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Advanced Hierarchical CFA-Zeolite for sustainable oily wastewater treatment: Fabrication Strategies, Adsorption dynamics and future Horizons.

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Abstract

Deficiency of fresh water is now listed among the most critical problems that become worse by rising population as well as globalization and industrialization trends. This review article provides an extensive evaluation of preparation, applications, and other processes, apart from a discussion on the strengths and weaknesses of each method and the costs and economic factors involved in the synthesis and application of zeolite-based composites for wastewater treatment. The integration of zeolites in treating wastewater in the concept of adsorption is well explored. This review offers a detailed discussion on regeneration of the fly ash-based zeolite composites for the effective treatment of pollutants and other practices associated with wastewater treatment. Both the economic and environmental studies provide effectiveness of applying fly ash-based zeolite in the wastewater treatment. And addition of some insights of the current knowledge on fly ash-based zeolite nanocomposites, towards efficient and environment friendly approach towards wastewater treatment.

Keywords: Fly ash based - Zeolites; Innovative synthesis; Molecular adsorption; Oily Wastewater; Adsorption materials; Circular economy

1. Introduction

Water pollution, intensified by industrialization and urbanization, has appeared as a serious environmental challenge in recent eras [1]. Customary wastewater treatment methods, including coagulation, membrane filtration, and chemical precipitation, frequently drop due to inadequacies, high operational costs, and secondary waste generation [2]. Primarily valued for their ion-exchange and molecular sieving properties, zeolites have developed into multipurpose materials with applications in catalysis, gas separation, and ecological remediation [3]. The 21st century has observed significant developments in the development of hierarchical zeolites, which incorporate multi-scale porosity to address the limitations of conventional zeolites [4]. This review aims to offer a comprehensive overview of the innovations in hierarchically structured zeolites derived from fly ash, concentrating on their applications in oily wastewater treatment [5]. The advanced methods for synthesizing hierarchical zeolites from fly ash, underlining innovations that develop porosity, functionality, and scalability by evaluating the physical and chemical processes that facilitate these materials to effectively adsorb and separate oil pollutants from wastewater [6]. The advanced techniques, including digital design tools, biomimetic functionalization, and policy assimilation, to unlock the full potential of these materials [7]. Developing trends point toward the integration of zeolites with nanotechnology, biotechnology, and renewable energy structures to produce hybrid materials with enriched functionalities[8].The reutilization of industrial by-products such as fly ash supports with global sustainability goals, reducing waste and conserving natural resources [9]. The

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development of fly ash-derived hierarchical zeolites signifies a confluence of environmental remediation and resource efficiency [10].

1.1. Fly ash and its importance

Fly ash is a suitable, powdery by-product produced through the combustion of coal in thermal power plants [11]. It mainly comprises of silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and bit amounts of other oxides and unburnt carbon as it is mentioned in Table 1. Usually, fly ash has been deliberated an industrial waste, deposited in landfills or ash ponds, generating main environmental and health hazards [12]. Regardless of its waste status, fly ash is progressively being accepted as a valuable resource due to its distinctive chemical composition and physical properties [13]. Rich in aluminosilicates, fly ash works as a superlative originator for the synthesis of zeolites microporous crystal-like materials with widespread applications in environmental remediation, catalysis, and ion exchange [14]. The consumption of fly ash for zeolite synthesis denotes a transformative method to sustainable material development. As global energy systems conversion toward greener alternatives, the heritage of coal-fired power plants leaves after an abundance of fly ash [15]. This assimilation of waste management and advanced material synthesis highlights the acute role of fly ash in driving innovation in wastewater treatment technologies [16].

Table 1 Primary chemical composition of coal fly ash and the zeolites synthesized from it.

SiO_2	Al_2O_3	Zeolite	Application
41.24	45.05	4 A	Removal of As (V) in solution
50.77	31.70	X	Adsorbent of CO_2
35.90	50.35	X	Removal of dioxins
47.60	43.34	NaP1	Adsorbent for Pb (II)
29.20	54.40	ZSM-5	Water treatment
23.20	50.67	P	Removal of glyphosate in water solution

1.2. Preparation of Fly ash-based Zeolites

The consumption of fly ash in zeolite synthesis dates back to the mid-20th century when researchers started discovering cost-effective and sustainable substitutions to conformist raw materials like natural clays and pure aluminosilicates [17]. Early efforts focused on the hydrothermal treatment of fly ash to renovate its silica and alumina content into zeolite frameworks. While the primary results were promising, the process was hindered by compositional changeability in fly ash and the deficiency of scalable methods [18]. The zeolites derived from fly ash have emerged as a seemingly miraculous solution to global problems of wastewater treatment, gas separation, and catalysis in the field of environmental science. Derived from the residual fine powder generated when coal is burned in thermal power plants, fly ash is high in aluminosilicates and so constitutes the exact applicant for forming zeolite [19]. The synthesis of fly ash-based zeolites has reformed significantly, determined by advancements in synthesis techniques and the increasing mandate for sustainable resources [20].

1.3. Synthetic approaches for Fly ash-based Zeolites

The synthesis of fly ash-based zeolites includes numerous approaches to alter aluminosilicate-rich fly ash into valuable crystalline constituents [21]. This section provides a detailed overview of these synthesis methods which involve Hydrothermal method, Alkali fusion, Microwave-assisted synthesis, Direct conversion methods and green synthesis. These methods are proceeding toward scalable, cost-effective invention of zeolites for environmental and industrial applications [22]. These all methods are also explained below in Fig.1

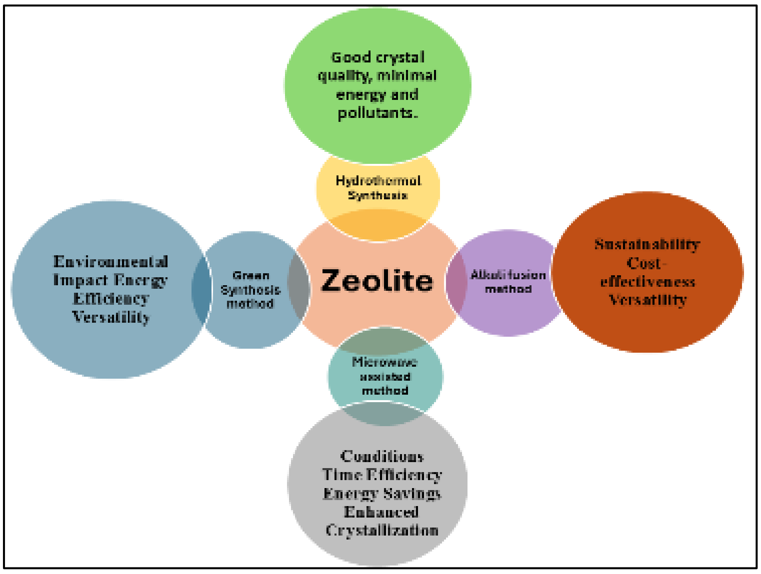

Figure 1 Synthesis methods and their advantages

1.4. Hydrothermal Synthesis

The hydrothermal method is the most extensively used and operative approach for synthesizing zeolites from fly ash as shown in Fig.2, mainly due to its capability to convert aluminosilicate-rich materials into highly crystalline, efficient structures under measured conditions [23]. This method exploits the discontinuation and reorganization of silica (SiO_2) and alumina (Al_2O_3) in an alkaline medium to form the distinguishing microporous frameworks of zeolites. The hydrothermal process typically includes the preparation of alkaline solution by mixing fly ash with an alkaline solution, generally sodium hydroxide (NaOH), to ease the dissipation of aluminosilicates [24]. Subsequently the mixture is stirred to form a homogenous slurry proving correct mixing of the reactants while the slurry is transferred to a sealed pressure vessel, an autoclave and heated at a range of 80-200°C for 12-48 hours [25]. The following product is filtered, washed to remove any remaining alkali content or feature and finally dried into crystalline zeolites. The hydrothermal method's specification, such as temperature, duration, and alkali concentration, can be adjusted to produce definite types of zeolites, including Zeolite A, X, and P. For instance, Zeolite A from coal fly ash using hydrothermal treatment at 100°C, demonstrating its high cation exchange capacity for wastewater treatment applications [26], Zeolite P from fly ash under hydrothermal conditions, highlighting its efficiency in eliminating ammonium ions from wastewater [27] and Zeolite X for use in gas separation and adsorption, emphasizing the role of exact temperature control during the hydrothermal process [28].

The hydrothermal method remains a basis of zeolite synthesis from fly ash due to its easiness, flexibility, and capability to produce high-quality materials. Recent developments, such as microwave-assisted synthesis and continuous-flow systems, have significantly improved its efficiency and sustainability [29]. Further researches should investigate the integration of the digital tools, examination of the methods hybrids, and the progression of in-situ functionalization to higher levels increase the ability of hydrothermal synthesis to produce additional zeolites for environmental and industrial purposes.

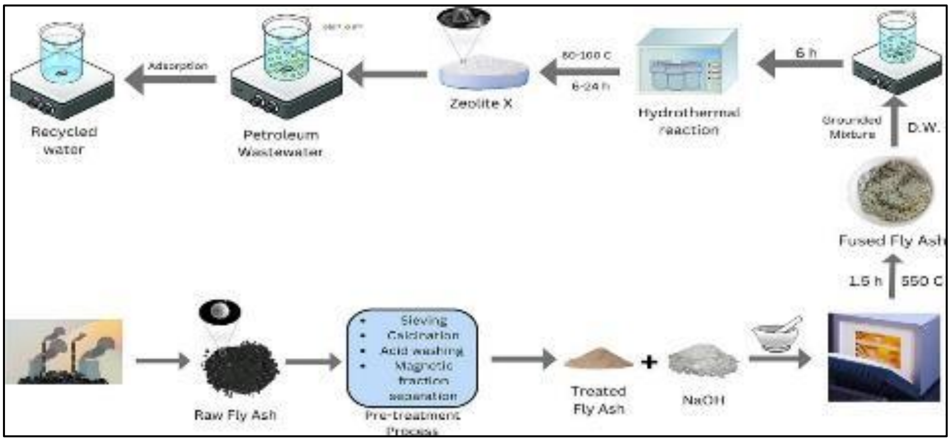

Figure 2 Hydrothermal synthesis of high-purity zeolite X from coal fly ash for heavy metal removal [30].

1.5. Alkali fusion method

The alkali fusion method turns out to be highly operational when it comes to synthesizing zeolites from fly ashes, especially where the material is less reactive in nature. [31]. This method involves treatment of fly ash at high temperature with solid alkali which will enhance dissolution of silica, SiO_2 and alumina, Al_2O_3 which are the basic constituents of zeolite frameworks as mentioned in Fig.3. The product formed by the merger is subjected to the hydrothermal crystallization process in order to develop pure zeolites and improved structural characteristics [32]. This method has improved attentiveness for its capacity to deal with fly ash with difficult alignments, it provides more control over the synthesis steps and permits fabrication of a number of kinds of zeolites.

This method is a beneficial as fusion step significantly enhance the reactivity of silica and alumina, allowing the adaptation of even low-grade fly ash into high-quality zeolites, Fly ash holding high levels of iron oxides or unburnt carbon, which hinder direct hydrothermal methods [33], can be efficiently treated using alkali fusion and this method can be used to produce various types of zeolites, including Zeolite X, P, and A, by regulating the synthesis parameters. For instance, Zeolite A from fly ash using the alkali fusion method, attaining high cation exchange capacity and excellent adsorption performance for heavy metals [34]. Zeolite P using a two-step alkali fusion and hydrothermal process, highlighting its high efficacy in ammonium ion removal from wastewater [35]. Zeolite X from fly ash using alkali fusion at 550°C, followed by hydrothermal treatment [36]. The alkali fusion method is a powerful and general method for converting fly ash to Zeolites, and this work provides solutions for changing harms from industries into useful materials in the environment [37]. By the integration of novel innovative processes, such as carbon neutrality, and flexible multifunctional zeolites, the subsequent studies should further enhance the capability of the alkali fusion method to boost the development of sustainable materials [38].

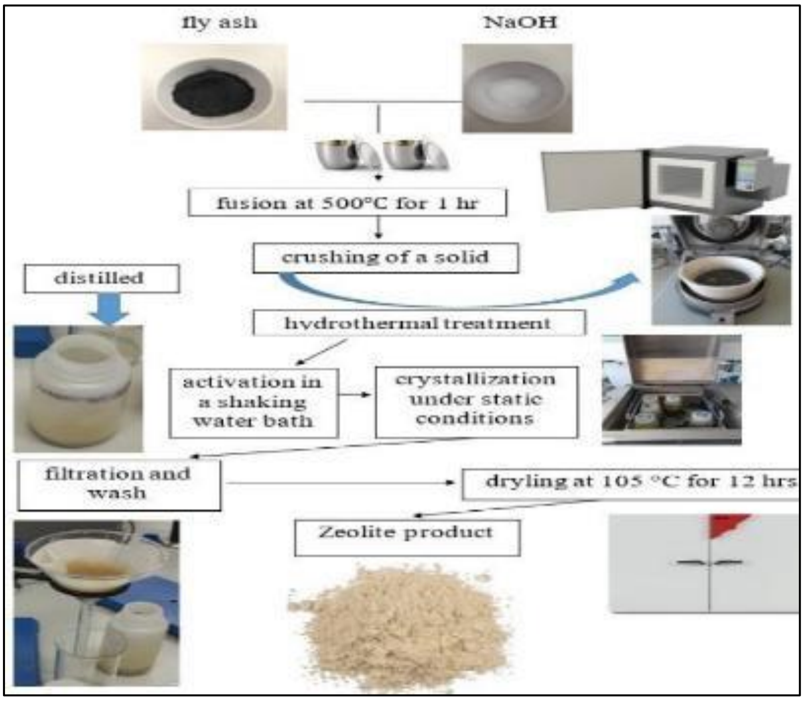

Figure 3 Synthesis of Zeolites from Coal Fly Ash Using Alkaline Fusion [39].

2. Microwave assisted method

Microwave method of synthesis is novel and energy efficient for synthesizing zeolites from fly ash. In contrast, most conventional heating methods heat through conduction, and microwave heating is proportional to polar molecules and ions resulting in quicker and uniform heating [40]. As shown in Fig.4, this unique mechanism substantially reduces synthesis time and energy input combined with the improved crystallinity and homogeneity of the prepared zeolite materials. Recently, microwave-assisted method has drawn much attention due to its green and efficient strategy for synthesizing various zeolites in large scale including the environmental applications such as water treatment and gas storage [41]. In the microwave-assisted method fly ash is mixed with an alkaline solution usually NaOH; which forms homogeneous slurry, the slurry is exposed to microwave irradiation in a sealed vessel. Microwaves get through the blend and heat the blend at a higher and faster rate and dissolve silica (SiO_2) and alumina (Al_2O_3) from the fly ash medium [42]. Under microwave heating, nucleation and crystallization occur quickly, forming zeolite structures. The process typically takes 15–60 minutes, compared to hours or days in conventional hydrothermal methods [43].

This method is valuable as it directly heats the reactants, diminishing heat loss and reducing overall energy consumption, the crystallization occurs rapidly, it significantly shortening the synthesis time compared to conventional method, microwave heating produces zeolites with enhanced crystallinity, uniformity, and fewer flaws and reduced energy necessities and shorter dispensation times align with green chemistry principles [44]. For future explorations, attention is to be paid to the application of microwave energy in synthesizing renewable energy and improved reactor for further potential of microwave assisted synthesis to be tapped over existing constraints. These incorporations make this method a potential generator of steady material science [45].

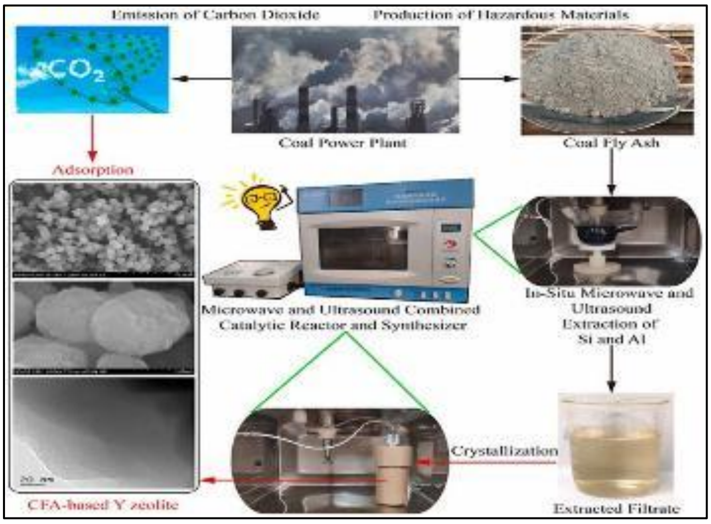

Figure 4 A combined *in situ* microwave and ultrasonic irradiation-assisted method [46] .

2.1. Direct conversion method

The direct conversion method is one of the simplest ways of producing zeolites from fly ash. Unlike methods involving preliminary treatments like alkali fusion or acid washing direct conversion affects the inherent aluminosilicate content of the fly ash [47]. The direct conversion technique reduces steps, time and cost of production as untreated or slightly treated fly ash to alkaline solution under controlled hydrothermal condition hence become an economic method of producing zeolites in large quantity. In this approach fly ash is blended with an alkali which may be sodium hydroxide NaOH or potassium hydroxide KOH each in a fixed proportion. The mixture is stimulated to form a homogenous slurry, confirming maximum contact between fly ash particles and the alkaline medium [48]. The slurry is imperiled to hydrothermal conditions in an autoclave, typically at temperatures of 80–200°C for 6–48 hours. This step eases the dissolution of silica (SiO_2) and alumina (Al_2O_3) and their subsequent reorganization into crystalline zeolite framework [49].

This method has some compensations like it eradicates pre-treatment steps, reducing complication and operational costs, uses untreated fly ash, minimizing waste generation and chemical usage, requires fewer reagents and less energy compared to alkali fusion or microwave-assisted methods and its straightforward process is easily scalable for industrial applications [50].

2.2. Green Synthesis method

This green synthesis method emphasizes on green approach of zeolites synthesis using fly ash where precaution is taken to include less hazardous chemicals, less energy consumption and use environmentally sustainable resources [51]. It is compliant with guidelines of green chemistry and circular economy, guaranteeing that synthesis possesses a minimal environmental signature and retains or surpasses effectiveness and purpose. Green synthesis is becoming paramount especially in the catchment of sustainable development and waste valorization, offers a potential substitute to the conventional synthesis processes that otherwise employ strong chemicals or consume enormous energy [52]. This method is a valuable as it reduces the dependency on harsh chemicals and energy-intensive processes, ensuring minimal environmental impact, eradicates or reduces expensive reagents and high-energy heating methods, helps the reuse of fly ash and other industrial by-products, contributing to waste minimization and aligns with global goals for sustainable resource management and environmental preservation [53], used ionic liquids as solvents for synthesizing Zeolite X produced from fly ash. This approach eliminated the need for strong alkalis and achieved high crystallinity while significantly reducing wastewater generation. The process minimized waste and energy input while producing zeolites with excellent ion-exchange capacities for wastewater treatment [54].

2.3. Fly ash-based zeolite use in oily wastewater treatment: Importance in Adsorption process

The treatment of oily wastewater is an important environmental challenge due to the difficulty and persistence of oil-water suspensions, hydrocarbons, and related organic pollutants [55]. By altering industrial waste (fly ash) into high-performance adsorbents, these materials address both water pollution and waste valorization, offering a circular economy solution [56]. Fly ash-based zeolites possess a microporous and mesoporous structure with a high surface area, enabling the effective adsorption of oil droplets, hydrocarbons, and other non-polar organic pollutants. Their pore size and structure can be tailored during synthesis to target specific pollutants [57].

As illustrated in the following Table.2, there are many examples in literature can be explained. The recent developments focus on the surface modification of the material by silanes, alkyls, or metal oxides to build up hydrophobicity and oil compatibility [58]. These alterations enhance the selectivity and adsorption capacity of zeolites for full oil molecules. New generation hierarchical zeolites with micro, meso and macro pore structures have enhanced the adsorption and diffusion function thus exhibiting increased application in the treatment of oily wastewaters [59]. The fly ash-based zeolites have been blended with carbon nanotubes, graphene oxide or polymers to obtain hybrid adsorbents with higher adsorption capacity and regeneration capabilities. New regeneration methods have been developed including the low-temperature thermal treatments, solvent washing, and microwave-assisted desorption to enhance the reusability of the zeolites and hence lower operational costs [60]. Fly ash has been enhanced and used to prepare nanostructure zeolites as a result of the increased surface area and adsorption site for faster pollutant removal. Opposing these innovations including photocatalytic and magnetic functionalities, bio-inspired designs, and the potentiality of fly ash-based zeolites can-opening the gateway for transformance technologies in water treatment and environmental remediation [61].

2.4. Fly ash-based zeolite in adsorption

Fly ash-based zeolites are regarded as very efficient adsorbents used in environmental applications because of their selective properties such as large surface area, ion exchange characteristics, variable pore and molecular sieving. Scientists turned fly ash, a coal combustion waste material, into useful products that can help solve some of the most pressing environmental problems of our day including water purification, natural gas separation and carbon capture [62]. Their adsorption potential makes them especially appropriate for removing organic pollutants, heavy metals, and gases from contaminated environments as shown in Fig.6. In ion exchange mechanism fly ash-based zeolites possess exchangeable cations (e.g., Na^+, K^+, Ca^{2+}) in their structure these ions can be replaced by heavy metals, ammonium, or other cationic pollutants during the adsorption process.

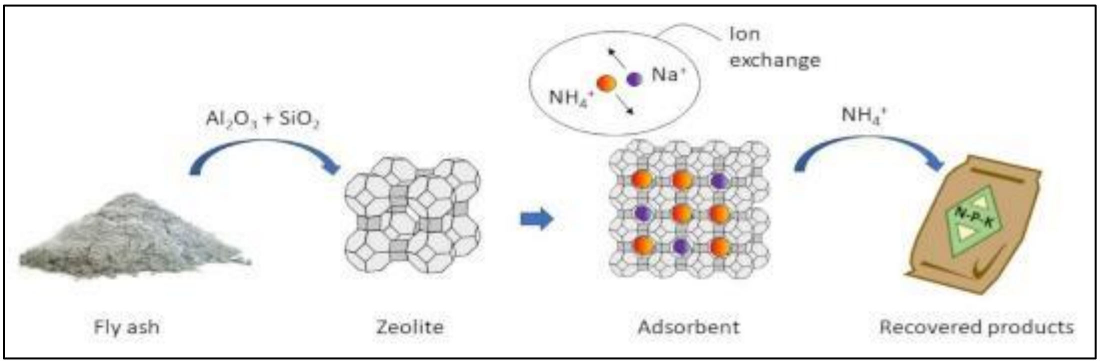

Figure 6 Fly ash-derived zeolites as adsorbents for the recovery of nutrients [63].

The hydrophobic interaction is another mechanism in which modified fly ash-based zeolites exhibit hydrophobic properties that increase the adsorption of non-polar organic compounds such as hydrocarbons in oily wastewater [64]. In Table 2. Different types of zeolites are explained for removal of different pollutants. In molecular sieving the well-defined pore size of zeolites allows selective adsorption of molecules based on size and shape, making them suitable for separating specific pollutants. In the surface functionalization functionalized fly ash-based zeolites may contain active groups or coatings such as silanes or metal oxides that increase its adsorption of some contaminants such as dyes, gases or heavy metals [65]. The development in the last few decades involved in the hierarchical frameworks, composite, and functionalized zeolites has improved their performance remarkably. Despite the fact that fly ash-based zeolites display eco-friendly and enhanced adsorption characteristics, the field of utilizing fly ash incorporates current invasions such as bio-inspired materials and multi-functional adsorbents which can only be explored in future work to make them a fundamental in sustainable environmental remediation technologies [66].

Table 2 Removal of wastewater pollutant by using zeolite composite through adsorption process.

Dye	Adsorbent	Adsorbent dosage	Time interval	References
Methylene blue	ZnO zeolite	100 mg	10 min	[67]
Methylene blue	LDHS-ANA Zeolite	3 g/L	1 h	[68]
Congo red	Zeolite	-	100 min	[69]
Xylenol (XO)	CH-ALG-BN	-	180s	[70]
Methylene blue	Fe_3O_4-GO-AHSA	0.03g	24h	[71]
Rhodamine B	Co-ZIF-9/GO	250mL	10min	[72]
Methylene blue	NaX-Zeolite	0.525g	15h	[73]

2.5. Mechanism of oily wastewater with Fly ash-based zeolite

Naturally modified fly ash-based zeolites introduced viable, cost-effective approach for other treatments of oily water through unprecedented physical and chemical properties. These zeolites differ from each other regarding their functioning and application capabilities like adsorption, ion exchange, molecular sieving and hydrophobic interaction [74]. Micellar and mixed micellar replication capability of the materials' microporous and mesoporous structures capture oil droplets and organic pollutants while ion-exchange eliminates ionic pollutants such as surfactants. Such alteration promotes selectivity for non-polar hydrocarbons, and thus makes the resulting zeolites highly efficient for oil-water separation [75]. Moreover, the surface modification with material such as nanoparticles introduces the concept of catalytic activity that facilitates concerted action of pollutant removal through degradation as well as adsorption. All these mechanisms make fly ash based zeolites an advanced and environment friendly method in solving some of the most difficult issues in wastewater treatment [76].

2.6. Adsorption mechanism

The main method by which fly ash-based zeolites eliminate contaminants, including organic pollutants, heavy metals, and oil molecules in wastewater is adsorption. This process depends on the characteristics of the zeolite itself such as; porosity, surface charge, and the ion exchange capacity of the pollutant [77]. Fly ash-based zeolites are somewhat superior to other zeolites because they have tunable pore size, large surface area and switchable surface chemistries and therefore they are highly selective for adsorption activities[78]. Molecules diffuse into the microporous and mesoporous framework of the zeolite, where they are held by weak forces. And it is good for trapping hydrocarbons, dyes, and small organic molecules [79].

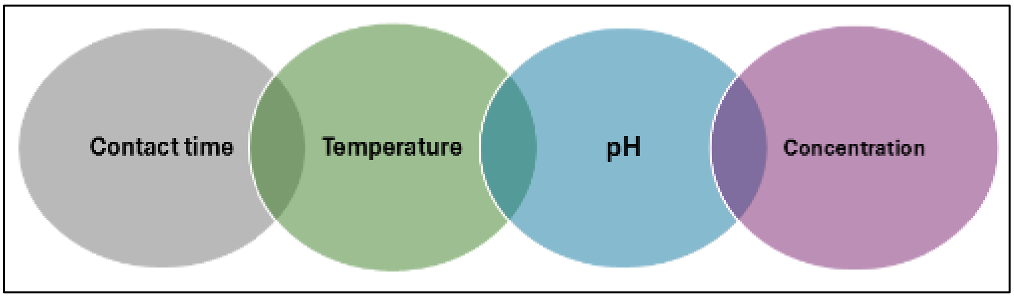

Figure 7 Different parameters affect adsorption.

The chemical adsorption which involves stronger, specific interactions like covalent or ionic bonds between pollutants and the zeolite surface. Active sites on the zeolite surface interact with specific functional groups of pollutants [80]. It is particularly effective for adsorbing heavy metals, such as lead (Pb^{2+}) and cadmium (Cd^{2+}). In ion exchange mechanism, exchangeable cations (e.g., Na^+, K^+) in the zeolite framework are replaced by positively charged pollutants like ammonium ions or heavy metals [81]. Pollutants strive with remaining cations in the zeolite, allowing their selective removal. And it is effective for ionic pollutants in wastewater, such as ammonium, surfactants, and charged organics [82]. Adsorption mechanism depend on several parameters as shown in Fig.7. Hydrophobic interactions involved non-polar organic pollutants, such as oil droplets, specially adsorb onto hydrophobic regions of the zeolite surface, functionalized zeolites with hydrophobic coatings enhance selectivity for oil and hydrocarbon adsorption. And it is essential for treating oily wastewater [83].

Other mechanism is molecular sieving in which zeolites selectively adsorb molecules based on size and shape, trapping smaller contaminants while excluding larger ones. The pore size and structure of zeolites dictate the selectivity for target pollutants [84]. It is Ideal for separating specific hydrocarbons or gases like CO_2 from mixtures. Recent advancements, such as hierarchical structures, hybrid materials, and functionalized surfaces, have significantly improved their performance and application range [85]. By incorporating cutting-edge innovations like bio-inspired designs and smart adsorbents, fly ash-based zeolites can be further optimized to address global challenges in water purification, air quality improvement, and resource recovery.

2.7. Role of micropore and mesopore in adsorption

Micropores and mesopores within the fly ash-based zeolites are radically significant for their applications, for instance, adsorption, catalysis, environmental technology, and materials science. Micropores with pore size <2nm and mesopores with pore size 2-50nm have corresponding advantages; they give high surface area of the material, good mass transfer and availability of pollutants. [86]. Knowledge of these different and closely related pore types is critical in enhancing zeolite performance for various uses. Micropores are able to offer a broad internal surface that is appropriate to the adsorption of small molecules including gases (CO_2, CH_4) and ionic pollutants (heavy metals, ammonium) [87]. Fly ash derived, Microporous Zeolite X had better CO_2 adsorption because of large surface area and molecular sieving phenomenon [88]. Because the micropores are of a similar size, the adsorption of molecules is selective with a reference to their size and shape and, therefore, useful for gas separation and for the removal of small organic pollutants from water. Microporous Zeolite A for removing ammonium ions from the water in wastewater treatment [89].

Micropores function as molecular sieves, admitting only molecules with a size that cannot exceed the diameter of the micropores, which provides evidence of pollutant selectivity. Synthetic zeolites obtained from fly ash selectively removed benzene and toluene from industrial emissions. Mesopores provide greater accessibility to large particles and complex molecules like emulsified oils, organic dyes, and bulky hydrocarbons enhancing the pollutant access time to the adsorption sites. New composite mesoporous zeolite P for oil-water separation application is presented, proving to have high efficiency motivated by increased diffusion [90]. Mesopores provide available space to accommodate active catalytic species such as metal nanoparticles and to accommodate bulky reactants to the access of done and relevant catalytic sites. For adsorbing macromolecules or mixed contaminants, the presence of mesopores makes them highly efficient for wastewater treatment and oil adsorption.

Indeed, the current development of materials such as hierarchical zeolites, hybrid materials and nano-zeolites has enhanced the flexibility and efficiency of the material [91]. Future investigations using such concepts as bioinspired designs and sustainable synthesis strategies will show that many-pored and pyrophoric zeolites contain even greater potential for overcoming global and local environmental and industrial problems.

2.8. Regeneration and Reusability

The cost-effectiveness and environmental advantages of fly ash zeolites are supported by regeneration, and their reusability demonstrates the suitability of the process for sustainable use of fly ash [92]. Regeneration encompasses the process of chemically or thermally stripping the pollutants to restore adsorption capabilities microwave assisted desorption, ultrasonic cavitation, photocatalytic and/or electro thermal treatments. Each method has unique advantages: thermal regeneration is effectual in eradicating organic contaminants but consumes considerable power; chemical methods are applicable to heavy metals but produce waste; microwave and photo catalytic approaches are energy friendly and do not deform the structure of zeolite hence appropriate for oils and dyes [93]. Some of the current developments include; the use of multiple regenerants as a cost-effective way of integrating the thermal and chemical regeneration process, biological solvents that are environment friendly and regeneration of zeolites that removes pollutants under light or electrical stimulus.

Illustrations from literature are as follows; silane treated zeolites was shown to have 85% oil removal efficiency after ethanol washing [94]. New innovations such as resource recovery in the process of pollutant desorption and utilizing renewable-powering equipment like solar-powered microwave systems are expected to improve the process even further. strengthening the material and making regeneration automated, carbon-neutral fly ash based zeolites can persist as practical and effective tools for environmental management and cleanup [95].

2.9. Environmental and Economic Implications

Synthetic zeolite derived from the fly ash is primarily environmental and equally an economic proposition as these fulfills the sustainability requirements while being cost effective. From an environmental perspective they can convert industrial waste into usable products thus reducing landfill disposal, cut down on emissions of greenhouse gases and minimized pollution control tools [96]. For instance, the ability to remove 95% of oil from the wastewater using the silane-treated zeolites, which will amount to environmental improvement. This includes their part in air purification by absorbing substances like CO_2 which will help counter climate change [97].

New progressions comprise of the development of hierarchical and hybrid zeolites, enhancing pollutant removal efficiency and multifunctionality, such as combining adsorption with photocatalysis for organic pollutants [98]. Sustainable synthesis methods using renewable energy and green solvents more reduce the environmental footprint of production. Innovations to consider in a review include, integration with circular economy models to recover valuable pollutants like metals or hydrocarbons, and scalable systems for dispersed water and air treatment [99]. These developments reflect the twofold environmental as well as economic benefits of fly ash-based zeolites to boost their mission as change agents in global sustainability.

Challenges and Future directions

Future directions and confronted challenges related to synthesis and applications of fly ash-based zeolite include:

- Regulating Fly Ash Composition: Variation in chemical nature of the fly ash sources influences the effectiveness of the corresponding zeolite. There is a need to continue the development in enhanced standardized pre-treatment protocols for future comparisons.
- High-energy consuming Processes: The synthetic methods such as alkali fusion and thermal regeneration require input energy in the recovery process. Microwave-assisted synthesis and the use of renewable energy for the systems can remain a solution for these problems.
- Versatility Issues: Unfortunately, the scale up of fly ash to industrial scale production as a source of synthesizing zeolites poses some difficulties in terms of maintaining consistent production and optimizing reactor configurations. The continuous-flow hydrothermal systems and linked reactors are two promising technologies.
- Inferior Waste Generation: Other regeneration processes that involve the use of chemical solutions create other wastes. For the application to be sustainable, green regeneration techniques are often used – by using, for example, bio-based solvents or photocatalysis.
- Resilience in Harsh Environments: It was found that exposing the structures of the zeolite to long-term effects of acidity, alkalinity, or high temperatures will affect its structures and composition. Polymeric coatings, combined materials, and reinforcement structures must be used to enhance sustainability.
- Enhancing Multifunctionality: Following materials should combine adsorption ability, catalytic activity and pollutant extraction for better interaction of future products with multifaceted environmental demands.
- Circular Economy Incorporation: Integrating fly ash-derived zeolites into systems that exploit valuable contaminants such as metals or hydrocarbons during treatment makes the product more sustainable and economically significant.
- Novelties in Green Synthesis: As a result, endeavor on green solvents, renewable energy, and carbon capture during the synthesis process extrapolates to sustainable global standards.
- Localized Treatment Solutions: The use of fly ash-based zeolites with dispersed water and air treatment systems makes it possible and less reliant on big structures especially in the rural and remote areas.
- Incorporation with Advanced Materials: While incorporating zeolites with new material such as graphene oxide, quantum dots can form composite structures with better adsorption, catalytic and electrochemical performance.

3. Conclusion

Fly ash-based zeolites are emerging as a sustainable and effective solution for addressing the critical issue of oily wastewater contamination, leveraging industrial byproducts for environmental remediation. These materials combine the principles of waste valorization and circular economy by repurposing fly ash—a byproduct of coal combustion—into high-performance adsorbents. The tailored structural and surface modifications, such as acid/base treatments, surfactant functionalization, and metal-ion incorporation, have significantly enhanced their adsorption efficiency, selectivity, and stability, enabling the removal of diverse pollutants under various environmental conditions. Recent advancements, including nanoscale structuring and the development of hybrid materials with multifunctional capabilities such as photocatalysis, magnetic recovery, and antimicrobial properties, have further expanded the application potential of fly ash-based zeolites. These innovations not only enhance pollutant removal efficiency but also simplify regeneration and reuse processes, making these materials cost-effective for industrial-scale operations. Moreover, their ability to integrate adsorption with additional treatment functionalities positions them as a versatile tool in wastewater management. Despite significant progress, challenges remain in scaling up production, achieving consistent quality, and ensuring durability under extreme wastewater conditions such as high salinity and variable pH. Addressing these issues will require the optimization of synthesis processes, the establishment of standardized protocols, and the integration of complementary technologies, such as photocatalysis or electrochemical methods, to create more comprehensive treatment systems. The transformation of fly ash into zeolites demonstrates a practical and scalable approach to mitigating industrial waste and water pollution, offering both economic and environmental benefits. With ongoing research and the adoption of advanced manufacturing techniques, fly ash-based zeolites have the potential to become a cornerstone in sustainable wastewater treatment. Their continued development and application will play a vital role in addressing global environmental challenges and advancing the goals of cleaner water and sustainable resource management.

Compliance with ethical standards

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Disclosure of conflict of interest

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Data availability

No data was used for the research described in the article.

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