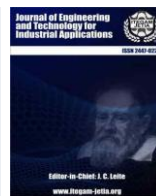




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RESEARCH ARTICLE

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A COMPREHENSIVE REVIEW OF TREATMENT TECHNOLOGIES AND SUSTAINABLE MATERIALS IN ENVIRONMENTAL CHEMICAL ENGINEERING

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ABSTRACT

With increasing concerns regarding pollution, climate change and resource limitations, Environmental chemical engineering is a crucial field that allows for the sustainable management of industrial processes and services. Although much advancement in treatment technologies has been made, current studies often fail to provide a more integrated approach that takes into consideration the combination of cutting-edge materials, hybrid processes and data-driven optimization strategies to better tackle complex (and emerging) contaminants. This review is designed to fill this gap by providing a systematic overview of recent developments in the aspects of various water treatment options, air pollution control methods, solid waste management as well as sustainable materials development. To do so, the study employs a full literature review approach with an examination of modern peer-reviewed studies regarding advanced oxidation processes, membrane-based systems, biological methods, catalytic technologies and AI-based optimization tools. The results found significant improvements in efficiency, pollutant removal and resource recovery with the application of hybrid treatment technologies, AI-assisted process control, new materials (i.e., graphene-based membranes, biopolymers), among others. These findings present significant potential for enhancements in environmental performance and facilitating circular economic efforts. This study is consistent with sustainable industrial applications as it opens avenues for cleaner production, use of waste and reduced environmental impact in line with global sustainability goals.



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I. INTRODUCTION

Environmental chemical engineering works to convert chemical principles into solutions that everyday people can use to minimize pollution and emphasize sustainability. With the rapid industrialisation, growth of population and increasing urban infrastructure the requirement for technologies that protect water bodies, soil and air quality has increased. Increased regulation and global climate accords have also forced development in this area.

The scope of this review is to present, in a single comprehensive review, the most important advances in environmental chemical engineering that are focused on the development of new materials, process hurdles improvements and novel gimmicks fostering cleaner factory practices. In this paper, we review simulation-driven approaches meant for improving water treatment applications with a focus on chemical engineering [1]. It discusses the use of numerical simulations for the computer-based modelling and analysis of several topics in water resource management with emphasis on the transition from linear towards circular water economy [2]. This review also discusses the basic concepts of water treatment, explaining complicated physicochemical and biological mechanisms which contribute to these techniques [3]. The figure 1 shows the main research domains that shape current work in environmental chemical engineering.

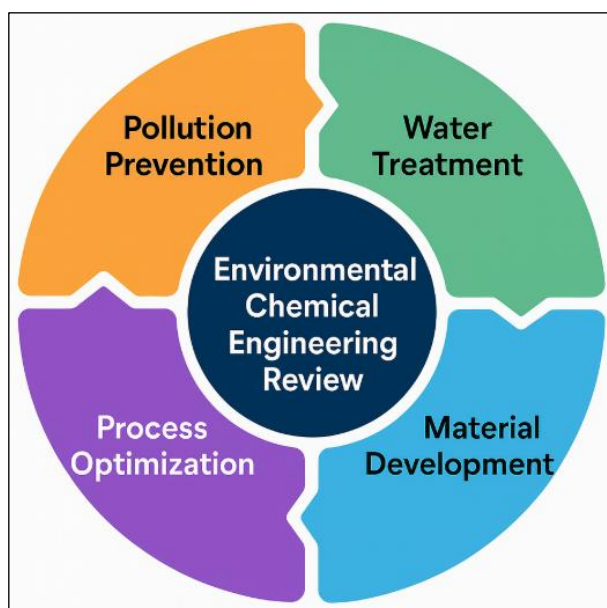


Figure 1: Focus Areas of Environmental Chemical Engineering.
Source: Authors (2026).

II. WATER AND WASTEWATER TREATMENT TECHNOLOGIES

Water pollution resulting from industrial effluents, agricultural runoff, pharmaceuticals pesticides and personal-care products has become a significant barrier. With the considerable input from environmental chemical engineering, highly efficient and energy-efficient treatment techniques have been developed. Conventional wastewater treatment, such as for example the one that usually consists of a combination of physical, chemical and biological processes to remove solids, organic matter and nutrients [4]. However, such traditional treatment methods may have difficulty coping with some new contaminants, micro-pollutants and antibiotic resistant bacteria and advanced treatments are required [2]. More contemporary techniques use sophisticated computational models and simulations to support the optimization of process parameters, equipment design, and managing conditions as well as improving treatment efficiency and minimizing resource consumption [3]. The figure 2 shows the three main technological approaches used for modern wastewater treatment.

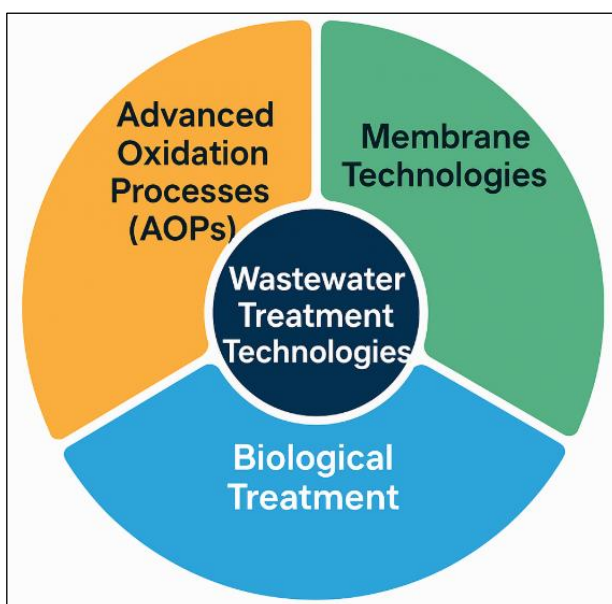


Figure 2: Major Wastewater Treatment Technologies.
Source: Authors (2026).

II.1 ADVANCED OXIDATION PROCESSES (AOPS)

AOPs utilise highly reactive species such as hydroxyl radicals for the oxidation of recalcitrant organic pollutants which are otherwise not amenable to conventional biological removal. Even if AOPs exhibit high efficiency of degradation, some issues related to energy consumption and catalytic stability have been reported. Thus, the future research is expected to meet these challenges as much as possible by developing new catalyst materials, optimizing engineering parameters, and coupling AOPs with other treatment systems to introduce an economical and sustainable strategy for water decontamination. Moreover, electrocoagulation and electrooxidation are being extensively explored by the chemical engineers to eliminate pollutants and disinfect water where the principles of electrodeposition are also applied for recovering valuable metals and ions [2]. In addition to chemical and electrochemical methods, wastewater treatment based on microorganisms as a promising biological method is environmentally friendly and cost effective for decolorization of organic dyes [5]. Biological treatment of wastewater (3c) Metabolism Wastewater treatment techniques such as activated sludge and trickling filters uses microbial decomposition to degrade pollutants, but their efficiency varies with the nature of the wastewater [4]. Nevertheless, biological treatments though commonly practiced are not very effective for low-strength wastewater and refractory pollutants; their performance is significantly influenced by temperature and influent fluctuation [6]. In this context, it is required to combine advanced physical and chemical processes with the biological ones, to attain a complete pollutant removal and reinforce the overall treatment reliability [7]. For this purpose, advanced oxidation processes are gaining more interest as important elements of integrated treatment trains providing effective tools to degrade recalcitrant organic pollutants which are not degradable by conventional biological methods [7], [8]. Indeed, AOPs are already beginning to play a key complementary role with respect to the conventional removal of wastewater pollutants, particularly in cases when conventional treatment is not adequate for treating excessive waste materials [9]. AOP effluents are often more suitable for further biological treatments, and therefore their integration as pre- or post-treatments in other industries is considered a favourable and cost-effective option for different industrial wastewaters, particularly those of food industry [10].

This integrated treatment has several advantages in enhancing the efficiency and effectiveness of wastewater treatment processes, by applying strong oxidants to degrade complex and refractory organic and inorganic pollutants before biodegradation [11]. In addition to this, the electrochemical technologies are also receiving greater attention for versatility, energy efficiency and environmental friendliness, when associated with biological process in order improve treatment performance [12-14]. This combination treatment also includes biological pre-treatment with AOPs as polishing techniques, reducing the costs of the overall process since biological processes are generally cheaper and more environmentally friendly compared to other advanced technologies [15]. Nevertheless, the cost and operational complexity of some AOPs, including ultrasound and ozone systems prevent them to be economically viable without further optimization [16]. Integrated AOPs are, therefore, required to be applied for complete degradation of pollutants [11]. The complex nature of industrial wastewater (comprising complex mix of recalcitrant pollutants) generally leads to poor performance by standalone biological treatment alone. In addition, the use of AOPs as pre-treatment can dramatically increase the biodegradability of high molecular weight organic compounds; it follows that the overall performance and cost-effectiveness of subsequent biological treatment processes is greatly improved [17]. This is particularly important in industries such as the food industry, where waste streams contain complex organic material which tends to inhibit biological action [18]. Consequently, the combination of AOPs with biological treatments can lead to an increased economic feasibility of biologically treated reactor effluent due to decreased requirement on high oxidant dosages shown under AOP-final treatment conditions [19]. The combination of the two processes are believed to be attributed to their inherent mechanisms which can overcome the defects existing in the individual Fenton reaction and CNTs-based catalyst process and subsequently developing a more efficient approach for wastewater treatment [20].

II.2 MEMBRANE TECHNOLOGIES

Fouling is still an issue, requiring maintenance, and the lifespan of MBRs are reduced. The development of new membrane materials and operation methods to fight membrane fouling and the improvement of long-term performance is the subject of current research (9). Some new developments have also targeted challenges leading to potential breakthroughs in efficiency and utilisation of resources and environmental sustainability of membrane systems [21]. For example, advanced membrane bioreactors are commonly used systems nowadays, since they can achieve high effluent quality, reduction of sludge volume and small footprints (valuable for such specific wastewater treatment application) [22]. The still major issue for such systems is the high fouling propensity impairing performance and shortening membrane life, as well as the complexity combined to the cost of residuals disposal [23], [24]. In addition, novel membranes such as graphene oxide and advanced ceramic membranes are being investigated to improve lifetime, selectivity, and fouling resistance [25]. These super materials are designed to address the natural shortcomings of standard polymeric membranes, which are prone to fouling and degradation [23]. Research into the combination of membrane treatment with other processes, such as advanced oxidation and biological systems is also being studied for complete removal of pollutants and resource recovery from complex wastewaters [26], [27]. Notably, embedding carbon nanotubes and graphene oxide in the membrane matrices has demonstrated great potential for improving permeability and anti-fouling properties of membranes for a better performance and longer lifetime [28], [25]. In addition, various advanced fouling control measures (including nanomaterials and manipulation of transport properties) and novel cleaning methods, such as dynamic membrane systems, are under development to ensure effective membrane operation and long-term service life for anaerobic MBR reactors [28]. Table 1 compares major membrane technologies and biological treatment systems in terms of developments, advantages, challenges and current research trends.

Table 1: Key Features of Membrane and Biological Wastewater Treatment Methods.

Category	Key Developments	Advantages	Challenges	Notes / Research Trends
Membrane Technologies	Graphene oxide nanofiltration membranes	High strength, good selectivity	Fouling, reduced lifespan	Super materials like graphene oxide and ceramic membranes improve durability
	Low-energy reverse osmosis modules	Reduced energy use	Scaling and fouling issues	Research on advanced anti-fouling strategies
	Thin-film composite membranes	Resistant to organic fouling, bacteria	Cleaning complexity	CNT/GO-embedded matrices enhance permeability
	Membrane bioreactors (MBR)	High effluent quality, compact design	High fouling, costly sludge disposal	Widely used in municipal and industrial wastewater treatment
	Forward osmosis (FO)	Low-energy desalination	Draw-solution regeneration	New materials developed for long-term performance
Biological Treatment Systems	Microbial communities for pollutant degradation	Effective for pharmaceuticals and antibiotics	Sensitive to temperature and shock loads	Tailored communities expand treatment scope
	Anaerobic membrane bioreactors (AnMBR)	High biomass retention, biogas recovery	Membrane fouling, operational complexity	Suitable for high-strength industrial wastewater
	Microbial electrochemical systems	Electricity generation during treatment	Scale-up limitations	Hybrid designs emerging
	Enzymatic treatment using laccases, peroxidases, amylases	Specific degradation of contaminants	Enzyme stability issues	Enzyme-based remediation gaining interest
	Hybrid systems (bio + physical/chemical)	High removal efficiency for complex waste	Process optimization needed	Photocatalysis-biological combinations promising

Source: Authors (2026).

II.3 BIOLOGICAL TREATMENT SYSTEMS

Biological technologies established are still indispensable, being more economically competitive and because of their high efficiency in the removal of biodegradable compounds. Temperature, lethal shocks, and the rate of pollutant load can all rapidly affect biological systems. Scientists aim to improve robustness and extend the scope of biological systems by combining them with novel physical and chemical techniques, such as membrane filtration or advanced oxidation processes, which leads to new hybrid treatments (including complex waste streams) [26], [29]. For example, biodegradation of new contaminants could be facilitated by photocatalytic conjunction with biological treatment, and it could be a method that is both environmentally safe and economical [30]. In addition, the development of advanced control strategies and high mass transfer bioreactors is highly essential for a better performance and enhanced stability of biological wastewater treatment plants under varying operational conditions [31]. These combined/optimized techniques are necessary to achieve effective removal of contaminants given the fact that conventional biological methods applied alone or not optimized will not efficiently remove such GRECs [30]. One of such potential technologies is the anaerobic membrane bioreactor (AnMBR), which combines the features of anaerobic digestion and membrane separation for an efficient treatment high strength industrial wastewaters with energy recovery accompanied by biogas generation [28], [32]. These hybrid systems are especially suitable for the purification of pharmaceutical wastewater, which typically contain recalcitrant pollutants that hardly can be removed by traditional biological approaches [33]. This becomes even more important, especially for wastewaters with large organic loadings, to treat waste properly by avoiding pollution and still produce reusable content as an energy source or nutrient-rich effluent suitable for irrigation [33]. In addition, the combination of biological remediation with physico-chemical procedures develops in biofiltration and electrochemical applications [22], [30] may contribute for great pollutant removal efficiency optimization and represent a viable alternative to overall system effects mainly when complex industrial effluents are under consideration. But traditional biological treatment processes still have shortages, for instance, low efficiency, high energy consumption and sludge overproduction, so comprehensive strategy is required to enhance the performance and sustainability [34]. Such comprehensive strategies often consist of integrating biological processes with physical and chemical treatment, to address the drawbacks associated with individual systems and improve removal efficiency of contaminants, particularly those emerging ones [34], [35].

III. AIR POLLUTION CONTROL TECHNOLOGIES

Industrial pollution caused by emissions from transportation and energy generation will still hang in the air propelling illness and climate instability. Chemical Engineering offers the solutions by means of catalyst and sorbent design process optimization. Advances in vehicle and industrial stack catalytic converters, for example, can make a significant impact on emissions of harmful pollutants while advanced sorbents are designed to trap pollutants (carbon dioxide, sulfur oxides) from flue gases. Figure 3 illustrates three major approaches for air pollution control: industrial gaseous emission control, particulate matter removal, and greenhouse gas mitigation. It also highlights the role of AI-based optimization in improving real-time monitoring, predictive control, and overall efficiency of pollution control systems.

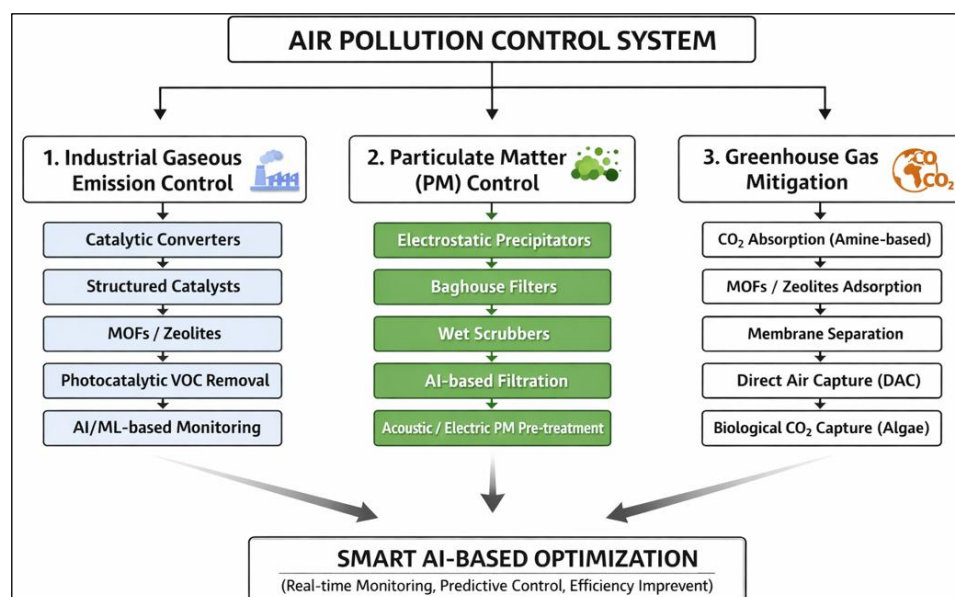


Figure 3: Integrated Air Pollution Control System with AI-Based Optimization.
Source: Authors (2026).

III.1 CONTROL OF INDUSTRIAL GASEOUS EMISSIONS

Recent advances in structured catalysts permit higher conversion at less severe operating temperatures. Novel absorbent materials (MOFs, zeolites, etc.) with improved selectivity and capacity for these greenhouse gases and other industrial pollutants are being developed [36]. The potential applications of these materials involved directly contribute to improving carbon capture technologies, sequestration and reduction of the atmospheric release of toxic gases [36]. Other studies are also targeted on the development and application of AI/ML algorithms to "smart" control and monitoring systems for real time air pollution abatement process optimization, leading toward more adaptable and effective emissions reduction bemoonds. This integration provides predictive maintenance and real-time optimization of operational parameters, which is required for achieving reliable performance in varying environmental and operation conditions [37]. Such AI-based models can predict trends of emissions, optimal control strategies and even equipment failures to ensure more eco-friendly industrial practices. Besides industrial utilizations, concerns are also turned to the treatment of ubiquitous organic air micro pollutants by advanced oxidation processes even at low content [38]. In addition, catalytic emission abatement approaches are being characterized and developed for enhanced performance-facilitated cost-reduction in areas such as biogas from landfills and sewage treatment plants [39]. It is also worth mentioning that new catalyst materials, especially containing a lower number of noble metals, are actively investigated as being one of the important topics for sustainability and cost-effectiveness improvements in these pollution abatement technologies [40]. For example, with the development of new catalyst materials, design strategies and operational approaches, it underlines again that the catalytic converters continue to be improved for more efficient control of harmful emissions like NO_x, CO and hydrocarbons [41]. This includes development of multifunctional catalysts, alternative technologies for combined removal of various pollutants and in-situ characterization methods that can give information on the catalyst performance under realistic operation conditions [42]. For instance, maximising the performance of materials, such as pollutants removal capacity is key in providing better learning cycles, and advanced analytical methodology like machine learning are very effective to improve the environmental performance and promote sustainable development [43].

III.2 PARTICULATE MATTER (PM) CONTROL

Predictive algorithms and machine learning models are now applied to predict levels of PM and to optimize its filtration. In addition to conventional methods, novel approaches are being developed to capture uPM by using acoustics, electricity, and chemicals (9,45), either as pre-treatment procedure aiming at increasing particle size and hence removal efficiency [44]. Other breakthroughs are the design of novel filters with hierarchical pores having self-cleaning functions as well as the use of computational fluid dynamics to optimize filter designs for enhanced particulate capture and lower pressure drop [44], [45]. Furthermore, real-time sensor networks can be utilized in combination with AI techniques to adjust the filter parameters on the dynamic conditions for its best performance under changeable pollutant loads and environmental contexts [46]. These advances are important to reduce the health impacts resulting from exposure to PM and comply with tightening air quality standards [47], [48]. Even photocatalytic materials are finding their way as passive but effective approaches for the reduction of ambient particulate matter through oxidative treatment of precursors in outdoor environment including surfaces on buildings and pavements [43]. Furthermore, wearable air quality sensors are growing increasingly advanced, permitting people to keep tabs on their own exposure to PM as well as taking actions to prevent adverse health effects [47]. The introduction of intelligent integrated triboelectric nanogenerator systems coupling with AI and ML technologies is significant progress in realizing autonomous adaptive operation under dynamic air environment [49]. Additionally, electro spun nanofibers are being used more frequently for their higher filtration effectiveness by virtue of their large porosity and high surface area and subsequently capturing airborne pollutants including microorganisms, toxic gases and heavy metal atoms [50]. Table 2 provides a clear comparison of key air pollution control technologies, outlining their main developments, benefits, limitations and ongoing research trends.

Table 2: Summary of Air Pollution Control Methods and Their Performance Characteristics.

Category	Key Developments / Techniques	Advantages	Challenges	Notes / Research Trends
Control of Industrial Gaseous Emissions	Low-temperature NO _x catalytic reduction	High NO _x removal at mild conditions	Catalyst deactivation	Structured catalysts improve conversion at lower temperatures
	SO ₂ absorption using optimized alkaline & amine blends	High SO ₂ selectivity	Solvent loss, regeneration energy	Improved solvents for better absorption efficiency
	Photocatalytic degradation of VOCs	Effective for low-concentration VOCs	Limited by light intensity and humidity	AI-aided catalyst design improves VOC oxidation
	Regenerative thermal oxidizers (RTOs)	High efficiency, energy recovery	High capital cost	Used widely in industrial stacks for VOC control
	MOFs, zeolites for gas adsorption	High selectivity, large surface area	Stability issues in humid conditions	Promising for CO ₂ and SO _x capture, ongoing material development
Particulate Matter (PM) Control	High-efficiency electrostatic precipitators	Effective for PM _{2.5}	Sensitive to humidity and conductivity	Improved charge release technologies emerging
	Baghouse filters with nano-coated fibers	High retention of fine particles	Fouling and pressure drop	Nano-fibers enhance capture and durability
	Wet scrubbers with surfactants	Better PM capture	Sludge generation	Surfactant-based formulations improve PM binding
	Acoustic, electric, chemical pre-treatment for uPM	Improves agglomeration before filtration	Still experimental	Helps capture ultrafine particles
	Real-time AI-based filtration control	Adaptive operation	Requires sensors and calibration	CFD-optimized filter design and smart control systems
Greenhouse Gas (GHG) Mitigation	Amine-based CO ₂ absorption	High absorption efficiency	High regeneration energy	New amines reduce energy penalty
	MOF-based adsorption	High CO ₂ uptake	Moisture sensitivity	AI helps design high-performance MOFs
	Membrane-based CO ₂ separation	Low energy use	Selectivity issues	AI models predict optimal membrane materials
	Catalytic CO ₂ conversion to fuels	Converts CO ₂ to methanol, ethanol	Catalyst cost	Research on low-cost and bimetallic catalysts
	Biological CO ₂ capture (algae)	Sustainable and scalable	Requires space and nutrient control	Produces biofuels and bioproducts
	Direct Air Capture (DAC)	Captures atmospheric CO ₂	High cost and energy requirement	Focus on sorbents and process optimization

Source: Authors (2026).

III.3 GREENHOUSE GAS (GHG) MITIGATION

Direct air capture technologies are developing but remain hamstrung by cost and scale. Current focus of research has thus been directed towards fabricating new sorbent materials and optimizing process parameters to lessen the energy penalty involved for making these advanced CO₂ capture technologies economically viable. Furthermore, innovation in biological carbon capture, including accelerated algal bioreactors for sustainable removal of atmospheric CO₂ and production of high value bio-products is also studied [51]. Beyond that, AI-based optimization models applied to those bio-refineries may dramatically improve the efficiency of CO₂ conversion routes, increasing productivity and financial sustainability [47]. Artificial intelligence is also used in the precise characterization and design of porous membranes for more efficient CO₂ separation. This type of AI based algorithms can predict optimal membrane performance, sure the best candidates for a membrane and optimize operative conditions to improve the CO₂ capture efficiency. This data-driven method using machine learning has also been reported to enhance the CO₂ adsorption precision from 53% to 61% [52]. Furthermore, AI-based CO₂ capture supports the optimization of industrial processes and power plants in terms of capturing and storing CO₂ as is relevant to precision energy conversion. More generally, the application of AI and machine learning to predict properties and performance of MOFs away from databases is investigated in another set of studies, allowing HT screening as well as generative models for new MOF designs [53]. In addition, they can also optimize temperature, pressure, flow rates and chemical reactions to improve the efficiency and performance of CO₂ capture processes [54].

IV. SOLID WASTE MANAGEMENT AND RESOURCE RECOVERY

Solid waste generation has accelerated with urban expansion, requiring systematic engineering strategies for treatment, recycling, and valorisation. The figure 4 presents major approaches for solid waste management, including waste-to-energy technologies and chemical/mechanical recycling methods for efficient resource recovery.

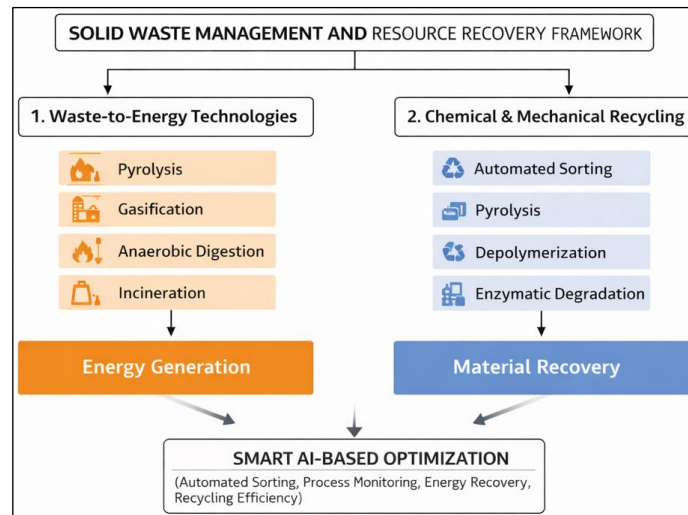


Figure 4: Solid Waste Management and Resource Recovery Framework.
Source: Authors (2026).

IV.1 WASTE-TO-ENERGY (WTE) TECHNOLOGIES

With the aid of catalyst during pyrolysis, the oil becomes more excellent, and fewer char is produced. Furthermore, the investigation on advanced gasification technologies aims to enhance syngas quality and quantity through new catalysts which can resist harsh operation conditions [55]. The real-time monitoring and operator controls have been improved by integrating artificial intelligence into the processes, which will optimize reaction parameters for a greater energy recovery and reduction in emissions [56]. It is also worth noting that AI-based models help predict the most effective waste feedstock mixture for gasification to produce highest degree of yield and purity of syngas while minimising impact on environment [57], [58]. Another application of AI is that it can greatly enhance the conversion efficiency from waste to energy by using automated waste sorting, process monitoring and predicting energy yields. This optimization is vital for decreasing environmental impacts and to contribute to the circular economy in waste-to-energy industry [59]. Regarding civil engineering, waste composition is analysed by AI based systems to determine the best treatment in hazardous waste management with higher efficiency and environmental benefits [60]. The application of machine learning in this area allows separating impurities from raw material, composts and solid digestate that reduces environmental hazards and raise benefits from the production of composts and anaerobic digestion products [61]. These waste-to-energy technologies are regarded as an increasingly popular alternative to the traditional form of waste disposal, reducing landfill demands and diverting resources to achieve energy generation [62]. This leads to a more environmentally friendly strategy for the disposal of waste by converting it into energy products/electrical power, heat, and synthetic fuels [63], [64]. The concept of poly-generation is also being considered, which involves designing a waste-to-energy plant that should be able to produce more than just electricity from waste (e.g., heat and possibly liquid fuels or chemicals), making waste less of a liability and a greater resource [55]. Advanced waste-to-energy technologies including pyrolysis and gasification have been developed to provide a cleaner, more efficient means of energy recovery with regards to emissions and residues [65]. These techniques are of particular importance, as they provide an approach for the valorisation of a wide range of waste streams such as municipal solid and industrial wastes into valuable energy vectors and chemical precursors [63]. However, the technologies for waste-to-energy such as incineration, pyrolysis, anaerobic digestion, gasification and landfill gas recovery all are facing challenges in particulate matters emitting [66].

IV.2 CHEMICAL AND MECHANICAL RECYCLING

These enhanced recycling methods are expected to decrease dependence on virgin materials and the environmental impact of plastic manufacture and disposal, which will contribute to creating a more circular economy [67]. Artificial Intelligence based solutions are also especially important when it comes to waste management, revolutionizing and accelerating that change by including aspects such as automated sorting, recycling or material recovery supported by autonomous systems, predictive analytics and generative AI [68]. Moreover, automated AI-based systems will potentially transform waste analysis by recognizing useful components and channelling them to the most appropriate feedstock and energy conversion routes, which can be of great help to poor communities where municipal solid waste management remains inadequate [69]. Technologies such as depolymerization and pyrolysis are also important for deconstructing complex polymers into monomers which can be reutilised, bypassing the restrictions faced by mechanical recycling processes with mixed waste streams [70], [71]. The use of the state-of-the-art robotic systems, which are equipped with AI and machine learning technologies, also improves accuracy and effectiveness in sorting recyclables, thereby reducing contamination as well as increasing yields of good quality recycled materials [72]. AI algorithms are also able to improve the efficiency and quality of recycling by involving processing conditions with chemical and physical data on different waste streams on a recycled stream [73].

Such an analytical capacity may possibly result in more clear distinction between different categories of plastics, and hence cleaner recycling streams [74]. Furthermore, biological methods using enzymes and microbial communities provide the potential for environmentally friendly degradation routes for different classes of polymers, and recently engineered strains that degrade a wide array of materials are making denovo production even more attractive [70]. These biotech advances, along with AI-extended optimization, are turning waste into resources—in tune with circular economy approaches [71]. Wilts et al. have shown that incorporation of AI in waste management system leads to significant improvement in recycling efficiency and material purity, representing a real impact on operational effectiveness (and safety) [75].

V. GREEN AND SUSTAINABLE MATERIALS

Chemical engineering has shifted toward designing materials that minimise environmental impact. The figure 5 presents how AI integrates bio-based materials, catalysts, and photocatalytic systems to enable efficient, low-impact, and sustainable material design and production.

V.1 BIO-BASED AND BIODEGRADABLE POLYMERS

Composites of cellulose-origin 5.95 within this report, focus will be directed on FDM adapted for graphene-reinforced composite manufacturing and study its applications using both nanocelluloses in the bioresources family. These materials feature lower carbon footprints but need increased performance. AI-enabled materials informatics could lead to accelerated discovery and optimization of new bio-based polymers by predicting targeted properties and synthetic routes. Moreover, AI models can open a new direction to develop biodegradable drugs with better environmentally friendly manner and make sustainable development in the pharmaceutical sector [76]. Ethylene chemistry is highly relevant for reducing the environmental footprint of drug production and consumption [77]. AI also promotes sustainable manufacturing by providing efficient resource usage, zero waste and keeping the environmental impact of industrial processes to a minimum through effective analytics on large datasets [78], [79]. It includes the creation of greener synthetic routes and increasing the circularity of chemical production lines to stimulate a more sustainable industrial ecosystem [80], [77]. These AI-based applications lead to prompting and updated control of chemical reactions, which in turn contributes towards efficient production with minimal hazardous by-products [60]. These smart systems are able to anticipate and prevent potential hazards of a chemical process, providing more safety and environmentally friendly production [78]. AI is also at the frontier in promoting environmental chemistry and sustainability, through applications of computational models and data analytics to interpret intricate environmental processes as these relate to pollution control [81]. This integration contributes to the effective exploitation of resources, greener production processes performance and improved recyclability of products, which are essential components for a circular economy [77]. These developments are consistent with the overall objectives of green engineering principles and circular economy to promote sustainable product design; extractive operations waste utilization, reuse and recycling [82], [83]. Yet the scale-up of bio-based polymer production can be impaired by the long and tedious process to acquire high quality data for reliable AI/ML prediction models (since literature data from different natural components and protocols is variable), as well as in identifying the best conditions [84]. However, AI and machine-learning technology show great promise to solve such problems by search for new material combinations as well as the optimization of synthesis condition toward scalability and performance [84]. AI-based methodologies are also key in solving complex sustainability challenges thanks to comprehensive, multiscale modelling and decision-support tools for handling intricate relations among social, natural and engineered systems [85]. AI can connect data and methods necessary to predict sustainability metrics that enable the design of sustainable chemical processes as well as closed-loop supply chains [86].

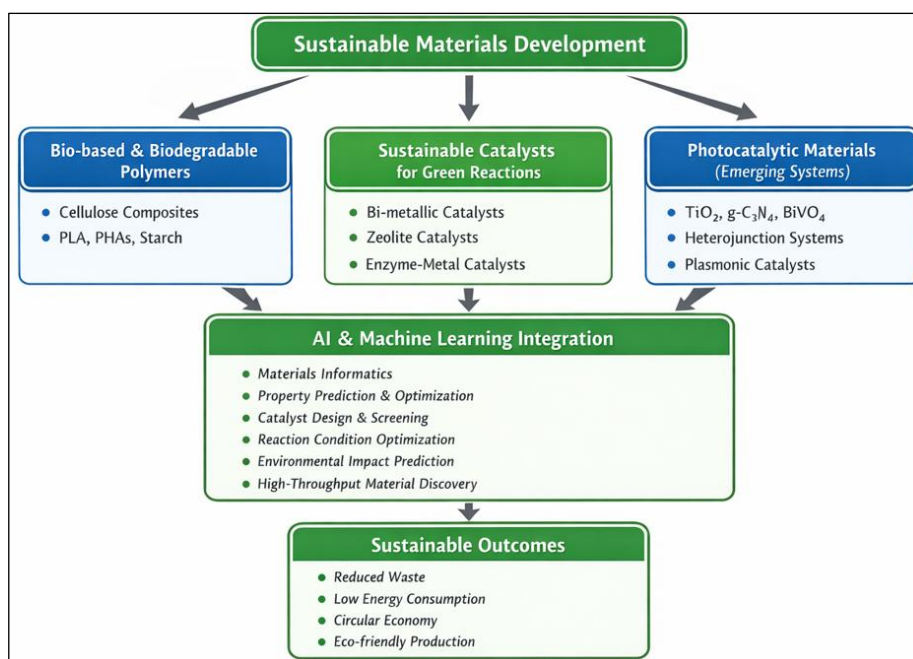


Figure 5: AI-Driven Framework for Green and Sustainable Material Development.
Source: Authors (2026).

V.2 CATALYSTS FOR SUSTAINABLE CHEMICAL REACTIONS

Green catalysts prefer to achieve high selectivity and low energy cost. AI-based methodologies have facilitated the fast discovery and rational design of novel sustainable catalysts and reaction pathways, thus minimizing waste production and energy consumption [87]. Such combination leads to catalysts of higher efficacy that have less dependence on precious metals activity and, consequently, pursuing cleaner chemical processes [77]. These new developments combined with AI-based optimization methods not only contribute to a quicker shift towards the circular economy but also increase the economic viability and market penetrability of biomaterials and green technology [88]. By utilizing AI, the chemical industry will be able to predict environmental and toxicological impact of new substances prior to their synthesis, which in turn can be beneficial for the development of safer alternatives and promote green chemistry by means of identifying eco-friendly materials and energy-efficient processes [81]. This predictive power dramatically speeds up the R&D by guiding efforts toward desirable candidates, which satisfy comprehensive and strict sustainability requirements [89]. This predictive discovery of eco-friendly new materials, at an early stage of technology integration, will result in rapid rates of deployment of data and AI and evaluation of the factors contributing to environmental impact [89]. Through inputting machine learning algorithms with pertinent multidimensional scientific and secondary data, AI simulations together with quality control predictions, will characterize substance properties adapted to given applications, environmental conditions and local context [90]. It enables rapid screening and development of materials with specific performance targets (e.g. specific energy, rate capability) while also minimizing their environmental impact from cradle-to-gate [89]. This involves leveraging AI to maximize the chemical process parameters used to convert waste oils into biodiesel thus improving both yield and product quality [56]. Table 3 provides a concise comparison of major green and sustainable material technologies, highlighting their developments, benefits, limitations and current research trends.

Table 3: Summary of Sustainable Material Technologies and Their Performance Characteristics.

Category	Key Developments / Techniques	Advantages	Challenges	Notes / Research Trends
Bio-based & Biodegradable Polymers	PLA, PHAs, starch blends	Lower carbon footprint	Performance limitations	AI-assisted materials informatics accelerates polymer discovery
	Cellulose-based composites & graphene-reinforced biocomposites	Renewable, compostable	Mechanical strength issues	Nanocellulose improves reinforcement in sustainable composites
	AI-enabled polymer design	Predictive property optimization	Requires high-quality datasets	Supports greener drug and chemical production
	Green synthetic routes	Reduced waste, low toxicity	Scale-up complexity	Supports circular chemical manufacturing
Catalysts for Sustainable Reactions	Bi-metallic catalysts	High selectivity, improved efficiency	Cost of metals	AI accelerates catalyst discovery and screening
	Zeolite catalysts with tunable pore size	Controlled reactions, reusable	Diffusion limitations	Widely explored for greener chemical pathways
	Enzyme-metal hybrid catalysts	Mild conditions, specificity	Stability issues	Biomimetic catalysts emerging rapidly
	AI-driven catalyst optimization	Faster design, less waste	High computational demand	Predicts environmental impact early in design
Emerging Photocatalytic Materials	Doped TiO ₂	Visible-light activity	Recombination losses	AI predicts optimal doping and band-gap tuning
	g-C ₃ N ₄ and heterojunctions	Good stability, low cost	Limited charge separation	ML models guide heterojunction engineering
	Z-scheme p-n junctions	High efficiency	Structural complexity	Designed for multi-pollutant degradation
	Plasmonic (Ag-based) photocatalysts	Enhanced electron mobility	Silver cost, stability	High-throughput AI screening for next-gen photocatalysts
	AI-optimized photocatalytic systems	Better reaction conditions	Requires experimental validation	Integrates DFT+ML for predictive catalyst design

Source: Authors (2026).

V.3 EMERGING PHOTOCATALYTIC MATERIALS

Photocatalysis harnesses sunlight to dismantle pollutants or generate fuels. AI-assisted simulations are essential for developing new efficient and stable photocatalytic materials optimized with respect to their band gap and charge separation properties, tailored for a large variety of environmental applications [81]. In concrete, AI can forecast the behaviour of heterogeneous catalysts by correlating their complex structure with their composition and reactivity as a function of various environmental conditions [91]. It provides a way to the more focused research on the advanced catalytic systems and make a new and better catalyst be discovered in an efficient way. In addition, ML algorithms can help to achieve the optimal conditions for reactions and make photocatalytic process more efficient with low environmental footprints [92], [93]. AI is also used to predict beneficial technologies for multiple pollutants and designing continuous flow systems (such as key chemical variables – catalyst-to-contaminant ratio, purity and pH of reactants and temperature) in catalytic reactions [94]. In addition, AI empowered design tools can be used for high throughput screening of large material libraries to identify best candidates for catalytic applications that maintain high activity, selectivity and stability under the operation relevant conditions [95]. This capacity greatly diminishes the number of time-consuming experimental trials, hence saves resources and accelerates next-generation catalyst design [96]. Such an integration not only improves the design efficiency, but also makes manufacturing process more sustainable, which may assist businesses in complying with new regulations about environmentally responsible production [78]. Furthermore, the integration of density functional theory with machine learning has facilitated the high throughput exploration of material properties and predicted catalytic performance and inverse designing specifically for binary photocatalytic systems [97]. Here, quantum-mechanical knowledge encoded in DFT is combined with the prediction ability of ML models for identifying new materials such as TiO₂, BiVO₄ and g-C₃N₄ and novel heterojunctions and co-catalysts to enhance light absorption and charge separation efficiency [97]. The enhancement of these materials lies in visible light absorption and electron mobility.

VI. CARBON MANAGEMENT AND CLIMATE SOLUTIONS

One of the most pressing is climate mitigation. This requires new ideas in carbon capture, utilization and storage (CCUS), for where AI plays a key role in optimizing capture processes and exploring new sorbents or catalysts [91], [81]. For instance, AI models can be used to predict desirable material properties for CO₂ adsorption and transformation leading to improvement of the efficiency and reducing the cost of carbon capture [95-98]. Furthermore, the AI based simulations for porous materials could accurately simulate the intricate interactions that occur in them and expedite discovery of new sorbents with high selectivity and capacity to capture CO₂. In addition, AI predictability is essential in the creation and discovery of novel catalytic materials for CO₂ conversion to high-value chemicals and become a key driver for the circular carbon economy [99], [100]. These AI-enabled approaches are the key to convergent reuse of waste CO₂ into valuable chemicals and implementing sustainable industrial symbiosis [101]. In addition to direct capture, AI helps monitor and verify carbon emissions around the world with unparalleled precision, helping ensure better policy interventions and adherence. Furthermore, AI-based systems can address the challenges associated with carbon utilization pathways by discovering and then developing recommended reactions for converting captured CO₂ to economically viable products (e.g., fuels and chemicals), strengthening the economic motivation to pursue projects that target motivations for sequestering CO₂ [54]. This holistic integrative strategy is not only to cope with environmental issues, but also to promote economic growth by turning these liabilities into assets in a sustainable manner [102]. AI in photocatalysis is also applicable to the case of hydrogen generation by water splitting; machine learning algorithms combined with density functional theory accelerates exploration for effective materials as well as their designing [97]. AI enhances these processes by improving sorbent regeneration, predicting breakthrough curves and designing new materials with exceptional CO₂ affinity and selectivity [81]. In addition, machine learning models can sift and process large data materials generated from both experimental and computational studies and predicting most performative material compositions and structure motifs with the highest CO₂ capture capabilities along with lowest energy penalties during regeneration [102]. It enables us to predict performance for CO₂ capture under different operating conditions, which speeds up the development of future generation capture technologies.

VII. CONCLUSION

Environmental chemical engineering is steadily moving toward methods that reduce pollution, conserve resources and support long-term sustainability. Progress across water and wastewater treatment, air pollution control, solid waste management and green material development shows how the field continues to respond to rising environmental pressures. Advanced oxidation systems, improved membranes, hybrid bioprocesses and data-driven optimisation strategies are helping address complex contaminants that conventional treatments cannot manage. Similar progress is seen in air quality management, where improved catalysts, filtration approaches and predictive control tools strengthen emission reduction efforts. Research on waste-to-energy routes, chemical recycling and resource recovery highlights the shift from disposal-driven practice to circular approaches. Work on bio-based polymers, sustainable catalysts and photocatalytic materials further supports cleaner production and reduced dependence on non-renewable inputs. Even with these advances, cost, operational stability, energy demand and scalability still limit widespread adoption. Addressing these constraints will require coordinated progress in materials research, process integration and digital tools that can support real-time optimisation. Continued collaboration among chemical engineers, environmental scientists and industry partners remains essential for translating emerging technologies into practical solutions. With sustained research and policy support, the technologies discussed in this review hold strong potential for cleaner production, improved environmental protection and more resilient resource management systems.

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X. REFERENCES

- [1] A. Abatan, A. Obaigbena, E. D. Ugwuanyi, B. S. Jacks, E. O. Sodiya, O. H. Daraojimba, and O. A. Lottu, "Simulation-driven strategies for enhancing water treatment processes in chemical engineering: Addressing environmental challenges," *Engineering Heritage Journal*, vol. 8, no. 1, p. 34, Jan. 2024. doi: 10.26480/gwk.01.2024.34.41.
- [2] N. C. Obiuto, K. A. Olu-lawal, E. C. Ani, E. D. Ugwuanyi, and N. Ninduwezur-Ehiobu, "Chemical engineering and the circular water economy: Simulations for sustainable water management in environmental systems," *World Journal of Advanced Research and Reviews*, vol. 21, no. 3, p. 1, Mar. 2024. doi: 10.30574/wjarr.2024.21.3.0647.
- [3] N. C. Obiuto, N. Ninduwezur-Ehiobu, E. C. Ani, K. A. Olu-lawal, and E. D. Ugwuanyi, "Simulation-driven strategies for enhancing water treatment processes in chemical engineering," *Engineering Science & Technology Journal*, vol. 5, no. 3, p. 854, Mar. 2024. doi: 10.51594/estj.v5i3.942.
- [4] R. Jarrar, M. K. G. Abbas, and M. Al-Ejji, "Environmental remediation and the efficacy of ceramic membranes in wastewater treatment: A review," *Emergent Materials*, vol. 7, no. 4, p. 1295, Apr. 2024. doi: 10.1007/s42247-024-00687-0.
- [5] M. S. Shekho and N. E. Hassan, "A review on techniques for the cleaning of wastewater," *GSC Advanced Research and Reviews*, vol. 18, no. 1, p. 118, Jan. 2024. doi: 10.30574/gscarr.2024.18.1.0005.
- [6] N. Nabbou, E. Benyagoub, M. Bekadour, B. Larabi, and A. Hamouine, "Removal of organic matters, phosphates and nitrates present in pond wastewater using chemical coagulant solutions," *Research Square*, Aug. 2025. doi: 10.21203/rs.3.rs-7364057/v1.
- [7] J. Fernandes, P. J. Ramísio, and H. Puga, "A comprehensive review on various phases of wastewater technologies: Trends and future perspectives," *Eng—Advances in Engineering*, vol. 5, no. 4, p. 2633, Oct. 2024. doi: 10.3390/eng5040138.
- [8] S. Satyam and S. Patra, "The evolving landscape of advanced oxidation processes in wastewater treatment: Challenges and recent innovations," *Processes*, vol. 13, no. 4, p. 987, Mar. 2025. doi: 10.3390/pr13040987.
- [9] C. B. Lecompte et al., "Advanced oxidation processes: Applications, trends, and prospects," *IntechOpen*, 2020. doi: 10.5772/intechopen.85681.
- [10] S. Jain and N. Jain, "Advanced oxidation processes," in *CRC Press eBooks*, 2024, p. 600. doi: 10.1201/9781003598152-83.
- [11] A. B. Ponnusami et al., "Advanced oxidation process combined biological process for wastewater treatment," *Environmental Research*, vol. 237, p. 116944, Aug. 2023. doi: 10.1016/j.envres.2023.116944.
- [12] M. L. Hernández-Macedo, J. A. López, K. I. B. Eguiluz, and G. R. Salazar-Banda, "Environmental biotechnology," *Revista Peruana de Biología*, vol. 27, no. 1, p. 43, Mar. 2020. doi: 10.15381/rpb.v27i1.17578.
- [13] S. Kathi et al., "Wastewater and sludge valorisation: A novel approach for treatment and resource recovery," *Frontiers in Chemical Engineering*, vol. 5, Apr. 2023. doi: 10.3389/fceng.2023.1129783.
- [14] V. Devda et al., "Recovery of resources from industrial wastewater employing electrochemical technologies," *Bioengineered*, vol. 12, no. 1, p. 4697, Jan. 2021. doi: 10.1080/21655979.2021.1946631.
- [15] R. Dewil, D. Mantzavinos, I. Poullos, and M. A. Rodrigo, "New perspectives for advanced oxidation processes," *Journal of Environmental Management*, vol. 195, p. 93, Apr. 2017. doi: 10.1016/j.jenvman.2017.04.010.
- [16] Y. Bashir, R. Raj, M. M. Ghangrekar, A. K. Nema, and S. Das, "Critical assessment of advanced oxidation processes and bio-electrochemical integrated systems for removing emerging contaminants from wastewater," *RSC Sustainability*, vol. 1, no. 8, p. 1912, 2023. doi: 10.1039/D3SU00112A.
- [17] G. Zhang et al., "Advanced oxidation processes," 2020, p. 173. doi: 10.1002/9781118928677.ch7.
- [18] M. Sievers, "Advanced oxidation processes," in *Elsevier eBooks*, 2011, p. 377. doi: 10.1016/B978-0-444-53199-5.00093-2.
- [19] A. Bhardwaj, S. Kumar, and D. Singh, "Tannery effluent treatment and its environmental impact: A review of current practices and emerging technologies," *Water Quality Research Journal*, vol. 58, no. 2, p. 128, May 2023. doi: 10.2166/wqrj.2023.002.
- [20] M. Kovačić, H. Kušić, A. L. Božić, and D. D. Dionysiou, "Advanced oxidation processes," in *Encyclopedia of Water*, 2019.
- [21] Z. Q. S. Nwokiediegwu et al., "A review of advanced wastewater treatment technologies: USA vs. Africa," *International Journal of Science and Research Archive*, vol. 11, no. 1, p. 333, Jan. 2024. doi: 10.30574/ijrsra.2024.11.1.0071.

- [22] A. Das and S. Mishra, "Reimagining biofiltration for sustainable industrial wastewater treatment," *Discover Sustainability*, vol. 6, no. 1, Aug. 2025. doi: 10.1007/s43621-025-01784-8.
- [23] M. Ahmed *et al.*, "Recent developments in hazardous pollutants removal from wastewater," *npj Clean Water*, vol. 5, no. 1, Apr. 2022. doi: 10.1038/s41545-022-00154-5.
- [24] J. Shamshad and R. U. Rehman, "Innovative approaches to sustainable wastewater treatment," *Environmental Science Advances*, 2024.
- [25] B. T. Akinyemi, O. D. Ogundele, and A. B. Afolabi, "Advancements in sustainable membrane technologies," *Acadlore Transactions on Geosciences*, vol. 2, no. 4, p. 196, Nov. 2023. doi: 10.56578/atg020402.
- [26] R. K. Langbehn *et al.*, "Treatment approaches for emerging contaminants," in *IWA Publishing eBooks*, 2024, p. 113. doi: 10.2166/9781789063752_0113.
- [27] E. D. Ugwuanyi *et al.*, "Review of emerging technologies for nutrient removal," *World Journal of Advanced Research and Reviews*, vol. 21, no. 2, p. 1737, Feb. 2024. doi: 10.30574/wjarr.2024.21.2.0520.
- [28] E. D. Ugwuanyi *et al.*, "Reviewing the potential of anaerobic membrane bioreactors," *International Journal of Science and Research Archive*, vol. 11, no. 1, p. 1830, Feb. 2024. doi: 10.30574/ijrsra.2024.11.1.0290.
- [29] N. Morin-Crini *et al.*, "Remediation of emerging contaminants," in *Environmental Chemistry for a Sustainable World*, 2021. doi: 10.1007/978-3-030-69090-8_1.
- [30] S. A. Bhat *et al.*, "Detection and treatment of emerging contaminants in wastewater," *IWA Publishing*, 2024.
- [31] H. Huang, R. Ma, and H. Ren, "Innovations in wastewater treatment in China," *Frontiers of Environmental Science & Engineering*, 2024. doi: 10.1007/s11783-024-1832-3.
- [32] A. IA *et al.*, "Water pollution: Effects, prevention, and climatic impact," *InTech eBooks*, 2018. doi: 10.5772/intechopen.72018.
- [33] A. Khalidi-Idrissi *et al.*, "Advances in biological wastewater treatment," *International Journal of Environmental Science and Technology*, 2023. doi: 10.1007/s13762-023-04867-z.
- [34] J. S. Sravan *et al.*, "Biological wastewater treatment processes," *Bioengineering*, 2024. doi: 10.3390/bioengineering11030281.
- [35] V. Kumar, M. Bilal, and L. F. R. Ferreira, "Recent trends in integrated wastewater treatment," *Frontiers in Microbiology*, 2022. doi: 10.3389/fmicb.2022.846503.
- [36] A. Sánchez, "Role of chemical engineering in environmental problems," *Frontiers in Chemical Engineering*, 2019. doi: 10.3389/fceng.2019.00001.
- [37] Y. Ye *et al.*, "LLMs4AI: A systematic review," *arXiv*, 2025. doi: 10.20944/preprints202510.1383.v1.
- [38] A. E. Ite and I. A. Ite, "Organic micropollutants in air," *Environment & Ecosystem Science*, 2024. doi: 10.26480/ees.01.2024.36.52.
- [39] Q. Huang, "Environmental catalysis challenges," *Frontiers in Environmental Engineering*, 2022. doi: 10.3389/fenve.2022.1087494.
- [40] F. M. Christensen *et al.*, "Nano-enabled environmental technologies," Technical University of Denmark, 2015.
- [41] V. Makwana, "Efficiency enhancement in automotive catalytic converters: Recent developments and future directions," *International Journal for Research in Applied Science and Engineering Technology*, vol. 12, no. 4, p. 2451, Apr. 2024. doi: 10.22214/ijraset.2024.60383.
- [42] D. Bakhchin, R. Ravi, O. Douadi, M. Faqir, and E. Essadiqi, "Integrated catalytic systems for simultaneous NOx and PM reduction," *Research Square*, May 2024. doi: 10.21203/rs.3.rs-4187531/v1.
- [43] L. Gao *et al.*, "Study on high stability and catalytic properties of MOF materials," *Research Square*, Oct. 2024. doi: 10.21203/rs.3.rs-4943522/v1.
- [44] X. Gao, C. Zheng, T. Sagawa, M. Sankar, C. Wu, and E. Tronconi, "Air pollution control for a green future," *Journal of Zhejiang University Science A*, vol. 19, no. 1, p. 1, Jan. 2018. doi: 10.1631/jzus.A17EU001.
- [45] M. R. Letsoalo *et al.*, "Sustainable approaches to monitoring urban particulate matter," *IntechOpen*, 2024. doi: 10.5772/intechopen.1007884.
- [46] E. Y. Kulikova, V. Sulimin, and V. Shvedov, "Artificial intelligence for ambient air quality control," *E3S Web of Conferences*, vol. 419, p. 3011, 2023. doi: 10.1051/e3sconf/202341903011.
- [47] R. Bhat *et al.*, "Improvement of air quality using sustainable technologies," *E3S Web of Conferences*, vol. 505, p. 3011, 2024. doi: 10.1051/e3sconf/202450503011.
- [48] J. Awewomom *et al.*, "Addressing global environmental pollution using control techniques," *Discover Environment*, vol. 2, no. 1, Feb. 2024. doi: 10.1007/s44274-024-00033-5.
- [49] F. Wang *et al.*, "Advances in particulate matter filtration via triboelectric nanogenerators," *Advanced Composites and Hybrid Materials*, vol. 8, no. 5, Sep. 2025. doi: 10.1007/s42114-025-01433-8.
- [50] N. A. Imam, N. Y. Dada, and F. A. Imam, "Natural polymer nanocomposites for eco-friendly applications," *International Journal for Research in Applied Science and Engineering Technology*, vol. 12, no. 5, p. 2401, May 2024. doi: 10.22214/ijraset.2024.62091.
- [51] S. U. R. Memon *et al.*, "A comprehensive review of carbon capture, utilization, and storage," *Scholars Academic Journal of Biosciences*, vol. 12, no. 7, p. 184, Aug. 2024. doi: 10.36347/sajb.2024.v12i07.003.
- [52] B. Panerua and B. Paneru, "Advancing carbon capture using AI," *arXiv*, Jan. 2025.
- [53] D. Liu and N. Sun, "Prospects of AI in sustainable separation processes," *Frontiers in Sustainability*, vol. 4, Jul. 2023. doi: 10.3389/frsus.2023.1210209.

- [54] A. K. Priya *et al.*, “Artificial intelligence enabled carbon capture: A review,” *Science of the Total Environment*, vol. 886, p. 163913, May 2023. doi: 10.1016/j.scitotenv.2023.163913.
- [55] K. T. Alao *et al.*, “Biomass and organic waste conversion for bioenergy,” *International Journal of Renewable Energy Development*, vol. 13, no. 4, p. 750, May 2024. doi: 10.61435/ijred.2024.60149.
- [56] M. I. Ali *et al.*, “Artificial intelligence in biotechnology,” *Nepal Journal of Biotechnology*, vol. 12, no. 1, Jul. 2024. doi: 10.54796/njb.v12i1.312.
- [57] M. Sharma *et al.*, “Recent developments in biofuel separation and storage,” 2025. doi: 10.2139/ssrn.5433358.
- [58] M. Rehan *et al.*, “Integrated waste biorefineries for sustainable development,” *Frontiers in Energy Research*, vol. 11, Dec. 2023. doi: 10.3389/fenrg.2023.1339666.
- [59] V. Melinda *et al.*, “Enhancing waste-to-energy conversion using AI,” *International Transactions on Education Technology*, vol. 2, no. 2, p. 183, May 2024. doi: 10.33050/itee.v2i2.597.
- [60] V. L. Sivakumar *et al.*, “AI-enhanced decision support systems for hazardous waste handling,” *International Journal of Civil Engineering*, vol. 10, no. 11, 2023. doi: 10.14445/23488352/IJCE-V10I11P101.
- [61] B. Fang *et al.*, “Artificial intelligence for waste management in smart cities,” *Environmental Chemistry Letters*, vol. 21, no. 4, p. 1959, May 2023. doi: 10.1007/s10311-023-01604-3.
- [62] I. U. Rahman *et al.*, “Recent waste-to-energy advancements,” *Discover Chemical Engineering*, vol. 5, no. 1, Mar. 2025. doi: 10.1007/s43938-025-00079-8.
- [63] N. Sharma *et al.*, “From waste to worth management,” *E3S Web of Conferences*, vol. 453, p. 1029, 2023. doi: 10.1051/e3sconf/202345301029.
- [64] R. Chaturvedi *et al.*, “Sustainability in manufacturing industry,” *E3S Web of Conferences*, vol. 453, p. 1036, 2023. doi: 10.1051/e3sconf/202345301036.
- [65] C. G. Achi *et al.*, “Advanced waste-to-energy technologies,” *Nature Environment and Pollution Technology*, vol. 23, no. 3, p. 1239, Sep. 2024. doi: 10.46488/NEPT.2024.v23i03.002.
- [66] A. Rejeb *et al.*, “Knowledge diffusion in circular economy,” *Circular Economy and Sustainability*, vol. 3, no. 1, p. 125, 2022. doi: 10.1007/s43615-022-00189-3.
- [67] B. Sukla *et al.*, “Innovations in sustainable engineering,” 2024. doi: 10.53555/kuey.v30i5.3511.
- [68] A. Snoun *et al.*, “AI-driven innovations in waste management,” *Engineering Proceedings*, vol. 12, Jun. 2025. doi: 10.3390/engproc2025097012.
- [69] K. S. Salem *et al.*, “Optimization of solid waste management systems,” *Matter*, vol. 6, no. 10, p. 3348, Aug. 2023. doi: 10.1016/j.matt.2023.08.003.
- [70] O. O. Alabi *et al.*, “Plastic waste recycling technologies,” *RSC Advances*, vol. 15, no. 48, p. 40541, 2025. doi: 10.1039/D5RA06715D.
- [71] M. Alaghemandi, “Innovative plastic waste recycling technologies,” *Sustainability*, vol. 16, no. 23, p. 10401, Nov. 2024. doi: 10.3390/su162310401.
- [72] J. J. Kanade and T. S. M. Varghese, “Solid waste management for environmental sustainability,” *Journal of Informatics Education and Research*, vol. 4, no. 1, Feb. 2024. doi: 10.52783/jier.v4i1.599.
- [73] T. Özsoy, “Role of AI in circular economy transition,” *Nisantasi University Journal*, vol. 11, no. 2, p. 369, Oct. 2023. doi: 10.52122/nisantasisbd.1345828.
- [74] N. L. Rane, J. Rane, and M. Paramesha, “AI and business intelligence in ESG strategies,” 2024. doi: 10.70593/978-81-981367-4-9_3.
- [75] N. Almtireen *et al.*, “PLC-controlled intelligent conveyor system with AI vision,” *Applied Sciences*, vol. 15, no. 3, p. 1550, Feb. 2025. doi: 10.3390/app15031550.
- [76] A. Ruiz-Gonzalez, “AI-driven chemical design,” *Future Pharmacology*, vol. 5, no. 2, p. 24, May 2025. doi: 10.3390/futurepharmacol5020024.
- [77] S. Saeed *et al.*, “Advancing circular economy in industrial chemistry,” *European Journal of Chemistry*, vol. 14, no. 3, p. 414, Sep. 2023. doi: 10.5155/eujchem.14.3.414-428.2452.
- [78] R. Namdeti, “Artificial intelligence in chemical engineering,” 2023.
- [79] F. A. Idoko *et al.*, “Green chemistry in manufacturing,” *World Journal of Advanced Research and Reviews*, vol. 23, no. 3, p. 2826, Sep. 2024. doi: 10.30574/wjarr.2024.23.3.2938.
- [80] J. Lee and A. Marrocchi, “Advances in green chemistry and engineering,” *Scientific Reports*, vol. 14, Mar. 2024. doi: 10.1038/s41598-024-53594-z.
- [81] V. P. Ananikov, “Top AI-based technologies in chemistry,” *Artificial Intelligence Chemistry*, vol. 2, no. 2, p. 100075, Jul. 2024. doi: 10.1016/j.aichem.2024.100075.
- [82] R. Márquez *et al.*, “AI and product-based learning in materials education,” *Research Square*, 2023. doi: 10.21203/rs.3.rs-2711749/v1.
- [83] N. A. Tarazona *et al.*, “Sustainable polymer materials in circular economy,” *MRS Energy & Sustainability*, vol. 9, p. 28, Feb. 2022. doi: 10.1557/s43581-021-00015-7.
- [84] T. Chen *et al.*, “Machine intelligence for plastic substitutes,” *Nature Nanotechnology*, vol. 19, no. 6, p. 782, Mar. 2024. doi: 10.1038/s41565-024-01635-z.
- [85] A. W. Dowling, “AI for sustainable engineering systems,” *Systems and Control Transactions*, vol. 3, p. 22, Jul. 2024. doi: 10.69997/sct.114705.
- [86] P. Glavič *et al.*, “Net-zero emissions in chemical industries,” *Processes*, vol. 11, no. 9, p. 2647, Sep. 2023. doi: 10.3390/pr11092647.
- [87] F. Kurul *et al.*, “Principles of green chemistry,” *Discover Chemistry*, vol. 2, no. 1, Apr. 2025. doi: 10.1007/s44371-025-00152-9.
- [88] X. Xue *et al.*, “AI and sustainable materials,” *Scientific Reports*, vol. 15, Oct. 2025. doi: 10.1038/s41598-025-20803-2.

- [89] A. Toniato, O. Schilter, and T. Laino, "AI in sustainable chemical industry," *CHIMIA*, vol. 77, no. 3, p. 144, Mar. 2023. doi: 10.2533/chimia.2023.144.
- [90] E. Hermann *et al.*, "Ethical AI in chemical research," *Science and Engineering Ethics*, vol. 27, no. 4, Jul. 2021. doi: 10.1007/s11948-021-00325-6.
- [91] P. Lakhani *et al.*, "Support materials in green catalysis," *Discover Catalysis*, vol. 1, no. 1, Oct. 2024. doi: 10.1007/s44344-024-00002-3.
- [92] M. S. Akhtar and W. Zaman, "Advancing sustainable catalysis," *Catalysts*, vol. 15, no. 6, p. 511, May 2025. doi: 10.3390/catal15060511.
- [93] W. Ren, "AI for catalyst design," 2024. doi: 10.52768/3067-7947/1010.
- [94] V. I. Pârvulescu *et al.*, "Catalytic water treatment," *Chemical Reviews*, vol. 122, no. 3, p. 2981, Dec. 2021. doi: 10.1021/acs.chemrev.1c00527.
- [95] L. Han and Z. Xiang, "Intelligent catalytic materials," 2023.
- [96] T. Xue *et al.*, "Photocatalytic NO_x removal," *Chemical Science*, vol. 15, no. 24, p. 9026, 2024. doi: 10.1039/D4SC01891E.
- [97] D. D. K. Wayo *et al.*, "AI and quantum computing in hydrogen production," *arXiv*, 2024.
- [98] S. M. Y. Bhuiyan *et al.*, "AI-driven hydrogen production optimization," *American Journal of Interdisciplinary Studies*, vol. 6, no. 1, p. 76, Apr. 2025. doi: 10.63125/06z40b13.
- [99] A. Li *et al.*, "AI-catalyst pipeline for industrial innovation," *Frontiers of Chemical Science and Engineering*, vol. 19, no. 7, May 2025. doi: 10.1007/s11705-025-2560-3.
- [100] H. Xin *et al.*, "Roadmap for AI in heterogeneous catalysis," 2025. doi: 10.26434/chemrxiv-2025-chn4j.
- [101] S. R. Pratihari *et al.*, "AI-accelerated materials innovation framework," *arXiv*, 2023.
- [102] W. Yan *et al.*, "Carbon capture innovation challenge," 2018.