ARTICLE

Particle technology in catalyst design for water treatment application: Review and bibliometric analysis

Risti Ragadhita, Asep Bayu Dani Nandiyanto*, and Ahmad Mudzakir

Universitas Pendidikan Indonesia, Bandung, Indonesia

ABSTRACT

This report aimed to examine particle technology's latest developments and potential applications in water treatment through bibliometric analysis. The results showed high interest in publications on particle technology for water treatment applications. Specifically, when it was during the period between 2021 and 2024. Research interest in particle technology was also shown in industries, concentrating on more specific topics such as energy and adsorption processes, catalyst surfaces, structures, and selectivity, wastewater and pollutant treatment, and zeolite materials. Furthermore, developed countries showed the most interest in the application of particle technology. Although the use of particles for water treatment applications has demonstrated great potential, there has not been much research on particle technology and there is still significant room for development. This study presented a new contribution in uncovering the under-explored potential applications of particle technology in specific regions or sectors and paves the way for further research in the optimization of particle technology for water quality improvement on a global scale.

*Corresponding author
Email Address: nandiyanto@upi.edu
Date received: 10 September 2024
Date revised: 11 November 2024
Date accepted: 30 December 2024
DOI: https://doi.org/10.54645/202518SupDJW-37

INTRODUCTION

Water pollution is a critical environmental problem facing the modern world, driven by increasing industrialization, population growth, and climate change (Sarker et al. 2021; Mishra 2023). Pollutants such as microorganisms, organic contaminants, and heavy metals, pose severe risks to human health, aquatic ecosystems, and biodiversity (Abubakar et al. 2024). As a result, water treatment technologies have evolved to meet the growing demand for clean and safe water. Among the various approaches to water purification, catalytic processes play a pivotal role in enhancing the efficiency and sustainability of water treatment systems (Parvulescu et al. 2021; Yu et al. 2020).

In many industrial applications, catalysts are crucial because they speed up chemical reactions without being wasted after the process (Datye and Votsmeier 2021). In water treatment, catalysts help break down pollutants, reduce toxic compounds, and transform harmful substances into less hazardous forms (Abu-Dief and Mohamed 2020; Das and Poater 2021; Lin et al. 2020). In this context, catalysts based on metals and non-metals are commonly utilized. The strong reactivity and capacity to stimulate oxidation-reduction reactions of metal catalysts, such as those based on transition metals (iron, nickel, cobalt) and noble metals (platinum, palladium), are well-known (Kumar and Kumar 2024). Non-metal catalysts, including carbon-based

KEYWORDS

Bibliometric analysis, Catalyst, Metal, Non-metal, Particle technology, Water treatment

materials (e.g. graphene, activated carbon) and organocatalysts, offer cost-effective and sustainable alternatives to metal catalysts, particularly in environmental applications (Barrio et al. 2020).

The structural design of catalysts is crucial to their effectiveness in water treatment since it directly affects their stability, reusability, and efficiency. Particle technology has emerged as a critical tool in the design and development of catalysts (Prieto et al. 2016; Luo et al. 2021; Lopez-Tejedor et al. 2018). By manipulating particle size, morphology, and surface area, researchers can create catalysts with enhanced properties tailored to specific applications (An and Somorjai 2012). For example, porous materials offer routes for improved mass transport of reactants and products, while nanoparticles provide a greater surface area-to-volume ratio, increasing the number of active sites accessible for catalytic reactions (Jose et al. 2024; Hwang et al. 2020).

New catalysts with enhanced performance in water treatment processes like adsorption, photocatalysis, and advanced oxidation processes (AOPs) have been developed due to recent developments in particle technology. These processes rely heavily on the interaction between the catalyst and the pollutant molecules, making the role of particle technology in catalyst design even more crucial (Hodges et al. 2018; Yang et al. 2020; Santhosh 206). Moreover, the environmental sustainability of these catalysts is of growing concern, prompting researchers to explore green chemistry principles and renewable resources in catalyst preparation.

The synthesis and uses of metal- and non-metal-based catalysts for water treatment have been the subject of several research. A thorough analysis incorporating current developments in particle technology with the larger framework of catalyst development is required. Furthermore, more intensive study is needed in this field, and determining existing research trends, gaps, and possibilities will help future researchers identify possible research directions. A bibliometric analysis was carried out to map research trends, important contributors, and new topics in this discipline. Some research trends can be summarized using bibliometric analysis (Al Husaeni and Nandiyanto, 2022). Therefore, this bibliometric analysis study aims to provide a comprehensive overview of recent developments in particle technology for water treatment. This analysis helps identify global trends, specific research foci, and the authors and countries that contribute most to this field.

METHOD

In this study, bibliometric analysis was used to help and reveal the research trends of a particular discipline and provide insights into the emerging field. Comprehensive instructions on how to apply bibliometric analysis can be found elsewhere (Rochman et al. 2024; Al Husaeni and Al Husaeni, 2022; Azizah et al. 2021; Al Husaeni and Nandiyanto, 2022). Figure 1 is an illustration of the stages for conducting a bibliometric analysis study, which is explained in detail as follows:

Data collection was done based on the Scopus database, in which the process involved compiling keywords relevant to the research topic such as "catalyst", "particle AND technology", and "water AND treatment" to obtain suitable literature. In this stage, data was collected by filtering the results based on parameters such as publication year which was restricted from 2019-2024, and document type was left unregulated. After that, the data obtained was exported to .RIS format for further analysis. The results of the related article documents that were successfully collected were 224 documents.
Descriptive statistics was used to examine the collected data to determine items like the number of publications annually, distribution by country, distribution by subject area, and distribution by document type. The results were presented as curves or tables to facilitate interpretation.

Network analysis was involved in mapping the relationships between various data components such as the relationships between keywords analyzed using VOSviewer software. This keyword-based network analysis was studied, especially relating to the relationships between keywords used in publications. Indeed, this helped identify co-occurring topics, trends, and emerging areas within those research topics.

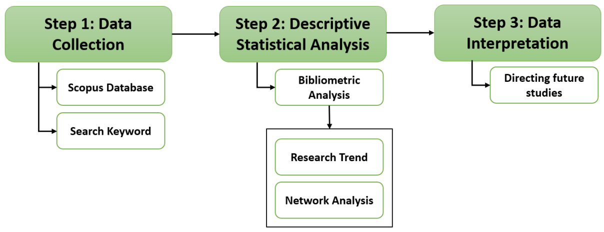

Figure 1: Step-by-step on conducting bibliometric analysis

RESULTS AND DISCUSSION

Support Literature with Qualitative Data based on Previous Studies Related to Water Pollution and Its Treatment Methods

Table 1 summarizes numerous reports about water pollution and associated remediation techniques. These results demonstrate the various strategies and tools used to address the persistent problems of water contamination and the range of efficacy of these techniques and technologies in multiple settings and geographical areas.

Table 1: Prior studies concerning water treatment

No	Title	Ref
1	Membrane bioreactor for domestic wastewater treatment: Principles, challenges, and future research directions	(Bilad 2017)
2	Changes of heavy metal concentrations in Shitalakhya river water of Bangladesh with seasons	(Kabir et al. 2020)
3	Monitoring heavy metal contamination levels and microbiological pollution in seawater of Agadir coastal zones	(Bazzi et al. 2020)
4	The comparison of electrodialysis and nanofiltration in nitrate removal from groundwater	(Touir et al. 2021)
5	Performance and energy consumption evaluation of rotating biological contactor for domestic wastewater treatment	(Waqas et al. 2021)

No	Title	Ref
6	Physico-chemical investigation of wastewater from the Sebdou-Tlemcen textile complex North-West Algeria	(Khelassi-Sefaoui et al. 2021)
7	Assessment of iron contamination in groundwater of catchment area water	(Boutebib et al. 2023)
8	Step-by-step fabrication of PVDF-TiO2 hollow fiber membrane and its application desalination of wetland saline water via pervaporation	(Mahmud et al. 2023)
9	Effect of water regime and soil maintenance mode on vegetative growth and peach tree production	(Laita et al. 2024)
10	Real time water quality monitoring system for smart city in Malaysia	(Amin et al. 2022)
11	Assessment and optimization of coagulation process in water treatment plant: A review	(Seng et al. 2023)
12	Effect of substrate and water on cultivation of Sumba seaworm (nyale) and experimental practicum design for improving critical and creative thinking skills of prospective science teacher in biology and supporting sustainable development goals (SDGs)	(Kerans et al. 2024)
13	Design-construction of a solar cell energy water pump as a clean water source for people in Sirnajaya village, Gununghalu district	(Irawan et al. 2021)
14	Design of micro-controlled swimming pool water quality monitoring system with SMS notification for educational purposes with cost analysis	(Purazo et al. 2024)
15	A step-by-step experimental procedure for water quality assessment of blue lagoon: Comparison to socio-demographic and economic profile for a teaching model	(Benito 2023)
16	Improvement of the technology of industrial wastewater treatment in the mining industry	(Qizi and Lolayevich 2023)
17	Plastic in water and its implications in human and biological systems	(Sarkingobir and Tukur 2025)
18	Education of dietary habit and drinking water quality to increase body immunity for elementary school	(Satria and Nandiyanto 2022)

Examples of the previous studies on bibliometric analysis are presented in Table 2. Bibliometric analysis can also provide data on the intellectual landscape surrounding catalyst research in water treatment, highlighting influential studies, journals, and researchers.

Table 2: Prior reports on bibliometric analysis

No	Title	Ref
1	The latest report on the advantages and disadvantages of pure biodiesel (B100) on engine performance: Literature review and bibliometric analysis	(Setiyo et al. 2021)
2	A bibliometric analysis of management bioenergy research using vosviewer application	(Soegoto et al. 2022)
3	Oil palm empty fruit bunch waste pretreatment with benzotriazolium-based ionic liquids for cellulose conversion to glucose: Experiments with computational bibliometric analysis	(Mudzakir et al. 2022)
4	Research mapping in the use of technology for fake news detection: Bibliometric analysis from 2011 to 2021	(Gunawan et al. 2022)
5	Management information systems: bibliometric analysis and its effect on decision making	(Santoso et al. 2022)
6	Sustainable Production-inventory model with multi-material, quality degradation, and probabilistic demand: From bibliometric analysis to a robust model	(Utama et al. 2023)
7	Phytochemical profile and biological activities of ethyl acetate extract of peanut (Arachis hypogaea L.) stems: In-vitro and in-silico studies with bibliometric analysis	(Sahidin et al. 2023)
8	Biomass-based supercapacitors electrodes for electrical energy storage systems activated using chemical activation method: A literature review and bibliometric analysis	(Hamidah et al. 2023)
9	Antiangiogenesis activity of Indonesian local black garlic (Allium Sativum ‘Solo): Experiments and bibliometric analysis	(Arianingrum et al. 2023)
10	Dental suction aerosol: Bibliometric analysis	(Ramadhan et al. 2022)
11	Bibliometric analysis of nano metal-organic frameworks synthesis research in medical science using VOSviewer	(Shidiq 2023)
12	Research trends from the Scopus database using keyword water hyacinth and ecosystem: A bibliometric literature review	(Nandiyanto et al. 2024)
13	Use of blockchain technology for the exchange and secure transmission of medical images in the cloud: Systematic review with bibliometric analysis	(Lizama et al. 2024)
14	Chatbot artificial intelligence as educational tools in science and engineering education: A literature review and bibliometric mapping analysis with its advantages and disadvantages	(Al Husaeni et al. 2024)
15	How technology can change educational research? Definition, factors for improving quality of education and computational bibliometric analysis	(Al Husaeni et al. 2024)
16	Effects of sustained deficit irrigation on vegetative growth and yield of plum trees under the semi-arid conditions: Experiments and review with bibliometric analysis	(Laita et al. 2024)
17	Hydroxyapatite as delivery and carrier material: Systematic literature review with bibliometric analysis	(Noviyanti et al. 2024)
18	Development of intelligent tutoring system model in the learning system of the Indonesian national armed forces completed with bibliometric analysis	(Kurniawan et al. 2024)
19	Artificial intelligence (AI)-based learning media: Definition, bibliometric, classification, and issues for enhancing creative thinking in education	(Solihat et al. 2024)
20	Bibliometric analysis of high school keyword using VOSviewer indexed by google scholar	(Al Husaeni and Nandiyanto, 2023)
21	The use of mobile learning in schools as a learning media: Bibliometric analysis	(Zafrullah and Ramadhani 2024)

Fundamental concepts of catalyst

Catalysis refers to the process in which chemical reactions are sped up by the presence of small amounts of external substances known as catalysts. While an appropriate catalyst can increase the speed of a reaction that is thermodynamically possible, it cannot alter the equilibrium position of the reaction (Nakaya and Furukawa, 2022). Catalysts are typically solid or liquid, though they can also exist as gases (Liu et al. 2022; Mondelli et al. 2020). To initiate the process of transformation into products, a complex between the reactants and the catalyst must first develop. Catalytic reactions are cyclic processes. After the reaction is complete, the reactants have been converted into products, then the next stage is the release of the catalyst, which continues to occur in a cycle. However, catalysts do not have an unlimited lifetime. Creating reaction byproducts or modifications to the catalyst's structure itself may result in catalyst deactivation. In real-world applications, used catalysts must be replaced or regenerated (Motagamwala and Dumesic, 2020; Roduner, 2014).

There are multiple types of catalysis reactions, such as: (i) homogeneous catalysis, which occurs when the catalyst and reactant have the same physical phase, as in the oxidation of toluene to benzoic acid in the presence of Co and Mn; (ii) heterogeneous catalysis, which occurs when the catalyst and reactant form distinct physical phases, as in the hydrogenation of vegetable oils on a Ni-kieselguhr catalyst (an organic catalyst) in the liquid phase and the synthesis of ammonia from elements using an iron catalyst (an inorganic catalyst) promoted in the gas phase; (iii) biocatalysis, namely when a reaction is catalyzed by enzymes or microorganisms that usually occur in biochemical reactions such as the isomerization of glucose to fructose, which is important in the production of soft drinks, using enzymes such as glucoamylase immobilized on SiO_2, and the conversion of acrylonitrile to acrylamide by corynebacteria cells trapped in polyacrylamide gels (Fukuzumi and Hong, 2014; Climent et al. 2012; Zaera, 2022).

The fundamental idea behind catalysis is that coordination bonds allow the catalyst's central atom, whose ligands are molecular species (homogeneous or biocatalysts), to form a complex with reactant molecules or nearby atoms on the surface of a solid medium (heterogeneous). Table 3 presents various catalyst materials commonly used in various industries and scientific applications.

Table 3: Common catalyst materials and their application functions

Catalyst Type	Function	Reference
Noble Metal		
Platinum (Pt)	Often used in hydrogenation reactions and automotive converter catalysts.	(Cova et al. 2019)
Palladium (Pd)	Used in dehydrogenation and hydrogenation reactions and as a catalyst in cross-coupling reactions (e.g., Suzuki coupling).	(Navlani-García et al. 2017)
Ruthenium (Ru)	Used in olefin metathesis reactions	(Kajetanowicz and Grela 2021)
Rhodium (Rh)	Used in catalysts in the chemical and automotive industries.	(Shelef and Graham 1994)
Aurum (Au)	Used as a nanocatalyst in carbon monoxide oxidation reactions and other organic reactions.	(Dey and Mehta 2020)
Transition Metals		
Nickel (Ni)	Utilized in the hydrogenation process	(Galhardo et al. 2021)
Cobalt (Co)	Utilized in Fischer-Tropsch catalysts, which convert gasses into fuels.	(Adeleke et al. 2020)
Copper (Cu)	Extensively employed in oxidation and reduction reaction catalysis.	(Popović et al. 2020)
Zinc (Zn)	Utilized to create methanol from carbon dioxide and hydrogen.	(Portha et al. 2017)
Tungsten (W)	Utilized in numerous heterogeneous and photocatalytic applications.	(Kumar and Rao 2015)
Metal Oxide		
Titanium Dioxide (TiO_2)	Photocatalysts are used in water and air treatment.	(Cha et al. 2019)
Zirconium Dioxide (ZrO_2)	Used in various heterogeneous catalytic reactions.	(Ibrahim et al. 2019)
Silica (SiO_2)	Generally used as a support material or matrix in heterogeneous catalysts.	(Liang et al. 2017)
Alumina (Al_2O_3)	Used as a support or as a catalyst in various reactions.	(Xu et al. 2016)
Ceria (CeO_2)	Used in oxidation and reduction reactions, especially in catalytic converters.	(Sendilvelan et al. 2017)
Zeolite		
Zeolit ZSM-5	Often used in petroleum refining and catalysis of the reaction of methanol to gasoline.	(Ghashghaee et al. 2019)
Zeolit Y	Used in the cracking process in petroleum processing.	(García et al. 2015)
Zeolit Beta	Widely used in organic reactions involving alkylation and isomerization.	(Fu et al. 2018)
Perovskite		
$LaMnO_3$ (Lantanum Manganite)	Utilized in oxygen batteries and fuel cells	(Miao et al. 2020)
$SrTiO_3$ (Strontium Titanate)	Used in photocatalysis applications and hydrogen production	(Phoon et al. 2019)
Carbon-based Catalyst		
Activated Carbon	Used as a support material or catalyst in water and air treatment.	(Reza et al. 2020)

Catalyst Type	Function	Reference
Graphene	Used in electrocatalysis and photocatalysis, especially in renewable energy applications.	(Khan et al. 2019)

Wastewater treatment is an important aspect of maintaining environmental sustainability and public health, considering the negative impacts that waste can have on the ecosystem. Adsorption, or the process of attaching contaminants from the liquid phase to the surface of a solid, is one technique that is frequently employed for wastewater treatment. Catalysts are essential to this technique because they speed up the adsorption rate and improve process efficiency. Substances known as catalysts can speed up reactions without permanently altering their chemical composition. Its use in wastewater adsorption aims to accelerate the process of binding pollutants by adsorbents, which are solid materials that absorb pollutants called adsorbates (Ragadhita and Nandiyanto, 2021; Nandasiri et al. 2016).

There are two primary types of adsorption processes: chemical (chemisorption) and physical (physical) adsorption. Whereas chemisorption entails the creation of strong chemical connections between the adsorbent and adsorbate, physical adsorption is accomplished by weak intermolecular forces such as van der Waals forces. Chemical adsorption is frequently preferred in wastewater treatment due to its more stable and effective nature. However, in both physical and chemical adsorption, the presence of a catalyst can increase the effectiveness of the treatment by increasing the surface capacity of the adsorbent, accelerating the reaction, and helping the adsorbent become more selective in absorbing certain pollutants (Ragadhita and Nandiyanto, 2021; Ragadhita et al. 2023; Nandiyanto et al. 2023).

Heterogeneous and homogeneous catalysts are the two categories of catalysts utilized in the wastewater adsorption process. Solid materials like metal oxides, activated carbon, or nanomaterials are typically the basis of heterogeneous catalysts, whereas homogeneous catalysts are typically in solution form and dissolve with the waste. Due to their huge surface areas and high adsorption capacities, nanomaterials like activated carbon and iron oxide nanoparticles are frequently selected. For instance, because of its high porosity, which enables the absorption of a variety of organic and inorganic contaminants, activated carbon is one of the most widely utilized adsorbents. When combined with metal or nanomaterial-based catalysts, the adsorption capacity of activated carbon can be significantly increased, making it more effective in capturing hazardous pollutants such as heavy metals, organic compounds, and other toxic substances (Jain et al. 2018; Gutierrez et al. 2018).

The role of catalysts in the adsorption process is not only limited to increasing the capacity of the adsorbent but also helps in the regeneration process of the adsorbent. Adsorbent regeneration is the process of releasing pollutants that have been absorbed so that the adsorbent can be reused. In some cases, the catalyst functions to help release pollutants from the surface of the adsorbent after saturation, so that the adsorbent can be reactivated for the next wastewater treatment cycle. This helps lower operating costs, reduce the use of new materials, and minimize the solid waste generated.

The use of catalysts in wastewater treatment through adsorption has many advantages, including increasing the speed of the treatment process, reducing energy consumption, and improving the overall efficiency of the treatment system. By accelerating the reaction rate, catalysts allow the treatment process to take place faster even under milder operating conditions, such as low temperature and pressure, which in turn reduces energy costs. On the other hand, catalysts also allow the adsorbent to be used in longer cycles through the regeneration process, which reduces material costs (Rashid et al. 2021; Burakov et al. 2018).

However, the challenges in the use of catalysts cannot be ignored. The high price of catalyst materials, particularly those based on noble metals or nanomaterials, is one of the primary obstacles. Nanotechnology-based catalysts, although efficient, often require high production costs, so further development is still needed to create more economical yet effective catalysts. In addition, catalyst stability is also an important concern, especially when used in the treatment of waste containing aggressive pollutants. Some catalysts can degrade during the process, which can reduce the treatment efficiency in the long term.

Catalyst applications in wastewater treatment have been applied in various industrial sectors, including textile, pharmaceutical, and metal processing industries, where organic pollutants such as dyes, pesticides, and heavy metals are often major problems. In domestic wastewater treatment, activated carbon combined with catalysts is also used to remove organic compounds and microorganisms, thus ensuring the safety of water discharged into the environment (Ismail et al. 2019). Overall, catalysts play a crucial role in improving the effectiveness of adsorption methods for wastewater treatment. By facilitating the binding process of pollutants, accelerating reaction rates, and enabling the regeneration of adsorbents, catalysts help make wastewater treatment processes more efficient, environmentally friendly, and sustainable. In the future, the development of cheaper, more stable, and environmentally friendly catalysts will be an important focus to expand the application of this method on a larger scale.

Types of catalysts for adsorption uses

In the adsorption process for wastewater treatment, numerous categories of catalysts are used to improve the adsorption performance by accelerating the reaction rate and increasing the capacity of the adsorbent. These catalysts are generally classified based on their material composition and working mechanism, which can be heterogeneous or homogeneous catalysts. Each type of catalyst has its advantages and disadvantages depending on the type of pollutant and the operational conditions faced. Table 4 summarizes the types of catalysts used in the adsorption process.

Table 4: Adsorbent characteristics for water treatment purposes

Material	Characteristics	Application	Advantages	Disadvantages
Activated Carbon	Activated carbon can have a specific surface area of 500–1500 m^2/g and has a high porosity. Through chemical or	In addition to eliminating tastes and odors from water, activated carbon is efficient at adsorbing	After regeneration, activated carbon can be used again through chemical or thermal procedures, in addition	One of the drawbacks is its relatively high cost, especially for high-quality activated carbon. In addition,

Material	Characteristics	Application	Advantages	Disadvantages
	physical activation methods, it can be made from a variety of materials, including biomass, wood, coal, and coconut shells.	organic pollutants such as dyes, pesticides, and phenolic chemicals. In certain instances, heavy metals including cadmium, arsenic, and mercury are also adsorbed using activated carbon.	to its high adsorption capability.	repeated regeneration can reduce the adsorption capacity.
Zeolite	Zeolites have a three-dimensional framework made of SiO_4 and AlO_4 tetrahedrons, with cavities that can accommodate water molecules or metal ions. Zeolites are also known for their ability to exchange cations, such as Na^+, K^+, and Ca^{2+}, with toxic metal ions such as Pb^{2+}, Cd^{2+}, and Zn^{2+}.	Zeolites are excellent in treating organic pollutants like amines and ammonia, as well as industrial waste that contains heavy metals. Additionally, zeolites are employed to remove phosphate and nitrogen from wastewater.	Zeolite has good thermal and chemical stability and high ion exchange capacity, making it suitable for adsorption processes in harsh environments.	Zeolite's primary drawback is that it is more expensive than other materials, including activated carbon. Furthermore, with multiple regenerations, its ion exchange characteristics may deteriorate.
Metal Oxide	One of the special chemical characteristics of metal oxides like FeO_3, ZnO, and TiO_2 is their capacity to interact with contaminants through ion exchange or redox processes. Metal oxides' increased surface area also improves their capacity to absorb both organic and inorganic contaminants.	Heavy metals including arsenic, lead, and mercury are frequently removed from wastewater using metal oxide catalysts. For instance, under UV light, titanium oxide (TiO_2) is a highly efficient photocatalyst in the breakdown of organic contaminants.	Metal oxide catalysts have strong adsorption capabilities and, in some cases, can break down pollutants into less harmful compounds through photocatalytic reactions.	The use of metal oxides sometimes requires UV light or more special reaction conditions (e.g., acidic environments), which increases operational costs. In addition, metal oxide nanoparticles can undergo agglomeration, which reduces their effective surface area.
Nanomaterial	Pollutant molecules can interact directly with nanoparticles like FeO_4, ZnO, or Ag via hydrogen bonds, covalent bonds, or electrostatic forces. Surface modification, such as coating with specific functional groups, can also improve the catalytic capabilities of nanomaterials.	With the use of an external magnetic field, magnetic nanoparticles—like FeO_4—that are employed to adsorb organic contaminants and heavy metals can be readily extracted from wastewater. Organic contaminants, including dyes and insecticides, with small to large molecules, are adsorbed onto graphene and carbon nanotubes (CNTs).	Nanomaterials' huge surface area and small particle size give them a very high adsorption capacity. Further benefits in terms of ease of separation from wastewater are provided by some nanomaterials, such as magnetic nanoparticles.	The primary obstacles to using nanomaterials are their comparatively high cost and the possibility of agglomeration of nanoparticles, which lowers the surface area available for adsorption. Furthermore, improper handling of nanoparticles can result in environmental issues.
Polymer-based	Polymer resins can be functionalized with groups such as -COOH, $-SO_3H$, or $-NH_2$ to attract pollutants through ion exchange or chemical bonding. These polymers can be in solid or gel form with adjustable porosity to	Heavy metal ions like copper, zinc, and nickel, as well as some organic contaminants, are frequently removed using polymer catalysts. Additionally, dyes and other hazardous organic	Polymers are ideal for a variety of applications due to their considerable chemical modification flexibility. They also fare well in challenging operational environments.	Although polymers can be produced in various forms, some polymer resins may have lower adsorption capacity compared to porous materials such as activated carbon or zeolites. In addition, polymer regeneration is

Material	Characteristics	Application	Advantages	Disadvantages
	control the rate of diffusion of pollutant molecules into the polymer matrix.	compounds can be adsorbed by polymers.		not always easy and may require complex chemical processes.
Bioadsorbent	The natural functional groups found in bioadsorbents, such as carboxyl, hydroxyl, and amino, enable interaction with a variety of contaminants through complexation or ion exchange processes.	Heavy metals including lead, cadmium, and arsenic are removed from industrial effluent along with organic contaminants using bioadsorbents. Derivable from crab shells called chitin, chitosan is highly efficient in adsorbing metal ions.	Bioadsorbent is a cheap, environmentally friendly material that is easily obtained from abundant sources. This material can also be naturally degraded without leaving harmful residues.	Bioadsorbents have limitations in terms of adsorption capacity, especially compared to synthetic materials. In addition, regeneration of adsorbents can be challenging due to their resistance to harsh chemical or physical processes.

Properties of the catalyst's physical and chemical nature for adsorption applications

In the adsorption process, the physical and chemical properties of the catalyst are crucial in determining how well and efficiently wastewater is treated. The catalyst needs specific physical and chemical characteristics that maximize the interaction between the adsorbent and adsorbate to maximize adsorption efficacy. The following is a detailed explanation of the physical characteristics of the catalyst that support the optimization of adsorption performance:

(i) High specific surface area. In adsorption, surface area is one of the most crucial physical parameters. High surface area catalysts have more active sites available for binding pollutants. The adsorption capacity of materials having micro or nanopores, like zeolites or activated carbon, is increased since they often have large surface areas (Jawad et al. 2021).

(ii) Pore size. Pollutant molecules that can be adsorbed vary in size and type depending on the catalyst's pore size. Catalysts with the right pore size distribution (micropores, mesopores, or macropores) will be more effective in adsorbing pollutant molecules of different sizes. Micropores (<2 nm) are ideal for small molecules, while mesopores (2-50 nm) and macropores (>50 nm) are more suitable for larger molecules. Proper pores also increase the diffusion of pollutant molecules into the catalyst structure, accelerating the adsorption process (Jawad et al. 2021; He et al. 2021).

(iii) Crystal structure. Catalysts with a regular crystal structure (such as zeolites) often have more distinct and defined active sites. This structure helps to tailor the interactions between pollutants and the catalyst surface. Metal oxide-based catalysts, for example, often have a specific crystalline structure that favors adsorption through specific interactions with pollutant molecules (Jin et al. 2020).

(iv) Particle size. There are more active sites on the surface of smaller catalyst particles that can be utilized to adsorb contaminants because of their larger surface area to volume ratio. However, too small a particle size can cause problems in the management and separation of the catalyst from the wastewater after the process is complete (Roy et al. 2021)

Chemical characteristics include:

(i) Chemical active site. Pollutants can interact with the catalyst in chemically active sites, which are reactive centers on the catalyst surface. Catalysts with a highly chemically active site, such as oxygen-containing functional groups (carboxyl, hydroxyl) or transition metal atoms, are more effective in binding pollutant molecules. In metal-based catalysts, metal atoms often serve as active sites that interact with pollutant molecules through chemisorption or complex formation (Nacalon et al. 2017).

(ii) Surface acidity and basicity. The acidity or basicity of the catalyst surface greatly influences its ability to adsorb pollutants. Acid catalysts, for example, are more effective in attracting and binding basic pollutant molecules or certain metal ions. Conversely, basic catalysts are more suitable for adsorbing acidic pollutants or anions. The acid-base properties of the surface can be adjusted by adding certain functional groups or by changing the structure of the catalyst material (Le Leuch and Bandosz, 2007).

(iii) Chemical affinity for adsorbate. The catalyst must have a high chemical affinity for the pollutant to be adsorbed. This affinity can come from electrostatic forces, hydrogen bonds, van der Waals interactions, or even covalent bond formation. For example, carbon-based catalysts often have a high affinity for organic pollutants through hydrophobic interactions and van der Waals dispersion forces. Meanwhile, transition metal-based catalysts can interact strongly with heavy metal ions through complex formation (Knappe, 2006; Wang et al. 2020).

(iv) Surface modification. Catalysts can be chemically modified to add certain functional groups to their surfaces, such as -OH, -COOH, or $-NH_2$, which can increase the adsorption affinity for certain types of pollutants. This modification can also increase the hydrophilic or hydrophobic properties of the catalyst, allowing the catalyst to be more selective in adsorbing organic or inorganic compounds (Rodrigues et al. 2011).

(v) Chemically stable. Catalysts used in wastewater treatment must be resistant to chemical reactions that can damage them, such as oxidation, dissolution, or degradation by aggressive pollutants. Catalysts that are not chemically stable will lose their effectiveness over time, so it is important to choose a catalyst with high chemical stability (Yang et al. 2020).

To optimize the adsorption performance, the right combination of physical and chemical characteristics of the catalyst is essential. High surface area, appropriate pore size, and optimal chemical active sites should be combined with high chemical affinity and good stability. For example, activated carbon-based catalysts modified with oxygen groups on their surfaces can improve the adsorption performance of organic pollutants through specific chemical interactions, while their large surface areas provide many active sites for pollutant adsorption.

The use of nanomaterials, such as metal oxide nanoparticles, is also gaining popularity due to their unique physical and chemical properties, such as small particle size, very large surface area, and electronic properties that allow strong chemical interactions with pollutant molecules. These nanoparticles can also often be surface-modified to improve adsorption selectivity and efficiency. By understanding and managing the physical and chemical characteristics of catalysts, wastewater treatment through adsorption can be optimized to produce faster, more efficient, and more environmentally friendly processes.

Controlled hierarchical catalyst particles with enhanced performances

The control of catalyst particle morphology seems to be possible by manipulating several structural and synthetic parameters related to three main aspects, namely unique morphology, porous structure, and hierarchical structure. A schematic illustration of catalysts with different particle designs is shown in Figure 2. A detailed explanation of how to control the morphology of catalyst particles based on the various types of structures shown is explained as follows.

(i) Unique morphology. Examples of morphology included in this category are nanoparticles, nanowires, nanotriangles, and nanocubes can be controlled through modification of temperature, precursor concentration, reaction time, and the use of surfactants or capping agents. Detailed explanations related to particle control in this type are explained as follows.
- Nanoparticle: By varying the precursor content, temperature, and reaction time as well as by adding surfactants or capping agents, nanoparticle morphology can be controlled. Surfactants prevent agglomeration, regulate particle development, and provide consistent particle sizes (Nguyen, 2013).
- Nanowire: Nanowire formation is usually controlled by solvothermal or hydrothermal methods by controlling temperature, solution type, and additives that can affect unidimensional growth. Chemical vapor deposition (CVD) processes are also often used to direct nanowire formation by controlling pressure and temperature (Singh, 2010).
- Nanotriangle: The use of surfactants or anisotropic stabilizers can help form particles with triangular (nanotriangle) geometry. Chemical environmental conditions, such as pH and additional ions, play a role in controlling the growth direction (Sajanlal et al. 2011).
- Nanocube: By varying the proportion of metal precursors and capping agents that restrict crystal development, nanocubes can be created. Low-temperature conditions are often used to maintain the cubic shape during synthesis (Yang et al. 2020).

(ii) Porous structure. Examples of morphologies included in this category are nanoporous, mesoporous, hollow, and nanotubes achieved by using pore-forming agents or through leaching techniques. The pores in the mesoporous structure can be adjusted by controlling the template size and reaction conditions such as temperature and aging time. To produce hollow structures, the core-shell method is used, where the core is removed to form a cavity, while nanotubes can be made through tubular template-based techniques. A detailed explanation of particle control in this type is explained as follows.
- Nanoporous: Nanoporous structures are usually formed through leaching techniques or template-assisted synthesis processes, where porogen's (pore-producing) materials such as polymers are used to form cavities in the material. Variations in pore size can be achieved by adjusting the size and shape of the template and the heating conditions (calorimetry) (Pavlenko et al. 2022; Kaplin et al. 2020).
- Mesoporous: Mesoporous structures with medium-sized pores (2-50 nm) are often created using templating agents such as surfactants or polymers. Pore size control is achieved by changing the surfactant concentration, temperature, and aging and drying time (Pavlenko et al. 2022; Kaplin et al. 2020).
- Hollow: Hollow structures can be obtained by a "core-shell" strategy in which the particle core is removed after synthesis, leaving a hollow structure. Solvothermal processes and the use of templates are two common methods for forming hollow particles (Wang et al. 2016; Zhang et al. 2009).
- Nanotube: The formation of nanotubes involves a method similar to nanowires but with the addition of a precursor agent or tubular mold. Temperature, pressure, and precursor material selection parameters are important for forming a uniform nanotube structure.

(iii) Hierarchical structure. Examples of morphologies included in this category are nanochain, onion-like, core-shell, and encapsulated produced by aggregation, layered deposition, or core-shell growth approaches. Nanochains are formed by controlled aggregation of nanoparticles with a binding agent, while core-shell structures are produced by deposition of a thin layer on the particle core through seed-mediated growth or electrostatic techniques. Onion-like structures are formed by layered layering through repeated deposition, and encapsulated structures are made by sol-gel techniques involving coating the core with a protective material. A detailed explanation of particle control in these types is explained as follows.

- Nanochain: Nanochain formation involves controlled aggregation of nanoparticles. The addition of binding agents and adjustment of the settling or dissolution rate are essential to control the aggregation process (Shiers et al. 2012).
- Onion-like: Onion-like structures are formed from layered layers of metal material, usually through repeated deposition techniques or layer-by-layer growth using sputtering methods or CVD techniques (Hovsepian and Ehiasarian, 2019).
- Core-shell: The core-shell structure consists of a core and a distinct outer layer. Control of core-shell growth can be achieved by the deposition of a thin layer on the core of the particle, through electrostatic techniques or highly controlled chemical processes, such as seed-mediated growth methods (Gawande et al. 2015; Mélinon et al. 2014).
- Encapsulated: Encapsulation involves a core particle surrounded by a protective layer. Sol-gel or polymerization techniques can be used to grow the protective layer, with control of the capsule thickness by adjusting the ratio of the constituents and process conditions (Sadabadi et al. 2022).

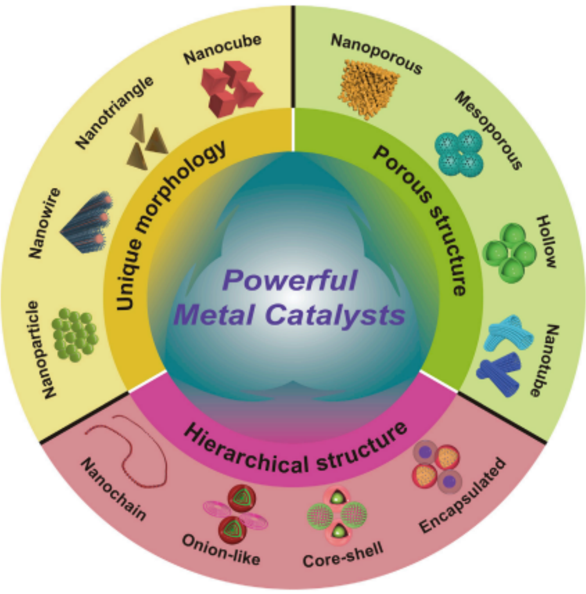

Figure 2: Catalyst schematic illustration with particle design (Wang et al. 2019)

Research trend

Figure 3 shows the research trends related to catalysts, particle technology, and water treatment from 2019-2024. Based on Figure 3, there are three important periods, including:

(i) Periode 2019-2021. In 2019, the publication of documents related to this research topic consisted of 30 documents. However, a decline in the number of publications occurred in 2020 and 2021, reaching a low of around 26 documents in 2021. This decline could be due to various factors, including a possible shift in research focus or restrictions in the research process due to the global pandemic that occurred during this period.

(ii) Periode 2021-2022. During this period, a spike in the number of publications occurred in 2022 with an almost two-fold increase from 26 documents in 2021 to more than 45 documents. This increase is indicated due to a sharp increase in interest in research in this field, for example, due to increased global attention to environmental issues, the need for more efficient technologies in water treatment, and the development of new methods in the use of catalysts and particle technology.

(iii) Periode 2022-2024. During this period, the number of published documents continued to increase until 2024. Indeed, the increase in the number of documents is more moderate than in 2020. However, this still shows that interest in the topics of catalysts, particle technology, and water treatment remains stable and continues to grow. New technological developments, improvements in the efficiency of water treatment processes, as well as the industry's need for more environmentally friendly solutions are likely driving this increase.

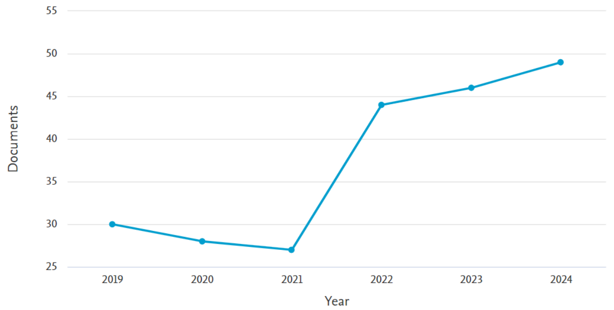

Figure 3: Number of publications related to catalyst, particle technology, and water treatment based on the Scopus database

Leading contribution country

Figure 4 shows the contributions of leading countries in catalyst, particle technology, and water treatment research throughout 2019-2024. The top four countries contributing the most to research on these topics are China, India, Saudi Arabia, and the United States. China dominated the research in this area with the highest number of publications (more than 120 documents), indicating that China has a high interest in innovations in particle technology and catalyst applications for water treatment, which may also be in line with their efforts to address environmental pollution and clean water needs in their vast territory. The second position is occupied by India with about 30 documents published. India is active in research in this area as it aligns with its efforts to address the significant clean water issues occurring in the country. Saudi Arabia and the United States occupy the third and fourth positions with an almost equal number of published documents, around 15 to 20 documents. Saudi Arabia's active participation may be driven by the need for water treatment technologies in the arid region, while the United States has long been a global scientific research center that continues to innovate in water treatment technologies. Other countries such as Iran, Malaysia, South Korea, Australia, Japan, and the Czech Republic also made significant contributions to this research, although the number of documents was less than the top countries. This shows that catalysts, particle technology, and water treatment are issues that receive global attention in both developed and developing countries.

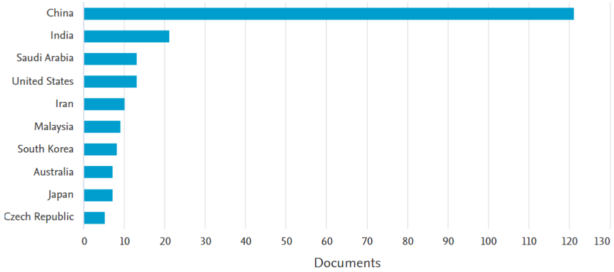

Figure 4: The most contributing countries

Document by type and subject area

Figure 5 shows the number of related research publications by document type. Scientific articles dominate the publications in this area with a percentage of 78.1%, indicating that the majority of research related to this topic is published in the form of journal articles that focus on experimental research results and innovations. Reviews came in second with 15.2%. This type of document serves to summarize the latest developments and provide a comprehensive view of the research trends and innovations that have been made in the field of particle technology for water treatment. This is important for researchers who want to understand the existing research landscape and seek new directions for further study. Conference papers account for 3.6% of the total, indicating a significant contribution from papers presented at academic or professional conferences, where discussion and sharing of new ideas takes place. Book chapters account for about 1.8%, followed by Conference Reviews (0.9%) and Notes (0.4%), which make up the smallest share of publications. Despite their small number, these contributions are still relevant as they present more specific or detailed topics in a broader context.

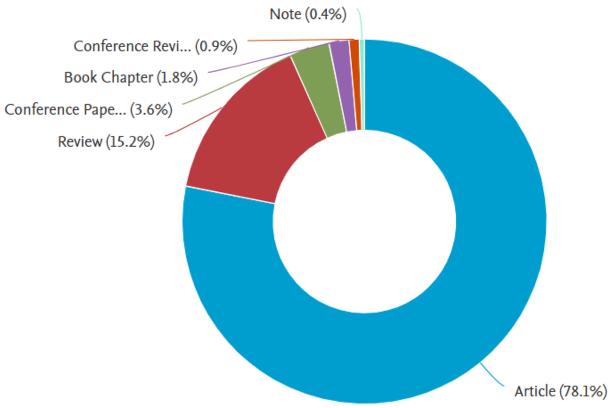

Figure 5: Publication types in the field of adsorption research

Regarding research fields as shown in Figure 6, there are three dominant research fields for this topic, namely Environmental Science, Chemistry, and Chemical Engineering. These five research areas dominate because the proportion of documents related to this research topic is more than 10% due to the following reasons:

(i) Environmental science (25.9%). This subject area dominates other subject areas because the topic of water treatment is directly related to efforts to mitigate environmental pollution, waste treatment, and conservation of water resources. Therefore, research in this area is growing rapidly due to the increasing global awareness of environmental issues and the need for solutions to the water crisis.

(ii) Chemistry (16.5%). Chemistry is the underlying field of science related to understanding catalyst reactions and particle interactions on a molecular scale. This chemistry-based approach is needed to develop new catalysts and improve the efficiency of chemical reactions in water treatment. Therefore, publications in this field are significant as advances in chemistry support technological developments for more effective water treatment.

(iii) Chemical engineering (14.6%). Chemical engineering focuses on the optimization of industrial processes including the use of catalysts and particle technology in water treatment processes, larger-scale production, and industrial waste treatment on an industrial scale. Therefore, publications from chemical engineering reflect the industrialization efforts of catalyst and particle-based solutions.

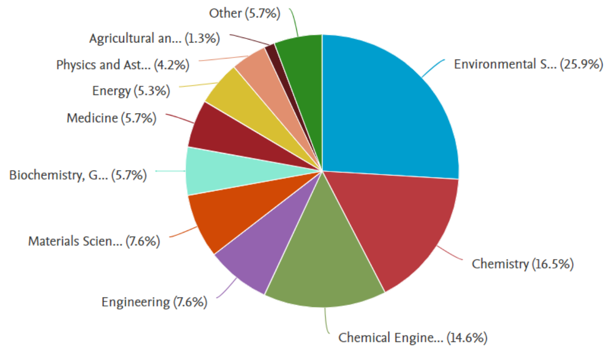

Figure 6: Distribution of research documents by subject area

Visualization bibliometric analysis on catalyst development

This study presents the qualitative analysis results of bibliometric analysis that provide a clearer understanding of the knowledge structure in the field of particle and catalyst technology in water treatment applications. By mapping the relationships between keywords, the main focus of research, recent innovations, and themes that require further exploration can be identified. Figure 7 is the result of network visualization where the visualization shows a total of 80 items (keywords) divided into 5 main clusters. Each cluster is marked with a different color, indicating groups of keywords that statistically frequently appear together in related research documents. There are a total of 564 links (keyword relationships) with an overall relationship strength of 733, which illustrates the strong interaction between keywords in each cluster. The green cluster focuses on the theme of water treatment, with keywords such as "wastewater", "pollutant", "adsorption technology", and "dye". This shows the importance of catalyst technology in wastewater and pollution treatment, as well as the adsorption process in removing pollutants. The red cluster focuses on the theme of chemical reactions and catalyst surfaces, with keywords such as "reaction", "catalytic activity", "adsorption energy", and "active site". This shows the important role of effective catalyst design in enhancing chemical reactions for water treatment. The blue cluster relates to the catalyst surface, including keywords such as “catalyst surface”, “oxygen species”, and “oxygen vacancy”. The catalyst surface is a critical aspect in improving the efficiency of chemical reactions used in water treatment. The purple cluster highlights recent advances in catalyst technology, including topics such as “conversion”, “catalytic conversion”, and “critical review”. This reflects the current trends in catalyst development to address challenges faced in water treatment. The lines connecting the clusters show the interactions between different themes. For example, the relationship between "adsorption process" and "water" shows the importance of adsorption technology in the context of water treatment. The visualization results reveal that: (i) the main themes in research on particle technology and catalyst design for water treatment, including pollutant adsorption, adsorption energy, and catalyst structure; (ii) recent innovations focusing on catalytic conversion and the development of new materials such as zeolites to improve water treatment efficiency; and (iii) close relationships between topics such as chemical reactions, adsorption kinetics, and catalyst surface design, all of which play a role in improving the effectiveness of catalyst technology for water treatment applications. From the bibliometric network visualization, underexplored areas can be identified based on several factors, such as smaller node (circle) size, thinner line thickness, and keyword positions that are more separated from the main cluster centers. This indicates that the keywords or topics have lower relatedness or appear less frequently in the analyzed literature. Based on the figure, here are some areas that appear to be underexplored, including:

(i) Adsorption kinetic;
(ii) Catalyst surface and oxygen vacancy;
(iii) Specific reactions related to flue gas and volatile organic compounds (VOC)
(iv) Special technologies and materials (zeolite);
(v) Ion interaction and water treatment process (ion adsorption)

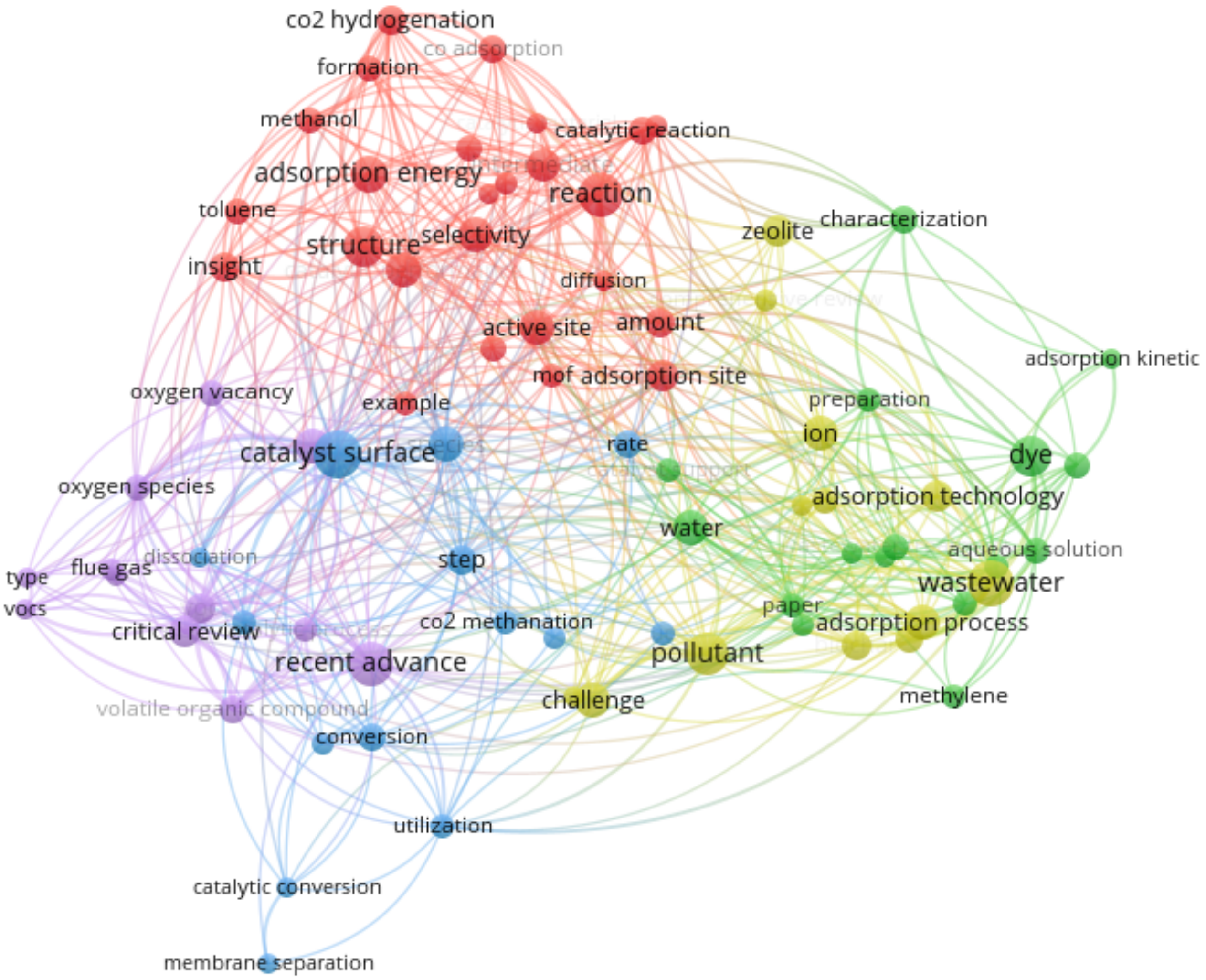

Figure 7: Network visualization related to particle technology, catalyst, and water treatment

The bibliometric overlay visualization as shown in Figure 8 provides additional information on research developments over time. The color of the nodes (circles) indicates the average year of publication of research related to certain topics. More yellow colors indicate that research on the topic is more recent (around 2020-2021), while dark blue or purple indicate older research (before 2020). Here is a comprehensive analysis based on this visualization:

(i) Newer and emerging topics (2020-2021)

- "Adsorption kinetics": This is an emerging area in recent research. Although the node size is relatively small, the yellow color indicates that this topic is starting to receive attention in more recent research. Adsorption kinetics is important for understanding the rate and efficiency of water treatment using catalysts.
- "Adsorption technology" and "adsorption process": These two topics have a relatively yellow color, indicating that adsorption technology is still an active research focus until 2020-2021. The development of more effective and efficient adsorption methods continues to be a trend.
- "Zeolite": This keyword is also shown in yellow, indicating that zeolite materials are being studied more intensively in the

development of catalyst technologies for water treatment. Zeolite is a material known for its good adsorption properties, and recent research may focus on modifying this material or improving its performance.

- "Ions" and "ion adsorption": This topic has also gained attention in recent years, indicating an increasing interest in dealing with ion-based pollutants, such as heavy metals, in wastewater. This could be an indicator that specific challenges in dealing with ions in wastewater are being addressed by researchers

(ii) Older and mature topics (before 2020)

- "Catalyst surface" and "reaction": these nodes are colored purple to dark blue, indicating that the catalyst surface and the reactions occurring on the catalyst surface are topics that understanding catalytic interactions and develop more efficient materials.
- "CO_2 hydrogenation" and "CO_2 methanation": These topics also seem to have been in the research focus for a long time and perhaps are now receiving less attention. CO_2 hydrogenation and methanation reactions are important in the context of catalysis, but they seem to have become mature fields and are no longer the latest trend.

(iii) "Oxygen vacancies": Oxygen vacancies on the catalyst surface are also a more mature area of research, although they are very important in understanding the mechanism of action of oxidation or reduction catalysts. Previous research may have focused heavily on this topic.

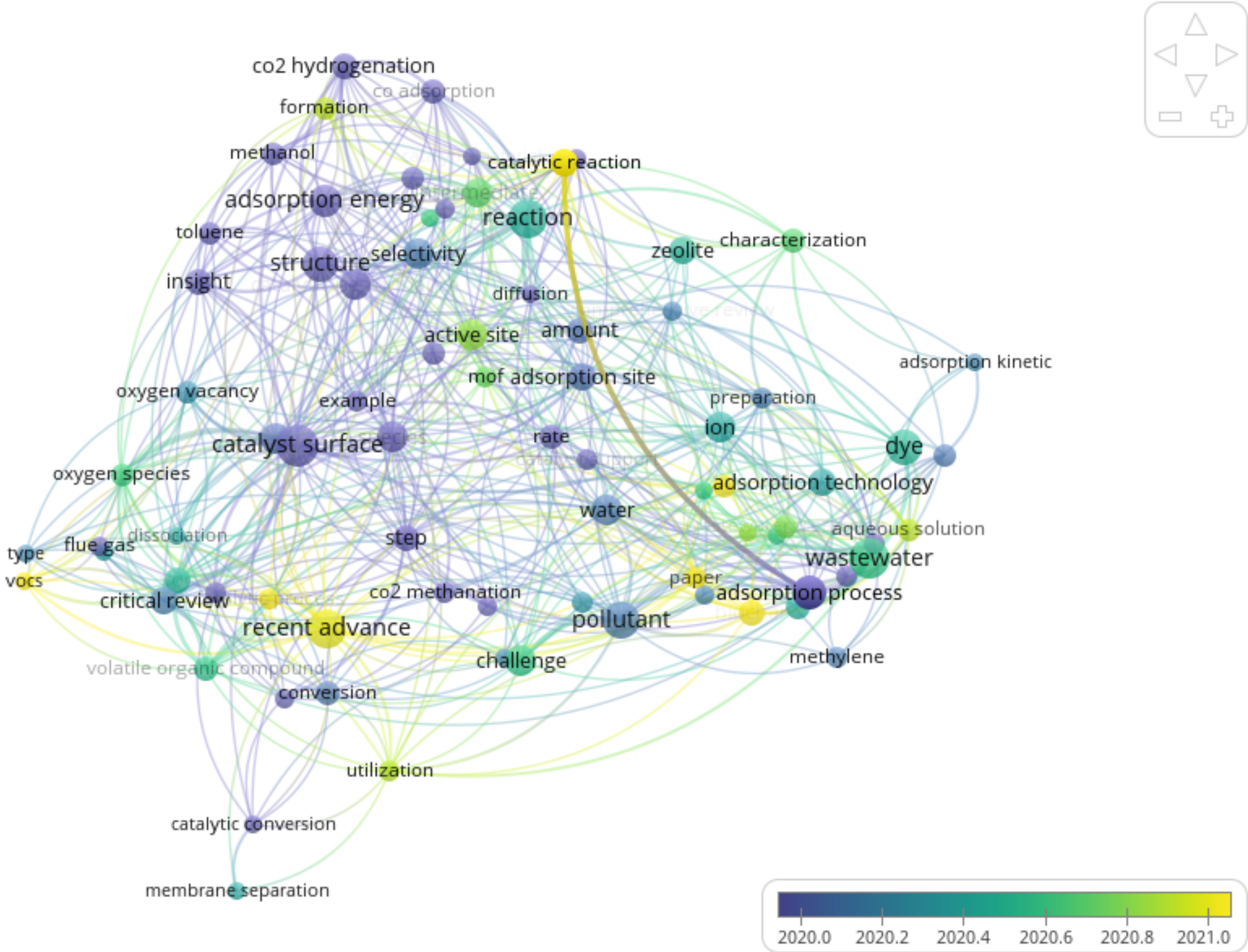

Figure 8: Overlay visualization related to particle technology, catalyst, and water treatment

CONCLUSION

This study highlights the importance of catalysts in accelerating chemical reactions without undergoing permanent changes, especially in water treatment applications. The basic concept of catalysts involves providing an active surface that supports the interaction of reactant molecules, lowering the activation energy, and accelerating the reaction process. Some common types of catalysts used for adsorption include heterogeneous catalysts, such as zeolites, activated carbons, and metal-organic frameworks (MOFs), which are known for their high adsorption capacities, as well as homogeneous and hybrid catalysts that offer efficiency in some specific applications. The physical and chemical characteristics of the catalyst, such as surface area, pore size, particle distribution, and chemical properties such as adsorption energy, greatly influence the performance of the catalyst in adsorbing pollutants from water. Controlling the hierarchy of catalyst particles, through engineering techniques for more ordered and porous structures, has been shown to improve the adsorption efficiency and reactivity of catalysts in wastewater treatment processes. From the bibliometric analysis, recent research trends highlight the increasing interest in the topics of adsorption kinetics, ion adsorption technologies, and the development of materials such as zeolites that are increasingly being studied for more innovative applications in water treatment.

ACKNOWLEDGMENT

The authors would like to express their deepest gratitude to the Ministry of Education, Culture, Research and Technology (Kemendikbud-Ristek) for providing research funding through the Fundamental Research program. This financial support was instrumental in the implementation of this research and enabled us to achieve the expected results.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

CONTRIBUTIONS OF INDIVIDUAL AUTHORS

Risti Ragadhita carried out the bibliometric analysis, compiled relevant research data, and wrote the initial draft of the manuscript. Asep Bayu Dani Nandiyanto designed the research framework, supervised the project, provided insights on particle technology and catalyst design, and critically reviewed and edited the manuscript. Ahmad Mudzakir contributed to refining the research methodology, offered valuable feedback on the analysis, and assisted in interpreting the results. All authors read and approved the final version of the manuscript.

REFERENCES

Abubakar MY, Ahmad KB, Mathew TS, Shamsudden R, Muhammad HM, Haladu M, Adam AB. Heavy metal pollution in aquatic ecosystems: A review of toxic impacts and remediation strategies. Kwaghe International Journal of Sciences and Technology 2024; 1(1): 416-427.

Abu-Dief AM, Mohamed WS. Development of nanomaterials as photo catalysts for environmental applications. Current Catalysis 2020; 9(2): 128-137.

Adeleke AA, Liu X, Lu X, Moyo M, Hildebrandt D. Cobalt hybrid catalysts in Fischer-Tropsch synthesis. Reviews in Chemical Engineering 2020; 36(4): 437-457.

Al Husaeni DF, Al Husaeni DN, Nandiyanto ABD, Rokhman M, Chalim S, Chano J, Al Obaidi ASM, Roestamy M. How technology can change educational research? Definition, factors for improving quality of education and computational bibliometric analysis. ASEAN Journal of Science and Engineering 2024; 4(2): 127-166.

Al Husaeni DF, Haristiani N, Wahyudin W, Rasim R. Chatbot artificial intelligence as educational tools in science and engineering education: A literature review and bibliometric mapping analysis with its advantages and disadvantages. ASEAN Journal of Science and Engineering 2024; 4(1): 93-118.

Al Husaeni DF, Nandiyanto ABD. Bibliometric using VOSviewer with Publish or Perish (using Google Scholar data): From step-by-step processing for users to the practical examples in the analysis of digital learning articles in pre and post Covid-19 pandemic. ASEAN Journal of Science and Engineering 2022; 2(1): 19-46.

Al Husaeni DF, Nandiyanto, ABD. Bibliometric using VOSviewer with publish or perish (using Google Scholar data): From step-by-step processing for users to the practical examples in the analysis of digital learning articles in pre and post covid-19 pandemic. ASEAN Journal of Science and Engineering 2022; 2(1): 19-46.

Al Husaeni DN, Al Husaeni DF. How to calculate bibliometric using VOSviewer with Publish or Perish (using Scopus data): Science education keywords. Indonesian Journal of Educational Research and Technology 2022; 2(3): 247-274.

Al Husaeni DN, Nandiyanto ABD. Bibliometric analysis of high school keyword using VOSviewer indexed by Google Scholar. Indonesian Journal of Educational Research and Technology 2023; 3(1): 1-12.

Amin MH, Sajak AAB, Jaafar J, Husin HS, Mohamad S. Real time water quality monitoring system for smart city in Malaysia. ASEAN Journal of Science and Engineering 2022; 2(1): 47-64.

An K, Somorjai GA. (2012). Size and shape control of metal nanoparticles for reaction selectivity in catalysis. ChemCatChem 2012; 4(10): 1512-1524.

Arianingrum R, Aznam N, Atun S, Senam S, Irwan AR, Juhara NQ, Anisa NF, Devani LK. Antiangiogenesis activity of Indonesian local black garlic (Allium Sativum 'Solo): Experiments and bibliometric analysis. Indonesian Journal of Science and Technology 2023; 8(3): 487-498.

Azizah NN, Maryanti R, Nandiyanto ABD. How to search and manage references with a specific referencing style using Google Scholar: From step-by-step processing for users to the practical examples in the referencing education. Indonesian Journal of Multidiciplinary Research 2021; 1(2): 267-294.

Barrio J, Volokh M, Shalom M. Polymeric carbon nitrides and related metal-free materials for energy and environmental applications. Journal of Materials Chemistry A 2020; 8(22): 11075-11116.

Bazzi I, El Mouaden K, Chaouay A, Addi AA, Hamdani M, El Issami S, Hilali M, Hammouti M, Abbiche K, Salghi R. Monitoring heavy metal contamination levels and microbiological pollution in seawater of Agadir coastal zones. Indonesian Journal of Science and Technology 2020; 5(3): 463-469.

Benito BSA. A step-by-step experimental procedure for water quality assessment of blue lagoon: Comparison to socio-demographic and economic profile for a teaching model. ASEAN Journal for Science Education 2023; 2(2): 107-120.

Bilad MR. Membrane bioreactor for domestic wastewater treatment: Principles, challenges, and future research directions. Indonesian Journal of Science and Technology 2017; 2(1): 97-123.

Boutebib AB, N'diaye AD, Elhoumed SAB, M'Baye BK, Ali YAEH, Hammouti B, Semega BM. Assessment of iron contamination in groundwater of catchment area water. Indonesian Journal of Science and Technology 2023; 8(3): 429-438.

Burakov AE, Galunin EV, Burakova IV, Kucherova AE, Agarwal S, Tkachev AG, Gupta VK. Adsorption of heavy metals on conventional and nanostructured materials for wastewater treatment purposes: A review. Ecotoxicology and Environmental Safety 2018; 148: 702-712.

Cha BJ, Saqlain S, Seo HO, Kim YD. Hydrophilic surface modification of TiO2 to produce a highly sustainable photocatalyst for outdoor air purification. Applied Surface Science 2019; 479: 31-38.

Climent MJ, Corma A, Iborra S. Homogeneous and heterogeneous catalysts for multicomponent reactions. RSC Advances 2012; 2(1): 16-58.

Cova CM, Zuliani A, Muñoz-Batista MJ, Luque R. Efficient Ru-based scrap waste automotive converter catalysts for the continuous-flow selective hydrogenation of cinnamaldehyde. Green Chemistry 2019; 21(17): 4712-4722.

Das TK, Poater A. Review on the use of heavy metal deposits from water treatment waste towards catalytic chemical syntheses. International Journal of Molecular Sciences 2021; 22(24): 13383.

Datye AK, Votsmeier M. Opportunities and challenges in the development of advanced materials for emission control catalysts. Nature Materials 2021; 20(8): 1049-1059.

Dey S, Mehta NS. Oxidation of carbon monoxide over various nickel oxide catalysts in different conditions: A review. Chemical Engineering Journal Advances 2020; 1: 100008.

Fu W, Shen R, Bai E, Zhang L, Chen Q, Fang Z, Tang T. Reaction route and mechanism of the direct N-alkylation of sulfonamides on acidic mesoporous zeolite β-catalyst. ACS Catalysis 2018; 8(10): 9043-9055.

Fukuzumi S, Hong D. Homogeneous versus heterogeneous catalysts in water oxidation. European Journal of Inorganic Chemistry 2014; 2014(4): 645-659.

Galhardo TS, Braga AH, Arpini BH, Szanyi J, Gonçalves RV, Zornio BF, Rossi LM. Optimizing active sites for high CO selectivity during CO2 hydrogenation over supported nickel catalysts. Journal of the American Chemical Society 2021; 143(11): 4268-4280.

García JR, Bertero M, Falco M, Sedran U. Catalytic cracking of bio-oils improved by the formation of mesopores by means of Y zeolite desilication. Applied Catalysis A: General 2015; 503: 1-8.

Gawande MB, Goswami A, Asefa T, Guo H, Biradar AV, Peng DL, Varma RS. (2015). Core-shell nanoparticles: synthesis and applications in catalysis and electrocatalysis. Chemical Society Reviews 2015; 44(21): 7540-7590.

Ghashghaee M, Shirvani S, Ghambarian M, Kegnæs S. Synergistic coconversion of refinery fuel oil and methanol over H-ZSM-5 catalyst for enhanced production of light olefins. Energy and Fuels 2019; 33(6): 5761-5765.

Gunawan B, Ratmono BM, Abdullah AG, Sadida N, Kaprisma, H. Research mapping in the use of technology for fake news detection: Bibliometric analysis from 2011 to 2021. Indonesian Journal of Science and Technology 2022; 7(3): 471-496.

Gutierrez AM, Dziubla TD, Hilt JZ. Recent advances on iron oxide magnetic nanoparticles as sorbents of organic pollutants in water and wastewater treatment. Reviews on Environmental Health 2017; 32(1-2): 111-117.

Hamidah I, Ramdhani R, Wiyono A, Mulyanti B, Pawinanto EE, Hasanah L, Diantoro M, Yuliarto B, Yunas J, Rusydi A. Biomass-based supercapacitors electrodes for electrical energy storage systems activated using chemical activation method: A literature review and bibliometric analysis. Indonesian Journal of Science and Technology 2023; 8(3): 439-468.

He H, Li R, Yang Z, Chai L, Jin L, Alhassan SI, Huang L. Preparation of MOFs and MOFs derived materials and their catalytic application in air pollution: A review. Catalysis Today 2021; 375: 10-29.

Hodges BC, Cates EL, Kim JH. Challenges and prospects of advanced oxidation water treatment processes using catalytic nanomaterials. Nature Nanotechnology 2018; 13(8): 642-650.

Hovsepian PE, Ehiasarian AP. Six strategies to produce application tailored nanoscale multilayer structured PVD coatings by conventional and high power impulse magnetron sputtering (HIPIMS). Thin Solid Films 2019; 688: 137409.

Hwang J, Ejsmont A, Freund R, Goscianska J, Schmidt BV, Wuttke S. Controlling the morphology of metal–organic frameworks and porous carbon materials: Metal oxides as primary architecture-directing agents. Chemical Society Reviews 2020; 49(11): 3348-3422.

Ibrahim MM, Mahmoud HR, El-Molla SA. Influence of support on physicochemical properties of ZrO2 based solid acid heterogeneous catalysts for biodiesel production. Catalysis Communications 2019; 122: 10-15.

Irawan AK, Rusdiana D, Setiawan W, Purnama W, Fauzi RM, Fauzi SA, Alfani AHF, Arfiyogo MR. Design-construction of a solar cell energy water pump as a clean water source for people in Sirnajaya village, Gununghalu district. ASEAN Journal of Science and Engineering Education 2021; 1(1), 15-20.

Ismail M, Akhtar K, Khan MI, Kamal T, Khan MA, M Asiri A, Khan SB. Pollution, toxicity and carcinogenicity of organic dyes and their catalytic bio-remediation. Current Pharmaceutical Design 2019; 25(34): 3645-3663.

Jain M, Yadav M, Kohout T, Lahtinen M, Garg VK, Sillanpää M. Development of iron oxide/activated carbon nanoparticle composite for the removal of Cr (VI), Cu (II) and Cd (II) ions from aqueous solution. Water Resources and Industry 2018; 20: 54-74.

Jawad AH, Abdulhameed AS, Wilson LD, Syed-Hassan SSA, ALOthman ZA, Khan MR. High surface area and mesoporous activated carbon from KOH-activated dragon fruit peels for methylene blue dye adsorption: optimization and mechanism study. Chinese Journal of Chemical Engineering 2021; 32: 281-290.

Jin R, Li G, Sharma S, Li Y, Du X. Toward active-site tailoring in heterogeneous catalysis by atomically precise metal nanoclusters with crystallographic structures. Chemical Reviews 2020; 121(2): 567-648.

Jose A, Mathew T, Fernández-Navas N, Querebillo CJ. Porous inorganic nanomaterials: Their evolution towards hierarchical porous nanostructures. In Micro 2024; 4(2): 229-280.

Kabir MH, Islam MS, Tusher TR, Hoq ME, Al Mamun S. Changes of heavy metal concentrations in Shitalakhya river water of Bangladesh with seasons. Indonesian Journal of Science and Technology 2020; 5(3): 395-409.

Kajetanowicz A, Grela K. Nitro and other electron withdrawing group activated ruthenium catalysts for olefin metathesis reactions. Angewandte Chemie International Edition 2021; 60(25): 13738-13756.

Kaplin IY, Lokteva ES, Golubina EV, Lunin VV. Template synthesis of porous ceria-based catalysts for environmental application. Molecules 2020; 25(18): 4242.

Kerans G, Sanjaya Y, Liliasari L, Pamungkas J, Ate GY. Effect of substrate and water on cultivation of Sumba seaworm (nyale) and experimental practicum design for improving critical and creative thinking skills of prospective science teacher in biology and supporting sustainable development goals (SDGs). ASEAN Journal of Science and Engineering 2024; 4(3): 383-404.

Khan K, Tareen AK, Aslam M, Zhang Y, Wang R, Ouyang Z, Zhang H. Recent advances in two-dimensional materials and their nanocomposites in sustainable energy conversion applications. Nanoscale 2019; 11(45): 21622-21678.

Khelassi-Sefaoui A, Khechekhouche A, Daouadji MZD, Idrici H. Physico-chemical investigation of wastewater from the Sebdou-Tlemcen textile complex North-West Algeria. Indonesian Journal of Science and Technology 2021; 6(2): 361-370.

Knappe DRU. (2006). Surface chemistry effects in activated carbon adsorption of industrial pollutants. In Interface Science and Technology 2006; 10: 155-177.

Kumar A, Kumar L. Nanostructured catalysts for CO_2 reduction: Systematic insights and emerging strategies. Research on Chemical Intermediates 2024; 50(1): 195-217.

Kumar SG, Rao KK. Tungsten-based nanomaterials (WO3 and Bi2WO6): Modifications related to charge carrier transfer mechanisms and photocatalytic applications. Applied Surface Science 2015; 355: 939-958.

Kurniawan B, Meyliana M, Warnars HLHS, Suharjo B. Development of intelligent tutoring system model in the learning system of the Indonesian national armed forces completed with bibliometric analysis. ASEAN Journal of Science and Engineering 2024; 4(2): 207-220.

Laita M, Hammouti B, Sabbahi R, Messaoudi Z, Benkirane R. Effect of water regime and soil maintenance mode on vegetative growth and peach tree production. Indonesian Journal of Science and Technology 2024; 9(1): 33-44.

Laita M, Sabbahi R, Elbouzidi A, Hammouti B, Messaoudi Z, Benkirane R, Aithaddou H. Effects of sustained deficit irrigation on vegetative growth and yield of plum trees under the semi-arid conditions: Experiments and review with bibliometric analysis. ASEAN Journal of Science and Engineering 2024; 4(2): 167-190.

Le Leuch LM, Bandosz TJ. (2007). The role of water and surface acidity on the reactive adsorption of ammonia on modified activated carbons. Carbon 2007; 45(3): 568-578.

Liang J, Liang Z, Zou R, Zhao Y. Heterogeneous catalysis in zeolites, mesoporous silica, and metal-organic frameworks. Advanced Materials 2017; 29(30): 1701139.

Lin L, Jiang W, Chen L, Xu P, Wang H. Treatment of produced water with photocatalysis: Recent advances, affecting factors and future research prospects. Catalysts 2020; 10(8): 924.

Liu L, Yao H, Zhou Q, Yan D, Xu J, Lu X. Optimization of poly (ethylene terephthalate) fiber degradation by response surface methodology using an amino acid ionic liquid catalyst. ACS Engineering Au 2022; 2(4): 350-359.

Lizama MG, Huesa J, Claudio BM. Use of blockchain technology for the exchange and secure transmission of medical images in the cloud: Systematic review with bibliometric analysis. ASEAN Journal of Science and Engineering 2024; 4(1): 71-92.

Lopez-Tejedor D, Benavente R, Palomo JM. Iron nanostructured catalysts: Design and applications. Catalysis Science and Technology 2018; 8(7): 1754-1776.

Luo J, Yu D, Hristovski KD, Fu K, Shen Y, Westerhoff P, Crittenden JC. Critical review of advances in engineering nanomaterial adsorbents for metal removal and recovery from water: Mechanism identification and engineering design. Environmental Science and Technology 2021; 55(8): 4287-4304.

Mahmud M, Elma M, Rahma A, Huda N, Lestari RA, Harivram ASK, Rampun ELA, Othman MHD, Bilad MR. Step-by-step fabrication of PVDF-TiO2 hollow fiber membrane and its application desalination of wetland saline water via pervaporation. Indonesian Journal of Science and Technology 2023; 8(3): 499-516.

Mélinon P, Begin-Colin S, Duvail JL, Gauffre F, Boime NH, Ledoux G, Warot-Fonrose B. (2014). Engineered inorganic core/shell nanoparticles. Physics Reports 2014; 543(3): 163-197.

Miao H, Wu X, Chen B, Wang Q, Wang F, Wang J, Zhang Q. (2020). A-site deficient/excessive effects of LaMnO3 perovskite as bifunctional oxygen catalyst for zinc-air batteries. Electrochimica Acta 2020; 333: 135566.

Mishra RK. Fresh water availability and its global challenge. British Journal of Multidisciplinary and Advanced Studies 2023; 4(3): 1-78.

Mondelli C, Gözaydın G, Yan N, Pérez-Ramírez, J. Biomass valorisation over metal-based solid catalysts from nanoparticles to single atoms. Chemical Society Reviews 2020; 49(12): 3764-3782.

Motagamwala AH, Dumesic JA. Microkinetic modeling: A tool for rational catalyst design. Chemical Reviews 2020; 121(2): 1049-1076.

Mudzakir A, Rizky KM, Munawaroh HSH, Puspitasari D. Oil palm empty fruit bunch waste pretreatment with benzotriazolium-based ionic liquids for cellulose conversion to glucose: Experiments with computational bibliometric analysis. Indonesian Journal of Science and Technology 2022; 7(2): 291-310.

Nakaya Y, Furukawa S. Catalysis of alloys: Classification, principles, and design for a variety of materials and reactions. Chemical Reviews 2022; 123(9): 5859-5947.

Nandasiri MI, Jambovane SR, McGrail BP, Schaef HT, Nune SK. Adsorption, separation, and catalytic properties of densified metal-organic frameworks. Coordination Chemistry Reviews 2016; 311: 38-52.

Nandiyanto ABD, Fiandini M, Al Husaeni DN. Research trends from the Scopus database using keyword water hyacinth and ecosystem: A bibliometric literature review. ASEAN Journal of Science and Engineering 2024; 4(1): 33-48.

Nandiyanto ABD, Ragadhita R, Fiandini M, Maryanti R, Al Husaeni DN, Al Husaeni DF. Adsorption isotherm characteristics of calcium carbon microparticles prepared from chicken bone waste to support sustainable development goals (SDGS). Journal of Engineering, Science and Technology 2023; 18(2): 1363-1379.

Navalon S, Dhakshinamoorthy A, Alvaro M, Antonietti M, García H. (2017). Active sites on graphene-based materials as metal-free catalysts. Chemical Society Reviews 2017; 46(15): 4501-4529.

Navlani-García M, Verma P, Mori K, Kuwahara Y, Yamashita H. Morphology-controlled Pd nanocrystals as catalysts in tandem dehydrogenation-hydrogenation reactions. Journal of Chemical Sciences 2017; 129: 1695-1703.

Nguyen TD. From formation mechanisms to synthetic methods toward shape-controlled oxide nanoparticles. Nanoscale 2013; 5(20): 9455-9482.

Noviyanti AR, Adzkia QAA, Novella I, Kurnia I, Suryana S, Ma'Amor AB, Irwansyah FS. Hydroxyapatite as delivery and carrier material: Systematic literature review with bibliometric analysis. ASEAN Journal of Science and Engineering 2024; 4(2): 191-206.

Parvulescu VI, Epron F, Garcia H, Granger P. Recent progress and prospects in catalytic water treatment. Chemical Reviews 2021; 122(3): 2981-3121.

Pavlenko V, Żółtowska S, Haruna AB, Zahid M, Mansurov Z, Supiyeva Z, Jesionowski T. A comprehensive review of template-assisted porous carbons: Modern preparation methods and advanced applications. Materials Science and Engineering: Reports 2022; 149: 100682.

Phoon BL, Lai CW, Juan JC, Show PL, Pan GT. Recent developments of strontium titanate for photocatalytic water splitting application. International Journal of Hydrogen Energy 2019; 44(28): 14316-14340.

Popović S, Smiljanić M, Jovanovič P, Vavra J, Buonsanti R, Hodnik N. Stability and degradation mechanisms of copper-based catalysts for electrochemical CO2 reduction. Angewandte Chemie 2020; 132(35): 14844-14854.

Portha JF, Parkhomenko K, Kobl K, Roger AC, Arab S, Commenge JM, Falk L. Kinetics of methanol synthesis from carbon dioxide hydrogenation over copper–zinc oxide catalysts. Industrial and Engineering Chemistry Research 2017; 56(45): 13133-13145.

Prieto G, Tüysüz H, Duyckaerts N, Knossalla J, Wang GH, Schüth F. Hollow nano-and microstructures as catalysts. Chemical Reviews 2016; 116(22): 14056-14119.

Purazo KN, Paris JMNT, Subaldo JIS, Bacal BB. Design of micro-controlled swimming pool water quality monitoring system with SMS notification for educational purposes with cost analysis. ASEAN Journal of Science and Engineering Education 2024; 4(1): 71-84.

Qizi PMB, Lolayevich SJ. Improvement of the technology of industrial wastewater treatment in the mining industry. ASEAN Journal for Science and Engineering in Materials 2023; 2(1): 45-52.

Ragadhita R, Amalliya A, Nuryani S, Fiandini M, Nandiyanto ABD, Hufad A, Al-Obaidi ASM. Sustainable carbon-based biosorbent particles from papaya seed waste: Preparation and adsorption isotherm. Moroccan Journal of Chemistry 2023; 11(2): 371-386.

Ragadhita R, Nandiyanto ABD. (2021). How to calculate adsorption isotherms of particles using two-parameter monolayer adsorption models and equations. Indonesian Journal of Science and Technology 2021; 6(1): 205-234.

Ramadhan DF, Fabian AM, Saputra HM. Dental suction aerosol: Bibliometric analysis. ASEAN Journal of Science and Engineering 2022; 2(3): 295-302.

Rashid R, Shafiq I, Akhter P, Iqbal MJ, Hussain M. A state-of-the-art review on wastewater treatment techniques: the effectiveness of adsorption method. Environmental Science and Pollution Research 2021; 28: 9050-9066.

Reza MS, Yun CS, Afroze S, Radenahmad N, Bakar MSA, Saidur R, Azad AK. Preparation of activated carbon from biomass and its' applications in water and gas purification, a review. Arab Journal of Basic and Applied Sciences 2020; 27(1): 208-238.

Rochman S, Rustaman N, Ramalis TR, Amri K, Zukmadini AY, Ismail I, Putra AH. How bibliometric analysis using VOSviewer based on artificial intelligence data (using ResearchRabbit Data): Explore research trends in hydrology content. ASEAN Journal of Science and Engineering 2024; 4(2): 251-294.

Rodrigues RC, Berenguer-Murcia Á, Fernandez-Lafuente R. (2011). Coupling chemical modification and immobilization to improve the catalytic performance of enzymes. Advanced Synthesis and Catalysis 2011; 353(13): 2216-2238.

Roduner, E. Understanding catalysis. Chemical Society Reviews (2014); 43(24): 8226-8239.

Roy A, Sharma A, Yadav S, Jule LT, Krishnaraj R. (2021). Nanomaterials for remediation of environmental pollutants. Bioinorganic Chemistry and Applications 2021; 2021(1): 1764647.

Sadabadi H, Allahkaram SR, Kordijazi A, Rohatgi PK. Self-healing coatings loaded by nano/microcapsules: A review. Protection of Metals and Physical Chemistry of Surfaces 2022; 58(2): 287-307.

Sahidin I, Nohong N, Manggau MA, Arfan A, Wahyuni W, Meylani I, Malaka MH, Rahmatika NS, Yodha AWM, Masrika NUE, Kamaluddin A, Sundowo A, Fajriah S, Asasutjarit R, Fristiohady A, Maryanti R, Rahayu NI, Muktiarni M. Phytochemical profile and biological activities of ethylacetate extract of peanut (Arachis hypogaea L.) stems: In-vitro and in-silico studies with bibliometric analysis. Indonesian Journal of Science and Technology 2023; 8(2): 217-242.

Sajanlal PR, Sreeprasad TS, Samal AK, Pradeep, T. (2011). Anisotropic nanomaterials: structure, growth, assembly, and functions. Nano Reviews 2011; 2(1): 5883.

Santhosh C, Velmurugan V, Jacob G, Jeong SK, Grace AN, Bhatnagar A. Role of nanomaterials in water treatment applications: a review. Chemical Engineering Journal 2016; 306: 1116-1137.

Santoso B, Hikmawan T, Imaniyati N. Management information systems: Bibliometric analysis and its effect on decision making. Indonesian Journal of Science and Technology 2022; 7(3): 583-602.

Sarker B, Keya KN, Mahir FI, Nahiun KM, Shahida S, Khan RA. Surface and ground water pollution: Causes and effects of urbanization and industrialization in South Asia. Scientific Review 2021; 7(3): 32-41.

Sarkingobir Y, Tukur U. Plastic in water and its implications in human and biological systems. ASEAN Journal for Science and Engineering in Materials 2025; 4(1): 1-12.

Satria RD, Nandiyanto ABD. Education of dietary habit and drinking water quality to increase body immunity for elementary school. ASEAN Journal of Agricultural and Food Engineering 2022; 2(1): 25-32.

Sendilvelan S, Bhaskar K, Nallusamy S. Experimental investigation on cerium oxide nanoparticles with alumina catalytic converter to increase emission conversion efficiency in automobiles. Rasayan Journal of Chemistry 2017; 10(2): 545-460.

Setiyo M, Yuvenda D, Samue OD. The latest report on the advantages and disadvantages of pure biodiesel (B100) on engine performance: Literature review and bibliometric analysis. Indonesian Journal of Science and Technology 2021; 6(3): 469-490.

Shelef M, Graham GW. Why rhodium in automotive three-way catalysts?. Catalysis Reviews 1994; 36(3): 433-457.

Sheng DPW, Bilad MR, Shamsuddin, N. Assessment and optimization of coagulation process in water treatment plant: A review. ASEAN Journal of Science and Engineering 2023; 3(1): 79-100.

Shidiq APA. Bibliometric analysis of nano metal-organic frameworks synthesis research in medical science using VOSviewer. ASEAN Journal of Science and Engineering 2023; 3(1): 31-38.

Shiers MJ, Leech R, Carmalt CJ, Parkin IP, Kenyon AJ. Self-assembled ultra - high aspect ratio silver nanochains. Advanced Materials 2012; 24(38): 5227-5235.

Singh DP. (2010). Synthesis and growth of ZnO nanowires. Science of Advanced Materials 2010; 2(3); 245-272.

Soegoto H, Soegoto ES, Luckyardi S, Rafdhi AA. A bibliometric analysis of management bioenergy research using vosviewer application. Indonesian Journal of Science and Technology 2022; 7(1): 89-104.

Solihat AN, Dahlan D, Kusnendi K, Susetyo B, Al Obaidi ASM. Artificial intelligence (AI)-based learning media: Definition, bibliometric, classification, and issues for enhancing creative thinking in education. ASEAN Journal of Science and Engineering 2024; 4(3): 349-382.

Touir J, Kitanou S, Zait M, Belhamidi S, Belfaquir M, Tahaikt M, Taky M, Elmidaoui A. The comparison of electrodialysis and nanofiltration in nitrate removal from groundwater. Indonesian Journal of Science and Technology 2021; 6(1): 17-30.

Utama DM, Santoso I, Hendrawan Y, Dania WAP. Sustainable Production-inventory model with multi-material, quality degradation, and probabilistic demand: From bibliometric analysis to a robust model. Indonesian Journal of Science and Technology 2023; 8(2): 171-196.

Wang M, Feng B, Li H, Li H. Controlled assembly of hierarchical metal catalysts with enhanced performances. Chem 2019; 5(4): 805-837.

Wang S, Sun B, Feng J, An F, Li N, Wang H, Tian M. (2020). Development of affinity between target analytes and substrates in surface enhanced Raman spectroscopy for environmental pollutant detection. Analytical Methods 2020; 12(47): 5657-5670.

Wang X, Feng JI, Bai Y, Zhang Q, Yin, Y. Synthesis, properties, and applications of hollow micro-/nanostructures. Chemical Reviews 2016; 116(18): 10983-11060.

Waqas S, Bilad MR, Man ZB. Performance and energy consumption evaluation of rotating biological contactor for domestic wastewater treatment. Indonesian Journal of Science and Technology 2021; 6(1): 101-112.

Xu J, Ibrahim AR, Hu X, Hong Y, Su Y, Wang H, Li J. Preparation of large pore volume γ-alumina and its performance as catalyst support in phenol hydroxylation. Microporous and Mesoporous Materials 2016; 231: 1-8.

Yang CH, Chang JS, Lee DJ. Chemically stable covalent organic framework as adsorbent from aqueous solution: A mini-review. Journal of the Taiwan Institute of Chemical Engineers 2020; 110: 79-91.

Yang TH, Shi Y, Janssen A, Xia Y. (2020). Surface capping agents and their roles in shape - controlled synthesis of colloidal metal nanocrystals. Angewandte Chemie International Edition 2020; 59(36): 15378-15401.

Yang Y, Li X, Zhou C, Xiong W, Zeng G, Huang D, Guo, H. Recent advances in application of graphitic carbon nitride-based catalysts for degrading organic contaminants in water through advanced oxidation processes beyond photocatalysis: A critical review. Water Research 2020; 184: 116200.

Yu G, Wang Y, Cao H, Zhao H, Xie, Y. Reactive oxygen species and catalytic active sites in heterogeneous catalytic ozonation for water purification. Environmental Science and Technology 2020; 54(10): 5931-5946.

Zaera, F. Designing sites in heterogeneous catalysis: Are we reaching selectivities competitive with those of homogeneous catalysts?. Chemical Reviews 2022; 122(9): 8594-8757.

Zafrullah Z, Ramadhani AM. The use of mobile learning in schools as a learning media: Bibliometric analysis. Indonesian Journal of Educational Research and Technology 2024; 4(2): 187-202.

Zhang Q, Wang W, Goebl J, Yin Y. Self-templated synthesis of hollow nanostructures. Nano Today 2009; 4(6): 494-507.