Application Analysis of Polyethylenimine (PEI-25K) in Water Treatment

Author: Liang Xiao
Organization: Guangzhou SIO New Material Co., Ltd.
Position: Materials Application Researcher
Email: support@sioresin.com

Abstract

Driven by the increasing demands for enhanced municipal wastewater treatment, advanced industrial wastewater purification, and drinking water safety, the development of efficient, stable, and adaptable cationic polymer water treatment agents has become an important research direction in the field of water environment management. Polyethylenimine (PEI), whose molecular chains are rich in primary, secondary, and tertiary amine groups, exhibits high cationic charge density, excellent water solubility, and multiple reactive functionalities. As a result, PEI demonstrates significant application potential in colloidal destabilization, flocculation and sedimentation, heavy metal adsorption, anionic pollutant removal, and membrane surface modification.

PEI-25K, a branched Polyethylenimine product with a nominal molecular weight of approximately 25,000, features high solid content, high amine group density, and strong interfacial adsorption capability. It achieves a favorable balance among flocculation efficiency, dispersibility, and engineering applicability. This paper systematically discusses the molecular structure, typical physicochemical properties, and water treatment mechanisms of PEI-25K, while summarizing its application characteristics in municipal wastewater, industrial wastewater, heavy metal wastewater, dyeing wastewater, micro-polluted raw water, and sludge dewatering systems. Particular attention is given to the influence of its high viscosity on onsite preparation, transportation, and stable dosing, together with corresponding engineering operation recommendations.

In addition, this paper reviews related domestic and international studies, compares the performance differences between PEI-25K and conventional inorganic coagulants as well as polyacrylamide-based agents, and comprehensively analyzes its environmental safety, engineering economics, and application limitations. Future development directions, including low-viscosity modification, immobilization, synergistic compounding, and intelligent dosing technologies, are also discussed. This study aims to provide a reference for the scientific selection and engineering application of PEI-25K in water treatment systems.[1]

Keywords: Polyethylenimine; PEI-25K; Water Treatment; Cationic Polymer; Flocculation; Heavy Metal Adsorption; Membrane Modification

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Chapter 1 Introduction

1.1 Research Background and Significance

In recent years, with the rapid advancement of industrialization and urbanization, the demand for treating complex industrial wastewater, heavy metal contamination, and high-organic-load wastewater has continued to increase. Traditional inorganic coagulants such as polyaluminum chloride (PAC) and polyferric sulfate (PFS) offer advantages including low cost and broad applicability; however, they generally suffer from high dosage requirements, large sludge generation, and limited effectiveness toward certain complexed pollutants. Although polyacrylamide (PAM)-based polymer flocculants exhibit strong bridging capability, their selectivity toward heavy metals and certain anionic pollutants remains relatively limited.

Therefore, cationic polymer materials capable of charge neutralization, bridging flocculation, chelation adsorption, and interfacial regulation have attracted increasing attention in both research and engineering applications.

Polyethylenimine (PEI) is a typical nitrogen-containing cationic polymer composed of repeating ethyleneimine structural units. Its molecular chains are rich in primary, secondary, and tertiary amine groups, which are readily protonated under acidic to neutral conditions, resulting in high cationic charge density. PEI can interact with various pollutants through electrostatic interaction, hydrogen bonding, and coordination bonding, showing strong application potential in flocculation destabilization, heavy metal adsorption[2], anionic pollutant removal, and membrane surface functionalization.

As a commercial medium-molecular-weight[3] branched PEI product, PEI-25K offers a balanced combination of dispersibility, flocculation efficiency, engineering applicability, and cost effectiveness, making it highly valuable for industrial water treatment applications.

1.2 Research Status of Polyethylenimine (PEI)

International research on PEI in separation materials, biomedicine, and water treatment has continued for decades. Studies indicate that branched PEI possesses higher amine density than linear PEI, allowing more efficient charge diffusion and particle adsorption in aqueous systems. Low-molecular-weight PEI exhibits good dispersibility but limited bridging capability, whereas high-molecular-weight PEI provides stronger flocculation performance but suffers from difficult dissolution and localized overconcentration.

In water treatment applications, PEI is commonly used as a flocculant, heavy metal adsorbent, membrane surface modifier, dye decolorizing agent, and phosphorus removal agent.

Domestic studies mainly focus on PEI-modified carrier materials and composite flocculant preparation, while systematic research on the engineering application of commercial medium-molecular-weight PEI-25K, high-viscosity operation standards, and full-scenario application comparison remains relatively insufficient. In practical engineering applications, inadequate understanding of viscosity characteristics, improper dilution, and non-standard dosing often lead to reduced treatment efficiency, equipment blockage, and unstable effluent quality, thereby limiting large-scale industrial adoption. Therefore, integrated studies covering the structure, mechanism, application, and operational practices of PEI-25K are urgently needed.

1.3 Product Characteristics and Research Value of PEI-25K

PEI-25K[4] is typically a colorless or pale-yellow high-viscosity liquid with a slight amine odor. It can form homogeneous systems with water and certain polar organic solvents, while exhibiting high amine group density and strong interfacial adsorption capability. Its typical technical characteristics include:

1. A nominal molecular weight of approximately 25,000, providing both bridging capability and good dispersibility;
2. Rich amine functional groups capable of strong interaction with heavy metal ions and anionic pollutants;
3. High solid content and high viscosity, enabling high effective ingredient concentration per unit mass;
4. Good water solubility and application adaptability over a wide pH range;
5. Synergistic compatibility with conventional agents such as PAC, PFS, and PAM.

This paper focuses on the structural characteristics, action mechanisms, engineering applications, key influencing factors, and onsite operational standards of PEI-25K, aiming to provide systematic guidance for related applications.

1.4 Research Content and Technical Route

1. Analyze the molecular structure, physicochemical properties, and five major water treatment mechanisms of PEI-25K;
2. Summarize the application modes of PEI-25K in municipal wastewater, industrial wastewater, heavy metal wastewater, dyeing wastewater, membrane modification, and sludge dewatering;
3. Investigate the effects of pH, ionic strength, temperature, and dosing methods on treatment performance;
4. Establish comprehensive operational standards for dilution, stirring, transportation, dosing, and storage of high-viscosity PEI-25K;
5. Evaluate environmental safety, storage stability, equipment material compatibility, and engineering economics;
6. Summarize application bottlenecks and propose optimization strategies and future development directions.

Chapter 2 Structural Characteristics and Water Treatment Mechanisms of PEI-25K

2.1 Molecular Structure and Physicochemical Properties of PEI-25K

PEI-25K is a branched Polyethylenimine containing primary amine (-NH_2), secondary amine (-NH-), and tertiary amine (-N<) structures within its molecular chains. Its branched structure provides high amine density and strong spatial adsorption capability, enabling the formation of stable cationic polyelectrolyte systems in aqueous phases.

Typical physicochemical properties are as follows:

- Nominal molecular weight: approximately 25,000
- Appearance: colorless to pale-yellow viscous liquid
- Solid content: >99%
- Viscosity: 200,000–350,000 mPa·s
- Total amine value: 17–20 mmol/g
- pH of 5% aqueous solution: 10–12
- Solubility: readily soluble in water and lower alcohols, with partial compatibility toward certain polar organic solvents

Compared with linear PEI, branched PEI generally exhibits higher cationic density and stronger interfacial adsorption capability, although its viscosity is also relatively higher.

2.2 Core Water Treatment Mechanisms

2.2.1 Charge Neutralization and Colloidal Destabilization

Colloidal particles, microorganisms, and fine suspended solids in water generally carry negative surface charges, forming stable dispersed systems. PEI-25K dissociates in water into high-density cationic polymers that rapidly neutralize the negative charges on particle surfaces, reduce zeta potential, and disrupt hydration films and electric double-layer structures, thereby destabilizing colloids and facilitating subsequent flocculation.

2.2.2 Polymer Bridging Flocculation

The medium-molecular-weight chains of PEI-25K can form multipoint adsorption bridges between destabilized particles, creating “particle–polymer–particle” floc structures. This promotes the aggregation of fine particles into larger, denser, and more settleable flocs, significantly improving sedimentation rate and solid-liquid separation efficiency.

2.2.3 Chelation and Coordination with Heavy Metal Ions

The amine groups in PEI molecules contain lone-pair electrons capable of forming stable coordination structures with heavy metal ions such as Cu^{2+}, Pb^{2+}, Cd^{2+}, Ni^{2+}, and Zn^{2+}, thereby enabling adsorption and removal of heavy metals.[6]

For certain complexed heavy metal systems, PEI can also enhance removal efficiency through electrostatic interaction and multipoint coordination mechanisms, making it valuable for electroplating wastewater, printed circuit board wastewater, and metallurgical wastewater treatment.

For anionic heavy metal pollutants such as Cr(VI), PEI primarily achieves removal through electrostatic adsorption and complex coordination. Some studies have also reported possible participation in synergistic reduction processes within composite systems, although the exact mechanism strongly depends on system conditions.

2.2.4 Adsorption and Removal of Anionic Pollutants

Due to its strong cationic nature, PEI-25K can efficiently capture anionic dyes, humic acid, phosphate, arsenate, sulfate, and other pollutants through electrostatic attraction combined with hydrogen bonding, thereby achieving decolorization, phosphorus removal, arsenic removal, and COD reduction.

2.2.5 Interfacial Modification and Enhanced Solid-Liquid Separation

PEI-25K can be applied to membrane surface modification through surface coating, interfacial polymerization, and crosslinking methods, thereby improving membrane hydrophilicity and anti-fouling performance.

Some studies have shown that PEI modification can reduce pollutant deposition on membrane surfaces and improve microbial adhesion behavior, contributing to enhanced membrane flux stability and longer operational lifetime.

2.3 Comparison of PEI with Different Molecular Weights

PEI products with different molecular weights and structural types exhibit significant differences in water treatment performance:

- Low-molecular-weight PEI: lower viscosity and better dispersibility, but limited bridging capability;
- High-molecular-weight PEI: stronger flocculation capability, but more difficult dissolution and transportation;
- Medium-molecular-weight PEI (such as PEI-25K): provides a favorable balance among charge neutralization, bridging flocculation, and engineering operability.

In addition, branched PEI and linear PEI differ in their action mechanisms. Branched PEI generally exhibits higher amine density and stronger charge neutralization capability, whereas linear PEI may possess advantages in molecular chain extensibility.[7]

Chapter 3 Typical Applications of PEI-25K in Water Treatment

3.1 Flocculation, Coagulation, and Advanced Purification of Municipal Wastewater

PEI-25K can be used as either a primary flocculant or a coagulant aid in primary enhancement and advanced treatment stages of municipal wastewater treatment systems. It effectively removes suspended solids, colloids, total phosphorus, COD, and color. Its advantages include the formation of dense flocs, rapid sedimentation, and reduced sludge generation, thereby lowering overall chemical consumption and sludge disposal costs.

3.2 Comprehensive Treatment of Industrial Wastewater

In wastewater from papermaking, mining, food processing, and chemical industries, PEI-25K can rapidly destabilize colloids and remove contaminants such as fine fibers, coal particles, starch, and proteins, thereby improving effluent clarity and reducing the load on biological treatment systems. Its broad pH adaptability allows stable performance under acidic, neutral, and alkaline conditions.

3.3 Advanced Treatment of Heavy Metal Wastewater

In wastewater treatment systems for electroplating, metallurgy, electronics, and printed circuit board industries, PEI-25K can remove heavy metal ions such as Cu, Ni, Pb, and Cd through the synergistic effects of coordination adsorption and flocculation.

For complex wastewater containing EDTA or cyanide complexes, PEI-25K is generally combined with traditional precipitation methods, oxidation processes, or inorganic coagulants to improve overall treatment stability.

The actual removal performance in different wastewater systems is closely related to factors such as initial concentration, complexing agent type, pH conditions, and process combinations.

3.4 Decolorization of Dyeing Wastewater and Removal of Organic Pollutants

Reactive dyes, direct dyes, and certain acid dyes in dyeing wastewater generally contain anionic functional groups. PEI-25K promotes dye aggregation and sedimentation through charge neutralization and adsorption bridging mechanisms, thereby achieving decolorization.

Literature reports and some laboratory test results indicate that high decolorization efficiency can be achieved for certain dyeing wastewater under optimized conditions. However, the actual

performance strongly depends on dye type, salt concentration, and combined treatment processes.

3.5 Purification of Micro-Polluted Raw Water and Circulating Cooling Water

PEI-25K can be used for turbidity removal, algae control, and natural organic matter removal in surface water and groundwater treatment. In circulating water systems, it can help control microbial sludge, disperse suspended solids, reduce equipment corrosion and scaling, and improve heat transfer efficiency and system stability.

3.6 Functional Modification of Membrane Separation Materials

PEI-25K can modify ultrafiltration, nanofiltration, and reverse osmosis membranes through coating, interfacial polymerization, and in-situ crosslinking methods, thereby improving membrane hydrophilicity, anti-fouling properties, antibacterial performance, and heavy metal rejection capability. These improvements help extend membrane service life and reduce cleaning frequency.

3.7 Sludge Dewatering Conditioning

As a cationic sludge conditioning agent, PEI-25K can neutralize the negative charges of sludge particles, release bound water, and improve floc structure. It significantly reduces filter cake moisture content, enhances the operating efficiency of filter presses, centrifuges, and belt dewatering systems, and decreases PAM consumption.

Chapter 4 Application Performance and Key Influencing Factors of PEI-25K

Important Note

All PEI-25K dosage values discussed in this chapter are calculated based on 100% active solid content. In practical engineering applications, the original product should first be diluted to a solution containing approximately 5%–20% solids before dosing. The dosing volume should then be calculated according to the effective active dosage to ensure adequate dispersion and avoid localized overconcentration.

4.1 Evaluation Index System for Water Treatment Performance

Literature reports and some laboratory test results indicate that under suitable pH conditions, reasonable dosage levels, and optimized treatment processes, PEI-25K can achieve effective removal of turbidity, suspended solids, certain heavy metals, and color.

Typical results include:

- Turbidity removal rate: generally above 90%;

- Removal rate of certain heavy metals: above 90%;
- Dyeing wastewater decolorization rate: high removal efficiency under optimized conditions;
- Sludge dewatering performance: improved floc structure and reduced filter cake moisture content.

The above data are significantly affected by water quality, initial pollutant concentration, process combinations, mixing conditions, and dosing methods, and should therefore be regarded as typical reference values only.

4.2 Analysis of Core Influencing Factors

4.2.1 Effect of pH

pH directly influences the protonation degree of amine groups and the cationic charge density. Experimental observations are summarized as follows:

- pH 4–5: stronger chelation effect but relatively weaker flocculation performance;
- pH 6–9: optimal charge density and bridging flocculation, with treatment efficiency improved by approximately 15%–30%;
- pH 10–12: excessively alkaline conditions reduce charge density and slightly decrease overall performance.

4.2.2 Dosage (Calculated Based on 100% Solid Content)

- Municipal wastewater: optimal dosage 0.5–1.5 mg/L
- General industrial wastewater: optimal dosage 1.0–3.0 mg/L
- Electroplating/heavy metal wastewater: optimal dosage 1.5–4.0 mg/L

Insufficient dosage leads to incomplete colloidal destabilization and removal efficiencies of only 50%–70%. Excessive dosage may cause charge reversal, resulting in colloid restabilization and deterioration of effluent quality.

4.2.3 Temperature and Ionic Strength

- Temperature below 15°C: reduced molecular mobility prolongs floc formation time by approximately 30%–50%, requiring extended mixing time;
- High-salinity wastewater: electrostatic interactions are suppressed, leading to a 10%–25% reduction in removal efficiency. Composite treatment systems are recommended to improve stability.

4.2.4 Mixing and Dosing Methods

- Rapid mixing (200–300 r/min for 30 s): promotes more complete charge neutralization;
- Slow mixing (50–100 r/min for 3–5 min): produces denser flocs with better settling performance;

- Excessive shear force may break flocs and reduce removal efficiency by 20%–40%.

4.3 Performance Comparison with Conventional Water Treatment Chemicals (Based on 100% Solid Content)

Compared with traditional inorganic coagulants, PEI-25K exhibits characteristics such as lower dosage requirements, multifunctionality, and stronger interactions with certain pollutants in some complex wastewater systems.

Compared with polyacrylamide (PAM), significant differences exist in their action mechanisms:

- PEI: primarily relies on charge neutralization, coordination adsorption, and medium-chain bridging;
- PAM: primarily relies on ultra-high-molecular-weight chain bridging.

Therefore, PEI is more suitable for applications requiring high charge demand and synergistic heavy metal removal, whereas PAM is more suitable for sludge dewatering and high-efficiency bridging applications.

In practical engineering applications, the two are often used together to achieve synergistic enhancement.

4.4 Composite Application Systems

Segmented dosing of PEI-25K together with inorganic coagulants can achieve synergistic effects:

1. PAC/PFS is dosed first to accomplish colloidal destabilization;
2. PEI-25K is added afterward to strengthen bridging flocculation and deep adsorption.

Engineering data indicate that such combined systems can further improve effluent quality by 10%–25% while reducing overall chemical consumption by 15%–30%.

4.5 Influence of Dilution Concentration on Dispersion and Performance

The viscosity of original PEI-25K solution can reach 200,000–350,000 mPa·s, making direct dosing of the concentrated product unsuitable.

In practical applications, the product is generally diluted to approximately 5%–20% solid content before use. After dilution, the viscosity decreases to approximately 800–1500 mPa·s, enabling:

- Uniform dispersion without agglomeration or encapsulation;
- Stable dosing without pipeline blockage;
- Optimal treatment performance.

The actual dilution ratio should be determined comprehensively according to:

- Dosing equipment;
- Transportation distance;
- Ambient temperature;
- Water quality conditions;
- Target dosage level.

Chapter 5 High-Viscosity Characteristics and Engineering Operation Guidelines for PEI-25K

5.1 Influence of High Viscosity on Engineering Applications

At room temperature, PEI-25K exists as a highly viscous liquid. Direct dosing of the concentrated product can easily lead to localized overconcentration, excessive colloidal destabilization, loose and floating flocs, inaccurate dosing, pipeline and valve blockage, increased pump wear, and significant fluctuations in treatment performance. Standardized dilution and dosing procedures are therefore essential for maintaining stable treatment efficiency.

5.2 Dilution and Preparation Procedures

1. Dilution concentration: 5%–20% is recommended and may be adjusted according to water quality, dosage requirements, and transportation distance;
2. Dissolution sequence: add water first, then slowly introduce PEI-25K along the vessel wall to prevent agglomeration and encapsulation;
3. Mixing conditions: low-speed stirring at 100–300 r/min for 20–40 minutes until the solution becomes uniform and transparent;
4. Dilution medium: deionized water or tap water may be used, while high-salinity, strongly acidic, or strongly alkaline water should be avoided.

5.3 Transportation and Dosing Equipment Compatibility

1. Original product transportation: screw pumps, gear pumps, or diaphragm pumps are recommended; ordinary centrifugal pumps should not be used;
2. Pipeline design: large-diameter, low-resistance pipelines are recommended to minimize elbows, tees, and dead zones and reduce blockage risk;
3. Low-temperature handling: when ambient temperature is below 15°C, viscosity increases significantly. Heating to 20–25°C is recommended to improve fluidity.

5.4 Storage and Stability of Diluted Solutions

The original PEI-25K product should be stored in sealed containers under cool and dry conditions, avoiding prolonged exposure to high temperatures and air.

After long-term storage, diluted solutions may undergo performance changes due to CO_2 absorption or microbial contamination. Therefore, freshly prepared solutions are recommended, and the allowable storage period should be determined according to onsite conditions.

5.5 Safety Operation Requirements

PEI-25K aqueous solutions are strongly alkaline. During preparation and dosing operations, protective goggles, acid/alkali-resistant gloves, and protective clothing should be worn. Direct mixing with strong acidic substances should be avoided to prevent intense exothermic reactions and splashing. In case of skin or eye contact, rinse immediately with large amounts of clean water and seek medical attention if necessary.

Chapter 6 Safety, Environmental Behavior, and Engineering Considerations

6.1 Environmental and Operational Safety

As a highly cationic polymer, PEI-25K can achieve relatively low residual concentrations in treated effluent under reasonable dosing and standardized operating conditions. Environmental release risks may also be reduced through sludge removal processes.

However, its environmental behavior should still be evaluated according to specific application scenarios. Some studies suggest that polymers with high cationic charge density may exhibit certain toxic effects on aquatic organisms at elevated concentrations. Therefore, engineering applications should carefully control dosage levels and monitor final discharge concentrations.

In addition, PEI aqueous solutions are alkaline and may cause irritation to skin and eyes. Appropriate chemical safety procedures should therefore be strictly followed during handling and operation.

6.2 Storage, Transportation, and Material Compatibility

- Recommended materials: stainless steel, polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC);
- Unsuitable materials: carbon steel, cast iron, copper, and brass (prone to oxidation, discoloration, and product contamination);
- Transportation requirements: sealed, protected from sunlight, rain, and moisture, while avoiding high temperatures, prolonged sun exposure, and severe mechanical impact.

6.3 Engineering Economic Analysis

Although the unit cost of PEI-25K is generally higher than that of conventional inorganic coagulants, its multifunctionality and relatively low effective dosage in certain applications provide potential comprehensive economic advantages in the treatment of complex wastewater systems.

Under combined treatment processes, PEI-25K can help reduce the consumption of certain inorganic chemicals and improve sludge characteristics, thereby potentially lowering subsequent sludge treatment burdens.

The actual economic performance should still be comprehensively evaluated according to raw water quality, treatment process configuration, and operating conditions.

Chapter 7 Review of Domestic and International Research Progress

7.1 Research on Flocculation and Colloidal Destabilization

The charge density, molecular weight, and dosage of branched PEI directly affect flocculation performance. Medium-molecular-weight PEI can achieve efficient synergistic destabilization and bridging effects in municipal wastewater, papermaking wastewater, and mining wastewater treatment, thereby improving floc strength and sedimentation performance.

7.2 Research on Heavy Metal Adsorption and Chelating Materials

PEI-based materials exhibit high adsorption capacity and selectivity toward heavy metals and can be applied in advanced treatment and resource recovery systems. Extensive application cases and theoretical studies have already been reported in electroplating and metallurgical wastewater treatment.

7.3 Research on Membrane Separation and Interfacial Functionalization

PEI modification can significantly improve membrane hydrophilicity, anti-fouling properties, and antibacterial performance while enhancing flux stability and separation precision. These improvements promote the advancement of membrane-based water treatment technologies for refractory wastewater, water reuse, and drinking water purification.

7.4 Research on the Removal of Dyes, Phosphorus, Arsenic, and Other Anionic Pollutants

Through the synergistic effects of electrostatic interaction and hydrogen bonding, PEI demonstrates high removal efficiency toward anionic dyes, phosphates, arsenates, and related pollutants. It can therefore be applied in municipal wastewater upgrading, advanced treatment of dyeing wastewater, and eutrophic water remediation.

Chapter 8 Application Challenges, Optimization Strategies, and Future Prospects

8.1 Existing Application Challenges

1. The high viscosity of PEI-25K increases the complexity of onsite dissolution, transportation, and dosing operations;
2. Its unit cost is higher than that of conventional inorganic flocculants, limiting its adoption in certain cost-sensitive applications;
3. Its resistance to interference in highly saline, strongly complexed, or high-organic-content wastewater systems still requires improvement;
4. Industry standards, dosing specifications, and testing methods have not yet been fully standardized.

8.2 Optimization Directions

1. Development of low-viscosity modified products, emulsified dispersions, and pre-diluted formulations to improve onsite operability;
2. Immobilization and supported loading technologies to reduce dissolved residues and improve regeneration and reusability;
3. Targeted graft modification to enhance selectivity toward specific pollutants such as heavy metals, phosphorus, and arsenic;
4. Establishment of standardized composite treatment systems, intelligent dosing models, and engineering operation protocols.

8.3 Future Development Prospects

1. Intelligent responsive PEI water treatment materials (pH-, temperature-, and ion-responsive);
2. Bio-based, degradable, and low-carbon green PEI composite materials;
3. Integration of flocculation–adsorption–membrane separation coupled processes and equipment;[8]
4. Resource recovery and high-value utilization of pollutants such as heavy metals and phosphorus.

Chapter 9 Conclusions

- As a branched cationic polymer, PEI-25K combines charge neutralization, adsorption coordination, and moderate bridging flocculation capability, demonstrating strong application potential in various water treatment scenarios.
- Compared with traditional inorganic coagulants, PEI-25K exhibits lower dosage requirements and multifunctional synergistic characteristics in certain complex wastewater treatment systems. Compared with PAM, it offers advantages in charge neutralization and heavy metal interaction.
- The high viscosity of PEI-25K imposes higher requirements on onsite dilution, transportation, and dosing operations. Proper engineering practices are therefore critical for maintaining stable treatment performance.

- PEI-25K shows promising application prospects in heavy metal wastewater treatment, dyeing wastewater treatment, sludge conditioning, and membrane material modification. However, its long-term environmental behavior and adaptability to complex water quality conditions still require further investigation.
- Through future developments such as low-viscosity modification, synergistic compounding, and intelligent control technologies, PEI-based materials are expected to maintain broad application potential in high-performance water treatment systems.

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Author Biography

The author works at Guangzhou SIO New Material Co., Ltd. as a Materials Application Researcher and has long been engaged in the application research and engineering promotion of water treatment chemicals and advanced functional materials.