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Machine Learning and Adsorption Studies for Controlling Environmental Pollution: A Review Article

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ABSTRACT: Environmental pollution is a serious global problem, and removing harmful contaminants from water, air, and soil is essential for protecting human health and the environment. Adsorption is one of the most widely used techniques for pollution control because it is simple, low-cost, and highly efficient. However, traditional adsorption research is often slow, expensive, and limited by repeated trial-and-error experiments. In recent years, machine learning (ML) has become an important tool for improving adsorption studies by predicting performance, optimizing experimental conditions, and designing better, cheaper, and eco-friendly adsorbent materials. This review explains how ML tools—such as data collection, feature extraction, and model evaluation—play a key role in developing advanced adsorbents for clean energy applications and greenhouse gas capture. ML methods help optimize synthesis conditions, understand feature–property relationships, and accelerate the development of high-performance adsorbents. Examples of ML-assisted adsorption applications, including the removal of heavy metals, dyes, gases, and organic pollutants, are also discussed. Overall, combining ML with adsorption offers faster, smarter, and more affordable solutions for controlling environmental pollution.

KEYWORDS: Environmental pollution, Adsorption, Machine learning, Greenhouse gas control, clean energy, and advanced adsorbents.

I. INTRODUCTION

Adsorption is a separation technique where specific substances from a fluid are selectively captured on a solid surface (adsorbent). It's widely used in pollution control, water treatment, and industrial processes due to its effectiveness in challenging separations. The process depends on the interaction between the adsorbate and adsorbent under specific conditions[8].Adsorption happens at the boundary between a solid (adsorbent) and a fluid (gas or liquid), where specific molecules (adsorbate) attach to the solid surface. It occurs via two main mechanisms: physical adsorption (weak van der Waals forces) and chemical adsorption (strong chemical bonds)[1].Adsorption isotherms show how much adsorbate sticks to a solid surface at a constant temperature, depending on its concentration in the fluid. They help determine adsorption capacity and are essential for designing effective adsorption systems[14].

Adsorption efficiency relies on how quickly the adsorbate moves to the adsorbent surface (mass transfer) and the equilibrium between them. The process includes adsorbate transport, surface adsorption, and occasionally desorption followed by re-adsorption[16].Activated carbon is a widely used adsorbent thanks to its large surface area and excellent adsorption capacity. However, its high cost has prompted research into cheaper alternatives like fly ash[4].Adsorption is widely used in pollution control, especially for removing heavy metals from wastewater, due to its straightforward operation and high efficiency[15].Although adsorption is an effective separation method, it faces key challenges. Choosing the right adsorbent and ensuring its regeneration are vital for keeping the process both cost-effective and environmentally sustainable. Ongoing research focuses on developing new adsorbents with greater capacity and lower cost to improve overall efficiency[16].Physisorption and chemisorption are two types of adsorption that differ in interaction strength. Physisorption relies on weak van der Waals forces, while chemisorption forms strong chemical bonds. These differences affect their behavior and applications in science and industry[18].Adsorbents are important materials used to clean water and wastewater. They work by attracting and holding contaminants on their surface. Different kinds of adsorbents have been developed, such as activated carbon, metal oxide nanoparticles, clays, bio-based materials, and polymer adsorbents. Each type has its own benefits and drawbacks, so they are used for different purposes in environmental and industrial water treatment.Activated Carbon: Activated carbon is one of the most commonly used adsorbents because it has a very large surface area and can adsorb many types of pollutants, such as dyes, heavy metals, and organic chemicals. It is made from carbon-rich materials and is known for being highly effective and versatile. However, it can be expensive, which is one of its main limitations[6].

Metal Oxide Nanoparticles: Metal oxide nanoparticles, like iron, titanium, and zinc oxides, work well as adsorbents because they have a high surface area and are very reactive. They are often combined with other materials to make composite adsorbents with better performance. These nanoparticles are especially good at removing dyes and heavy metals from wastewater[2].

Clays: Clays are natural adsorbents that are easily available and inexpensive. They can adsorb a large amount of pollutants, especially organic dyes and heavy metals, which makes them useful for large-scale water treatment applications[17].

Bioadsorbents: Bioadsorbents come from natural sources like agricultural waste and biomass. They are eco-friendly and inexpensive, and they are commonly used to remove dyes and heavy metals from wastewater[4].

Polymer-based Adsorbents: Polymers and polymer composites are useful because they can be designed for specific adsorption needs. They work well for removing many types of pollutants, including dyes and heavy metals, and are often combined with other materials to improve their performance. Each adsorbent type has its own advantages, so the best choice depends on the application, cost, and environmental impact[2].Recently, composite adsorbents—made by mixing different materials—are becoming popular because they offer better adsorption efficiency and are more cost-effective.

II. ENVIRONMENTAL POLLUTION AND ADSORPTION APPLICATIONS

Adsorption is a well-known method used to reduce environmental pollution, especially for cleaning water and air. In this process, different adsorbent materials are used to trap and remove pollutants like organic compounds, heavy metals, and other harmful substances. Adsorption is popular because it is simple, low-cost, and offers many choices of adsorbent materials.

Natural Adsorbents: Natural materials such as coconut peel, orange peel, rice husk, and corn straw are widely used to remove pollutants from water because they are cheap and easily available.Agricultural waste and other biosorbents are also effective in removing heavy metals and organic pollutants[5].

Advanced Nanomaterials: Graphene-based nanomaterials, such as graphene oxide, have very high adsorption capacity because they have a large surface area and many active functional groups. They are especially good at adsorbing basic compounds and positively charged ions (cations).Three-dimensional graphene-based materials (3D GBM) work even better because they have a porous structure and can be reused. These materials are very effective for removing dyes, oils, and heavy metals from water[13].

Activated Carbon and Other Adsorbents: Activated carbon is still a top choice for controlling pollution because it can adsorb a lot of contaminants and comes in many forms like granules, pellets, and powder.Other low-cost materials such as fly ash, cellulose, and lignocellulose compounds are also used because they can remove many different pollutants effectively[11].

Industrial Applications: Adsorption is widely used in petrochemical industries to clean flue gases, treat wastewater, and remove sulfur-containing compounds. To improve the process, scientists use kinetic models and isotherms like the Langmuir and Freundlich models, which help predict and optimize adsorption efficiency[12].Although adsorption is a very effective method for pollution control, it also has some challenges. Regenerating or disposing of used adsorbents can sometimes harm the environment. The efficiency of adsorption can also change depending on the type of pollutant and operating conditions. Natural and low-cost adsorbents show good potential, but their availability and consistent performance can be a problem.Even with these challenges, continuous research and new developments in adsorbent materials and methods are improving the use of adsorption for environmental pollution management.

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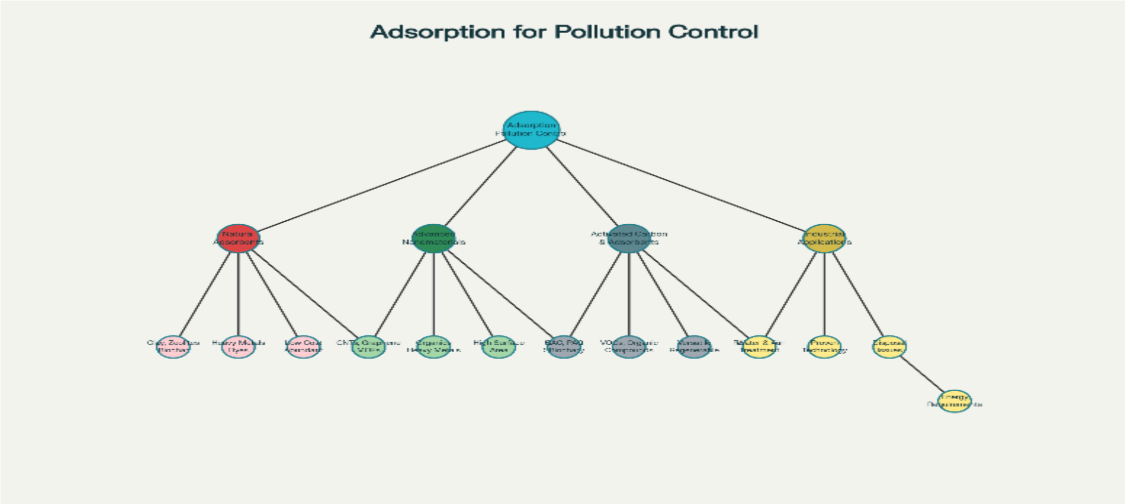

Figure 1: Adsorption for pollution control

III. MACHINE LEARNING (ML) IN ADSORPTION

Machine learning has become a powerful tool for improving adsorption processes used in pollution control. With ML, researchers can better design and develop adsorbent materials, predict how much a material can adsorb, and understand complicated adsorption mechanisms.By combining ML with adsorption technology, scientists can create more effective solutions for removing many types of pollutants, such as greenhouse gases, pharmaceuticals, antibiotics, microplastics, and heavy metals[9],[7].

ML in Adsorbent Development

Machine learning (ML) helps speed up the discovery and improvement of adsorbent materials. ML tools—like data collection, feature selection, and model testing—make it easier to design better adsorbents for clean energy uses and greenhouse gas removal. These tools help scientists understand how different material properties affect performance and also help optimize synthesis conditions. For carbon-based adsorbents, ML methods such as Gaussian process regression and artificial neural networks are used to predict how well antibiotics will be adsorbed. These ML models work better than traditional isotherm models because they can generalize more accurately and give faster, more reliable predictions[10],[3].

ML for Pharmaceutical and Microplastic Adsorption

Machine learning (ML) is used to study how pharmaceuticals get adsorbed onto materials like biochar. ML helps researchers understand the adsorption process better and improve the experimental conditions. It also works more accurately and efficiently than traditional modeling methods.

For microplastics, ML models such as random forest and support vector machines are used to predict how microplastics interact with organic pollutants in water. These models help quickly estimate the adsorption behavior, making it easier to assess contamination and improve treatment methods[3].

Heavy Metal and Air Pollution Control

Machine learning methods like support vector regression and random forest are used to predict how well different adsorbents can remove heavy metals. These models help create a general method that works for many adsorbent–metal combinations.For air pollution, ML is used to study and understand data about harmful substances in the air. This helps in detecting pollution levels quickly and taking the right steps to control and reduce air pollution[19].

IV. FUTURE PERSPECTIVE

Automation of adsorption experiments, smart sensors for real-time pollution monitoring, and ML-based optimization of industrial wastewater treatment are some of the latest advancements in environmental management. These new technologies can make water treatment faster, cheaper, and more sustainable. The use of AI and machine learning is especially important because they can predict outcomes and optimize processes better than traditional methods.

V. CONCLUSION

Machine learning is becoming an important tool in adsorption research. It improves prediction, optimization, and the design of better adsorbent materials. ML also helps in controlling environmental pollution more effectively. In the future, combining ML with nanotechnology and eco-friendly adsorbents will make adsorption processes even more efficient and sustainable.

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