manufactured zeolites promotes environmental sustainability and supports the development of a CE. Their unique properties make zeolites valuable for various scientific and engineering applications. This review highlights the potential of manufactured zeolites to advance several UN SDGs, including:

- SDG 6: Clean water and sanitation, through effective pollutants removal.
- SDG 9: Industry, innovation, and infrastructure, by enhancing catalysis and waste valorisation.
- SDG 11: Sustainable cities and communities, by reducing landfill needs.
- SDG 12: Responsible consumption and production, via waste valorisation.
- SDG 13: Climate action, for its potential for removing GHG emissions through land application.
- SDG 14: Life below water, through applications in fish feed and ammonia removal.
- SDG 15: Life on land, supporting biodiversity.

However, ongoing research is needed to explore the mechanisms and long-term risks associated with manufactured zeolites. Most studies are currently limited to laboratory scales, creating uncertainty about their large-scale environmental impacts. Additionally, challenges such as high production costs, difficulties in scaling up, and performance limitations persist. Nevertheless, increased interest will lead to technological innovations, resulting in more cost-effective processes. Furthermore, large scale adoption may contribute positively to lowering the cost due to economies of scale. Addressing these challenges is crucial to maximize the benefits of zeolite technologies within the SDG framework and contribute to local and global sustainability goals. Overall, manufactured zeolites represent a promising area of green chemistry with significant potential to advance the UN SDGs.

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