ENGI 9605: Water and Wastewater Treatment

Application of Advanced Materials for Wastewater Treatment

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Executive Summary:

Water is a necessary resource for human life and to carry out an endless number of daily activities ranging from domestic to industrial. Drinking water is withdrawn from water bodies, such as surface water or groundwater, and passes through treatment systems before being distributed to households. After being used, the water is transported through a sewage system to be collected and treated in treatment plants, to finally be discharged into surface water. Due to the increasing global water crisis, it is urgent need for innovative and sustainable solutions in wastewater treatment (Vasiljević et al. 2023). That's why water scarcity poses a critical challenge globally, necessitating innovative and sustainable solutions for wastewater treatment. This paper explores the transformative potential of advanced materials in addressing this crisis, focusing on Metal-Organic Frameworks and low-cost activated carbon derived from organic waste.

The first case study delves into the intellectual structure and research trends surrounding MOF applications in wastewater treatment. Through bibliometric analysis, it reveals a growing interest and significant contributions globally, emphasizing the interdisciplinary nature of research and key themes such as adsorption properties and reactor design (Naseer et al. 2022).

The second case study examines the efficiency of activated carbon from coconut shells, banana peels, and orange peels in pollutant removal. These materials demonstrate promising adsorption capabilities, with unique physical characteristics influencing their performance. Notably, orange peel-derived activated carbon shows exceptional efficiency, potentially due to functional groups enhancing adsorption capacity (Sudheer et al. 2020).

Furthermore, the paper highlights emerging technologies like nanosorbents and nanostructured catalytic membranes, offering efficient and environmentally benign solutions. However,

challenges such as cost, compatibility issues, and health hazards persist, necessitating the development of modified nanomaterials that are cost-effective, eco-friendly, and easily deployable for widespread adoption in wastewater treatment (García-Ávila, Avilés-Añazco, Sánchez-Cordero, Valdiviezo-Gonzáles, & Ordoñez, 2021)

In conclusion, this paper underscores the urgent need for sustainable solutions in wastewater treatment and outlines the promising avenues offered by advanced materials and emerging technologies. By addressing key challenges and leveraging innovative approaches, the path towards efficient and accessible water treatment solutions becomes clearer, contributing to global water security and sustainability.

Keywords: Wastewater, Advanced Materials, Nanomaterials, Membranes, Activated Carbon.

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Objectives of the Study:

1. Investigate the role of advanced materials, including Metal-Organic Frameworks (MOFs) and low-cost activated carbon derived from organic waste, in revolutionizing wastewater treatment.
2. Analyze the intellectual structure and research trends surrounding MOF applications in wastewater decontamination through bibliometric analysis.
3. Evaluate the efficiency and potential of activated carbon from various organic sources in pollutant removal, focusing on their unique physical characteristics and adsorption capabilities.
4. Explore emerging technologies such as nanosorbents and nanostructured catalytic membranes, highlighting their potential to offer efficient and environmentally benign solutions for wastewater treatment.

Details of the Steps Followed in the Study:

1. **Literature Review:** Conduct an extensive review of existing literature on advanced materials and emerging technologies in wastewater treatment, including Metal-Organic Frameworks (MOFs), activated carbon from organic waste, nanosorbents, and nanostructured catalytic membranes. Gather relevant research articles, reviews, and scholarly publications to establish a comprehensive understanding of the current state-of-the-art.
2. **Case Study Analysis:**

   (a) MOFs for Wastewater Decontamination: Utilize bibliometric analysis to investigate the intellectual structure and research trends surrounding MOF applications in wastewater treatment. Employ systematic searches of databases such as Web of Science to identify relevant publications. Analyze author demographics, publication trends, journal distributions, and keyword frequency to gain insights into research themes and emerging topics.

(b) Efficiency of Activated Carbon: Evaluate the efficiency of activated carbon derived from coconut shells, banana peels, and orange peels in pollutant removal. Examine characteristics of activated carbon samples through Scanning Electron Microscopy (SEM) to understand their physical properties. Assess pollutant removal efficiency based on experiments conducted at varying sizes, concentrations, and pH ranges.

3. **Comparative Analysis:** Conduct a comparative analysis of MOFs and activated carbon in terms of their effectiveness, cost-efficiency, and environmental impact in wastewater treatment. Compare the adsorption capacities, surface properties, and scalability of these materials to identify their respective strengths and limitations.
4. **Exploration of Emerging Technologies:** Investigate the potential of emerging technologies such as nanosorbents and nanostructured catalytic membranes in wastewater treatment. Review recent advancements, case studies, and experimental findings to assess their efficiency, feasibility, and applicability in real-world scenarios.
5. **Synthesis and Interpretation:** Synthesize findings from the literature review, case studies, and comparative analysis to draw conclusions regarding the role of advanced materials and emerging technologies in sustainable wastewater treatment.

Case Studies:

Case Study 1: Metal-Organic Frameworks for Wastewater Decontamination: Discovering Intellectual Structure and Research Trends (Naseer et al. 2022).

Metal-Organic Frameworks (MOFs) have garnered significant attention in recent years as promising materials for wastewater treatment due to their unique structural properties and high adsorption capacities. This case study delves into the evolving landscape of MOF applications in wastewater decontamination, drawing insights from the comprehensive analysis presented in the article (Naseer et al. 2022).

Materials and Methods: The study employed a robust methodology to conduct a bibliometric analysis of the research trends in MOF applications for wastewater treatment. Initially, a systematic search was conducted using the Web of Science database to identify relevant publications spanning the last 50 years. A total of 1187 articles were extracted, encompassing a wide range of studies focusing on the use of MOFs in wastewater treatment.

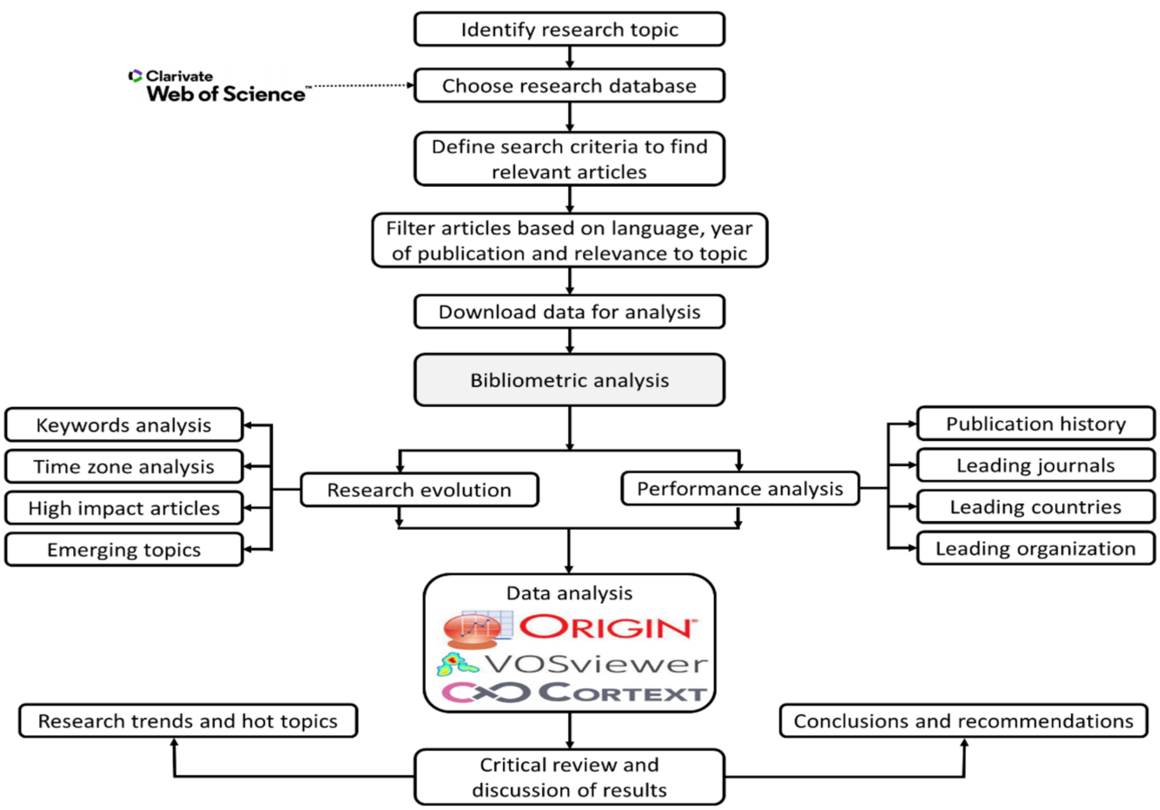

Figure 1: The research methodology used in this study (Naseer et al. 2022).

Subsequently, the researchers utilized bibliometric tools to analyze various aspects of the collected literature. Author demographics were examined to understand the geographical distribution of research contributions, highlighting the key countries and institutions driving advancements in this field. Furthermore, the analysis delved into publication trends, identifying leading journals and prolific authors in the domain of MOF applications for wastewater decontamination.

In addition to author demographics, the study explored keyword frequency and co-occurrence to uncover the prevalent research themes and emerging topics in MOF-based wastewater treatment. By identifying key keywords and their relationships, the researchers gained insights into the evolving research landscape and the focal points of current investigations in this area. This comprehensive analysis provided a holistic view of the intellectual structure and research trends shaping the field of MOF applications for wastewater decontamination (Naseer et al. 2022).

Results and Discussion: The results of the bibliometric analysis shed light on the global research landscape of MOF applications in wastewater treatment, revealing a growing interest and significant contributions from researchers worldwide. The analysis of author demographics highlighted the prominent role of countries such as China, Iran, and Saudi Arabia in advancing research in this field, underscoring the international collaboration and knowledge exchange driving innovation in MOF-based wastewater treatment technologies (Naseer et al. 2022).

Moreover, the examination of publication trends and journal distribution showcased the diverse interdisciplinary nature of research in this domain, with contributions from fields such as materials science, engineering, and environmental science. The keyword analysis provided valuable insights into the key research themes and hot topics, emphasizing the focus on adsorption properties, reactor design, and performance enhancements of MOFs for efficient wastewater decontamination.

Overall, the materials and methods employed in this study facilitated a comprehensive analysis of the research trends and intellectual structure of MOF applications in wastewater treatment, offering valuable insights for researchers, policymakers, and industry stakeholders involved in advancing sustainable solutions for wastewater decontamination.

Case Study 2: Low-cost activated carbon production from organic waste and its utilization for wastewater treatment (Sudheer et al. 2020).

The research centered on transforming organic waste materials, including coconut shell, orange peels, and banana peels, into activated carbon using phosphoric acid as a catalyst at temperatures ranging from 200 to 300°C. The primary objective was to explore the potential of this activated carbon in wastewater treatment. Through extensive Jar tests, different particle sizes and concentrations of activated carbon were evaluated to gauge their effectiveness in removing pollutants from wastewater. The findings showcased remarkable pollutant removal rates, particularly for COD and TSS. Notably, activated carbon derived from orange peels exhibited superior performance, suggesting its promise as a cost-effective solution for wastewater treatment in Oman. This study highlights the feasibility of utilizing locally sourced organic waste to produce activated carbon, thereby addressing both environmental concerns and the management of organic waste materials in a sustainable manner (Sudheer et al. 2020).

The global challenge of accessing safe drinking water is particularly acute in Oman, where freshwater resources are limited. Consequently, there's a critical need for wastewater treatment and recycling to alleviate pressure on these resources. Researchers are actively exploring cost-effective methods such as adsorption, membrane filtration, and reverse osmosis to render wastewater reusable. Activated carbon, known for its efficiency, is a favored technique, but the high cost of coal-based activated carbon has spurred interest in cheaper alternatives like agricultural waste such as coconut shells, orange peels, and banana peels. These materials contain functional groups with significant pollutant absorption capacities, making them ideal for adsorption and offering economic benefits through waste recycling.

Studies have shown that activated carbon derived from agricultural waste possesses excellent pollutant absorption capabilities, with factors like activation process and raw materials significantly influencing its efficiency. Chemical activation, especially with phosphoric acid, enhances activated carbon's porous structure, increasing its surface area and pore volume. Despite extensive research on activated carbon globally, there's a dearth of studies in Oman. Furthermore, while low-cost adsorbents hold promise for wastewater treatment, there's insufficient data on their performance with real wastewater. This study aims to address these gaps by evaluating various activated carbons derived from waste materials in Oman and investigating the impact of different particle sizes and concentrations on absorption efficiency, thereby enhancing the understanding and utilization of low-cost adsorbents for wastewater treatment in the region (Sudheer et al. 2020).

Materials and methods:

Preparation of activated carbon

The process commenced with gathering 250 grams of coconut shell, banana peels, and orange peels from household kitchens. These materials underwent preparation by being diced into small fragments, rinsed with tap water, and left to air dry under sunlight for a duration of 24 hours. Subsequently, they were exposed to specific incineration temperatures suited to their individual attributes within a muffle furnace, with the temperature gradually increasing at a rate of 20°C per minute until the desired levels were achieved. Following cooling, the samples were cleansed with distilled water to eliminate any impurities and then subjected to drying in an oven set at 105°C.

To activate the materials with acid, they were immersed in concentrated phosphoric acid for a duration of 24 hours to enhance their porosity and surface area. Thereafter, they underwent the same incineration process as previously described. After acid activation, any residual acid was eliminated by soaking the samples in distilled water containing sodium bicarbonate, followed by repeated rinsing until a neutral pH was attained. The cleansed samples were subsequently dried at a temperature of 110°C.

Finally, the activated carbon derived from each material was further refined through milling and sieving to achieve various particle sizes, including 75 µm, 150 µm, and 425 µm mesh sizes. These meticulously processed, dried, and sieved samples were then stored in sanitized, dry containers for subsequent utilization. This stringent procedure ensures the production of activated carbon with customized characteristics ideally suited for efficient adsorption in wastewater treatment applications (Sudheer et al. 2020).

Physical Properties Analysis of Activated Carbon (AC) and Pollution Removal Efficiency:

The physical characteristics of activated carbon obtained from coconut shell (CSAC), banana peels (BPAC), and orange peels (OPAC) with a particle size of 75 microns were investigated through scanning electron microscopy (SEM) at the Central Analytical and Applied Research Unit (CAARU), Sultan Qaboos University, Oman. Following this examination, the effectiveness of these activated carbons in removing pollutants was evaluated. For each material, nine conical flasks were arranged, each containing different amounts of activated carbon (10 mg, 20 mg, and 50 mg) with various particle sizes (75, 150, and 425 microns). Prior to adding activated carbon, each flask was filled with 100 ml of wastewater sample. The samples were stirred at 120 rpm and maintained at 20°C for 1 hour using an Orbital Shaker. After allowing the samples to settle for 30 minutes, they were filtered using 40-grade Whatman filter paper. Following filtration, water quality parameters such as pH, Chemical Oxygen Demand (COD), and Total Suspended Solids (TSS) were determined in accordance with AWWA/APHA standard protocols (Sudheer et al. 2020).

Conclusions and Discussion:

This study highlights the urgency of addressing global water scarcity through innovative and sustainable wastewater treatment solutions. By exploring the transformative potential of advanced materials such as Metal-Organic Frameworks (MOFs) and low-cost activated carbon, alongside emerging technologies like nanosorbents, it underscores the importance of interdisciplinary research and development. Despite challenges such as cost and compatibility issues, the promising efficiency and environmental benefits of these materials offer a clear path towards enhancing water security and sustainability worldwide.

The case study based on the first case study (Naseer et al. 2022) underscores the importance of advanced materials, particularly Metal-Organic Frameworks, in revolutionizing wastewater treatment technologies. The insights gleaned from the analysis of research trends and intellectual structure in MOF applications for wastewater decontamination provide a roadmap for future developments in sustainable water treatment solutions.

Moving forward, continued research and innovation in the field of advanced materials for wastewater treatment are essential to address the pressing environmental challenges posed by water pollution. By leveraging the unique properties of MOFs and other advanced materials, researchers and practitioners can enhance the efficiency and effectiveness of wastewater treatment processes, ultimately contributing to the preservation of water resources and environmental sustainability.

Overall, the case study serves as a testament to the transformative potential of advanced materials in advancing wastewater treatment technologies and underscores the need for ongoing collaboration and innovation to drive progress in this critical area of environmental science.

The case study based on the second case study (Sudheer et al. 2020) states that activated carbon made from coconut shells, banana peels, and orange peels shown encouraging promise as adsorbents for the removal of pollutants. Each form of activated carbon has a different adsorption capability depending on its physical characteristics; larger concentrations and smaller particle sizes result in greater removal of pollutants. OPAC performed exceptionally well, maybe because it has functional groups that allowed for better adsorption. The generation of activated carbon from inexpensive organic resources provides a sustainable approach to waste management and wastewater treatment (Sudheer et al. 2020).

Although water is an essential resource for life, many areas still struggle to achieve basic demands such as drinking, sanitation, and economic growth. Water management needs to be investigated in order to solve these problems, particularly in light of population expansion, urbanization, and globalization. Nanosorbents and nanostructured catalytic membranes are two examples of the effective and environmentally benign solutions that are being used more and more in the treatment of water pollutants. However, due to financial concerns, these techniques are not yet often employed. Despite their great efficiency, drawbacks include compatibility issues with traditional techniques, health hazards, and a lack of real-time monitoring. Despite this, water treatment might be completely transformed by nano-engineered materials, especially for point-of-use and decentralized systems. Modified nanomaterials that address cost and facilitate commercialization for wastewater treatment are desperately needed. These materials must also be effective, efficient, eco-friendly, and easy to handle (Jangid, & Prabhu Inbaraj, 2021).

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