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Harnessing Solar Energy for Wastewater Treatment: A Comprehensive Analysis of Sustainable Solutions

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Abstract: ***Wastewater treatment is essential for environmental protection and sustainability, but conventional methods often rely heavily on energy-intensive processes and non-renewable energy sources, contributing to greenhouse gas emissions and escalating operational costs. As the world shifts towards greener solutions, the integration of solar energy into wastewater treatment processes presents a novel approach to reducing these drawbacks. This paper focuses on two energy-intensive wastewater treatment techniques, electrocoagulation and photocatalytic treatment, and examines their potential when powered by solar energy. Through a comprehensive review of existing literature, this study assesses the efficiency, cost-effectiveness, and environmental benefits of solar-powered systems. A key aspect of the research is the use of Geographic Information Systems (GIS) to map wastewater treatment plants in India alongside regional solar potential, providing insights into optimal locations for solar integration. The novelty of this work lies in its comparative analysis of both electrocoagulation and photocatalytic processes, powered by renewable energy, and its use of GIS to guide strategic deployment. The findings reveal that solar-powered wastewater treatment systems can significantly reduce energy consumption and costs, while maintaining high pollutant removal efficiency. However, challenges such as high initial costs and the need for technical expertise remain. This study contributes to the growing body of knowledge on sustainable wastewater treatment and encourages further innovation in scaling solar-powered technologies for diverse applications, offering a cleaner, more sustainable path forward for global water and energy challenges.***

Keywords: solar energy, wastewater treatment, electrocoagulation, photocatalytic treatment, sustainability

1. Introduction

The global shift towards sustainable living is increasingly becoming a priority, with wastewater treatment for reuse emerging as a key initiative. However, conventional wastewater treatment methods often have significant drawbacks, such as high energy consumption, which leads to increased greenhouse gas emissions and exacerbates climate change (Grzegorzek et al., 2023). Additionally, outdated treatment systems frequently rely on inefficient or excessive chemical use, contributing to water pollution and harming aquatic ecosystems. These issues highlight the urgent need for more sustainable solutions in wastewater treatment, particularly in terms of reducing energy consumption (Bera et al, 2022; Pandey et al., 2021).

One promising solution to this challenge is the integration of solar power, which has gained substantial traction as an efficient, clean, and environmentally friendly alternative to conventional energy sources. Solar energy, which has seen steady growth in India over the past decade, offers immense potential to revolutionize wastewater treatment by reducing both the environmental and economic costs associated with energy consumption. Figure 1 highlights the rapid expansion of solar power in India, as evidenced by significant increases in solar power generation from 2014 to 2024 (with slight decline in 2018–2019 due to project slowdowns and in 2019–2021 due to the COVID-19 pandemic) (Vikramsolar, 2019), positions the country as a global leader in this domain. As of May 2024, India ranks as the world's third-largest solar power producer (TOI, 2024). This growing emphasis on sustainability further underscores the need to incorporate renewable energy sources, such as solar power, into essential processes like wastewater treatment.

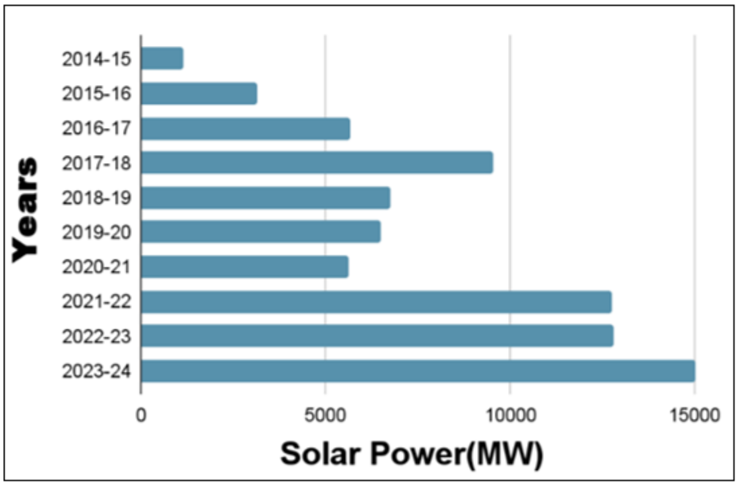

Figure 1: Annual Solar Power Generation Trends in India (2014-2024) Measured in Megawatts (MW). The chart illustrates the growth and fluctuation in India's solar power capacity over the years, with notable increases in recent years and temporary declines during the 2018-19 and 2019-21 periods, due to project slowdowns and the COVID-19 pandemic.

The primary challenge with conventional wastewater treatment systems is their high operational cost, which is largely driven by energy consumption (Shah et al., 2020; Eniola et al., 2022; Hafeez et al., 2021). Energy expenses represent one of the major costs for most wastewater treatment plants (Dutta et al., 2021; Santos et al., 2022). Inefficient energy use can lead to inadequate treatment processes, resulting in untreated wastewater being discharged into natural water bodies, thereby harming aquatic ecosystem (Sharma et al., 2019; Pratap et al., 2023). Furthermore, improper sludge disposal can contaminate soil and pose health risks to nearby communities. High reliance on fossil fuel-based energy sources exacerbates greenhouse gas emissions, further contributing to global climate change and public health concerns (Singh, 2021; Shamoon et al., 2022).

In light of these challenges, this paper aims to review and compare conventional and solar-powered wastewater treatment methods. Through a comparative analysis, this research assesses the efficiency of solar-powered wastewater treatment plants and their sustainability. The research also explores the limitations, scope, applications, and key challenges associated with these technologies to provide a comprehensive understanding of their potential. Additionally, the study integrates a Geographic Information System (GIS) analysis, mapping the distribution of wastewater treatment plants alongside regional solar potential, to identify optimal locations for the implementation of solar-powered systems. The study seeks to evaluate how effective solar-powered technologies are in treating wastewater, the cost implications of using solar energy in this process, and the main limitations or challenges in implementing these technologies. The ultimate objective of this paper is to advance the discourse on solar-powered wastewater treatment, encouraging researchers to explore new insights and develop innovative solutions for a sustainable future.

2. Literature Review

Solar-powered wastewater treatment technologies have demonstrated significant potential for enhancing sustainability, reducing costs, and improving treatment efficiency. Various studies have explored different solar-driven approaches, providing valuable insights into their applications, benefits, and challenges. Nawarkar and Salkar (2019) researched the use of solar-powered electrocoagulation systems for municipal wastewater treatment. Their findings emphasized critical operational parameters, including current density, detention time, and total dissolved solids (TDS). By employing aluminum electrodes powered by solar energy stored in batteries, the study revealed that photovoltaic coagulation is a sustainable and cost-effective technique for reducing key pollutants such as turbidity and chemical oxygen demand (COD). This method proved to be a viable alternative to conventional energy-intensive treatment processes.

Similarly, Sansaniwal (2022) performed a comprehensive evaluation of various solar-powered wastewater treatment technologies, examining their mechanisms, cost-efficiency, and environmental impacts. The research concluded that solar-driven water treatment systems present a practical solution to global water and energy challenges. In particular, these systems help mitigate mercury contamination while reducing carbon emissions through improved disposal mechanisms. The research emphasizes on the growing significance of solar energy in promoting sustainable water treatment practices, underscoring its potential to revolutionize the sector. On the other hand, Fikri et al. (20233) investigated the influence of electrocoagulation contact time on pH levels and total suspended solids (TSS) in wastewater. Their study determined that the optimal contact time for effective electrocoagulation is 30 minutes, which resulted in enhanced water quality by reducing turbidity. However, prolonged treatment beyond this point reduced the efficiency of the process. The research concluded that solar-powered electrocoagulation systems are effective, portable, and environmentally friendly, making them suitable for various wastewater treatment settings. This adaptability offers promise for regions with limited infrastructure or access to centralized treatment systems.

Muscetta et al. (2024) focused on applying solar-powered photocatalysis for water purification, exploring the effectiveness of various photocatalysts in disinfecting and decontaminating wastewater across different industries. Although the study highlighted the high potential of photocatalysis, particularly in industrial wastewater treatment, it also identified key challenges related to commercialization, particularly the cost of implementing photocatalytic systems. The authors concluded that addressing these economic barriers is crucial for the widespread adoption of solar-powered photocatalysis technologies in the wastewater treatment sector. Al-Zghoul et al (2023) explored the combination of chemical coagulation with solar-powered electrocoagulation for pharmaceutical wastewater treatment, analyzing the effects of several operational parameters, including coagulant dosage, electrode configuration, and current density. They concluded that increasing the number of electrodes enhanced COD removal efficiency due to larger surface areas and lower current densities. However, operational costs rose with higher current densities and longer reaction times. Despite the high initial investment in solar photovoltaic cells and panels, the integration of solar energy significantly reduced the overall cost of the process, highlighting its economic feasibility in the long term.

Mohammad et al (2021) researched the application of solar-powered electrocoagulation systems for textile wastewater treatment, which is characterized by high concentrations of hazardous, non-biodegradable chemicals. Their study examined the impact of current density, electrolysis time, electrode material, and initial wastewater acidity on the removal of suspended solids, turbidity, and COD. The researchers found a direct relationship between the settling period, electrolysis duration, and treatment efficiency. Their findings support the use of solar-powered electrocoagulation as a cost-effective and efficient solution for treating complex industrial wastewater streams, while also identifying future research directions for improving system performance. Syam Babu et al (202) evaluated electrocoagulation for the treatment of wastewater from various industries, including textiles, distilleries, pharmaceuticals, and tanneries. Their research provided data on several treatment measures, such as COD, turbidity, color, and pH. The authors also explored the combination of electrocoagulation with other processes, including hydrogen peroxide and ozone filtration, demonstrating the potential for improved treatment outcomes. The study concluded with a comprehensive energy and cost analysis, revealing that electrocoagulation is an economically viable option for industrial wastewater treatment, particularly when combined with other treatment methods.

Shareef and Mushtaq (2023), analyzed the potential of photocatalytic wastewater treatment as a more eco-friendly alternative to conventional biological or physical methods. They investigated various photocatalysts, including titanium dioxide (TiO2), metal-doped catalysts, and carbon-based materials, while also exploring different reactor configurations, such as suspended photocatalytic reactors and photocatalytic membrane reactors. Their research concluded that photocatalytic treatment is highly effective, cost-efficient, and environmentally safe, with the added advantage of not producing secondary pollutants. The authors emphasized the adaptability and versatility of photocatalytic systems, positioning them as promising alternatives to conventional wastewater treatment technologies. Sinar Mashuri et al (2020) reviewed several photocatalytic wastewater treatment techniques, such as doping, morphology manipulation, and metal loading. They assessed the impact of critical variables, including catalyst dosage, pH, irradiation time, and temperature, on the efficiency of the process. Their findings showed that photocatalysts have significant potential to completely degrade organic pollutants, though additional research is needed to improve process durability and stability. The study highlighted future research directions, focusing on the development of more effective photocatalytic systems capable of addressing large-scale wastewater treatment challenges.

Kositzi et al (2004), investigated the use of heterogeneous and homogeneous photocatalytic methods for reducing organic content in synthetic municipal wastewater under solar irradiation. They compared the performance of various photocatalysts, including TiO2 and photo-Fenton reagents, and concluded that combining TiO2 with oxidants significantly enhanced the rate of mineralization. However, photo-Fenton reactions were faster and more efficient than those involving TiO2 alone. The study called for further research into the cost and energy implications of scaling up photocatalytic wastewater treatment processes. Collectively, these studies demonstrate the growing potential of solar-powered wastewater treatment technologies. They highlight the importance of continued research and innovation in overcoming the current challenges, particularly regarding commercialization, cost, and system efficiency. By exploring diverse approaches, from electrocoagulation to photocatalysis, these technologies present promising solutions for advancing sustainable wastewater treatment while reducing environmental impact and operational costs.

Table 1: Summary of Literature Review: Comparative Analysis of 10 Studies on Electrocoagulation and Photocatalytic Wastewater Treatment

S. No.	Researchers	Aim of study	Type of wastewater	Use of solar power	Results (Data)	Inference/Conclusion
1	Nawarkar and Salkar; 2019	To investigate the applicability of EC in treatment of MWW by studying effect of parameters (COD, TDS, turbidity, current density)	Municipal	Yes	The optimum conditions were 40A/m2 and 20 min and removal efficiencies of 92.01%, 93.97% and 49.78% were observed for COD, turbidity and TDS and 2.27 kWh/m3 energy required at optimum condition was calculated	The solar powered EC method proved to be effective, sustainable as well as cost effective. The reactor configuration used by them is feasible for the treatment of MWW.
2	Sansaniwal; 2022	Investigating Advances and challenges in solar powered wastewater treatment technologies for sustainable development.	Used several studies as a reference so no particular wastewater used.	Yes	He provides the example of various studies investigating different solar-powered techniques to WWTP and compares several studies done on a particular technique (Solar desalination having sub-techniques: HDH desalination, still desalination)	Indirect solar desalination and solar photocatalytic are the most robust techniques and HDH plans are suitable for decentralized demand. Solar based oxidation reduces electricity costs as well as risk of Hg contamination. Disposal of residues(brine) offsets a large part of water cost and has a negative impact on the environment.
3	Fikri et al.; 2023	The study investigates the effect of electrocoagulation contact time on pH and TSS of wastewater discharged from Psychiatric hospital of West Java province, West java, Indonesia.	Hospital wastewater	No	Optimum contact time to improve the quality of water is 30 minutes as per pH analysis and it is again 30 minutes as per TSS analysis.	A solar powered EC system is shown to be efficient and eco-friendly particularly in terms of neutralizing the acidity(pH) and reducing the Total suspended solids(TSS).
4	Muscetta et al.; 2024	To provide a comprehensive review on photocatalysis delving into dynamics of photocatalytic reactions	Municipal and industrial (drawbacks and	Yes	They provide data regarding advantages and drawbacks of photocatalysis for separate municipal and industrial	Nanomaterials play a pivotal role in achieving optimal outcomes for photocatalytic water remediation and

		kinetics, several types of reactors and elucidating significance of materials employed and further discuss challenges to photocatalysis.	advantages provided for separate industry-wise wastewater)		wastewater as well as data for each type of reactor, kinetics and photocatalytic materials.	pretreatment of wastewater is essential by conventional methods before photocatalysis.
5	Al-Zghoul et al; 2023	To investigate the effectiveness of chemical coagulation assisted EC process by studying the effect of parameters: distance between electrodes, number of electrodes, operating time, current density, electrode configuration, on COD removal efficiency.	Pharmaceutical	Yes	The COD removal efficiency was 26% at optimum coagulant dosage and it is directly proportional to number of electrodes and inversely to distance between electrodes and highest with MP-S configuration. The optimum reaction time was 20 min for each (1.553,3.105,4.658 mA/cm^2) reached to 89.4%,88.7%, and 88.3%	The combination of chemical coagulation and electrocoagulation together boost COD elimination and is more economically feasible than conventional methods.
6	Mohammad et al.; 2021	To investigate the effect of EC on treating textile wastewater with regards to certain parameters (for eg: electrolysis time, electrode material, turbidity, TSS)	Textile industry	Yes	Longer settling periods, increase in electrolysis time, rise in current density lead to growth in removal efficiencies of SS, TUR and COD. In contrast, they fall when pH increases and COD removal with Al electrodes exceed the one with Fe electrodes.	The iron electrodes were more suitable than aluminum electrodes. The treatment process is eco-friendly and suitable for rare areas and different wastewater conditions.
7	Syam Babu et al.; 2020	To investigate and provide a comprehensive review for the electrocoagulation process for industrial wastewaters by specifically discussing numerous industrial waste water and their treatment separately as well as coupling EC with other processes and checking its efficiency.	Industrial	No	They have provided a vast amount of data separately for different industrial wastewater as well as data for coupling EC with other processes, specifically and separately for each process. They also provide a cost and energy analysis of the technique (EC).	EC is a sustainable tool for treatment of industrial wastewater and can act as a pre-treatment and treatment process. It is cost effective, safe, can remove a wide range of contaminants and convenient in operation.
8	Sharif and Mushtaq; 2023	To investigate wastewater treatment by photocatalysis by reviewing different approaches, mechanisms, applications and challenges.	Industrial and domestic	No	They provide data on different approaches (For eg: TiO2 based, and metal doped photocatalysts), mechanisms (suspended photocatalytic reactor, photocatalytic membrane reactor) as well as applications and challenges.	Photocatalytic treatment is versatile, inexpensive, risk-free, non-toxic and can be used for a range of scenarios.
9	Mashuri et al.; 2020	Investigating photocatalysis for organic wastewater treatment: from basis to challenges.	Organic	No	They start by explaining various hybridized photocatalysts (for eg: metal-doped, heterojunction), techniques (for eg: physical, chemical, Sol-gel) as well as the effect of certain parameters (for eg: photocatalyst Dosage, pH of wastewater) and hypothesize on future direction.	Photocatalysts show promising techniques to degrade organic pollutants to eco- friendly substances by allowing both spontaneous and non-spontaneous reactions. Hybridisation photocatalyst has certain drawbacks such as promoting the center of recombination, absence of interfacial interaction and imposing lower photocatalytic degradation.
10	Kositzi et al.; 2004	To investigate the photocatalytic organic content reduction of a selected synthetic municipal wastewater by the use of heterogeneous and homogeneous photocatalytic methods under solar irradiation	Synthetic Municipal	Yes	They present their results of experiments with TiO2, photo-fenton and ferrioxalate reagent and concluded that the reaction TiO2 with oxidants leads to substantial increase of the initial reaction rate and extent of mineralization whereas the photo-fenton experiments were much faster than those with TiO2	The reduction of the organic content of a synthetic municipal wastewater has been successfully carried out by applying a heterogenous and homogenous solar photocatalytic method.

3. Methodology and data analysis

This study aims to evaluate the integration of solar energy into wastewater treatment technologies, focusing on electrocoagulation and photocatalytic processes as well as discussing the current situation and scope of solar power integration in wastewater treatment plants in India. The research relies on data collected from existing literature, government reports, and databases to assess the feasibility, energy efficiency, and cost-effectiveness of solar-powered wastewater treatment systems.

3.1 Data Collection

The data for this study were sourced from a combination of peer-reviewed academic papers, technical reports, and publicly available datasets from government and international agencies. The focus was on studies that explored the use of solar energy in wastewater treatment, particularly those involving electrocoagulation and photocatalysis. These studies provided insights into various operational parameters such as energy consumption, system efficiency, treatment effectiveness, and cost implications for both conventional and solar-powered systems. Key data points collected from the literature include:

- Energy consumption of wastewater treatment plants (both conventional and solar-powered).
- The operational costs associated with solar-powered treatment technologies.
- The environmental impact in terms of energy savings and greenhouse gas emission reductions.
- Case studies demonstrating successful implementation of solar-powered wastewater treatment systems across different geographic regions.

Additionally, governmental sources such as the Ministry of New and Renewable Energy (MNRE) in India provided data on solar potential, including solar radiation levels and installed solar capacities across different regions.

3.2 GIS Integration and Mapping

A geographic information system (GIS) approach was employed to map the distribution of wastewater treatment plants and the corresponding solar potential across different regions of India. The GIS mapping integrated two key datasets:

- **Wastewater Treatment Plant Data**: This dataset provided the locations and capacities of wastewater treatment plants (WWTPs) across India, allowing us to identify areas with high wastewater treatment demand.
- **Solar Potential Data**: Solar energy potential data, including solar radiation levels and installed solar capacities, were obtained from government sources such as the National Institute of Solar Energy (NISE). This data helped in identifying regions with high solar power generation potential.

The integration of these datasets allowed for a comprehensive analysis of regions where solar-powered wastewater treatment could be most effectively implemented. Regions with both high wastewater treatment demand and strong solar potential were identified as ideal candidates for the deployment of solar-powered systems.

3.3 Analytical Approach

The analysis focused on comparing the operational and environmental benefits of solar-powered wastewater treatment systems with conventional energy-intensive plants. The collected data were analyzed to:

- Quantify the energy savings achievable through solar energy integration.
- Estimate the reduction in greenhouse gas emissions (particularly CO2) due to the decreased reliance on fossil fuels.
- Assess the cost savings associated with reduced energy consumption, considering both initial investment in solar infrastructure and long-term operational expenses.

Statistical methods were used to analyze the data, particularly in regions with varying solar potential and wastewater treatment needs. By overlaying the GIS maps of wastewater treatment plants and solar potential, the study identified areas where solar-powered systems could offer the most significant energy and cost savings. The analysis also explored how these systems could be scaled to meet growing wastewater treatment demands.

3.4 Comparative Analysis of Technologies

A key aspect of the methodology involved comparing different solar-powered wastewater treatment technologies, primarily focusing on electrocoagulation and photocatalysis. Data from various studies were synthesized to evaluate:

- The effectiveness of each technology in reducing pollutants.
- The operational cost differences between solar-powered and conventional systems.
- The energy efficiency of each method when integrated with solar power.

This comparative analysis provided insights into the practicality and scalability of these technologies, helping to identify which methods are most suitable for specific regional contexts based on the solar potential and wastewater treatment capacity. The methodology overall combines a detailed review of existing literature with GIS mapping of solar potential and wastewater treatment plants to provide a comprehensive analysis of the feasibility and benefits of solar-powered wastewater treatment systems in India. This approach enables the identification of optimal regions for implementing solar energy in wastewater treatment and offers valuable insights into the energy and cost savings that could be achieved through such integration.

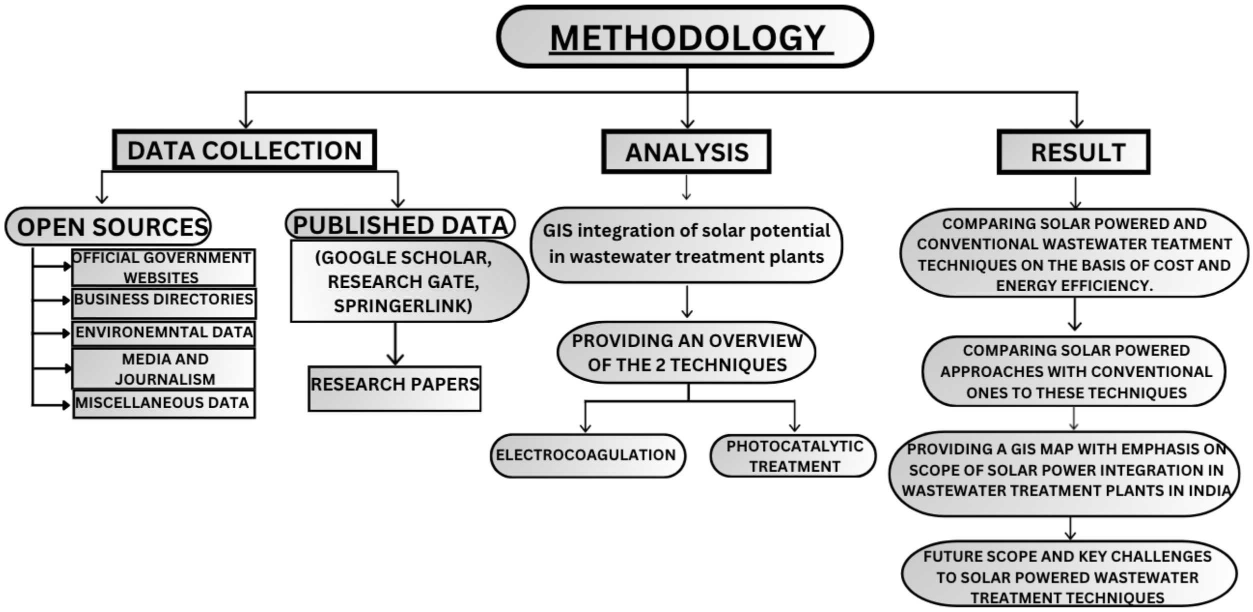

Figure 2: Flowchart Depicting the Methodology Applied for This Research Paper. The diagram outlines the data collection process from open sources and published data, followed by GIS-based analysis of solar potential in wastewater treatment plants, and concludes with a comparative evaluation of solar-powered and conventional wastewater treatment techniques.

4. Results and Discussion

4.1 Comparative analysis between solar-powered wastewater treatment plants and conventional wastewater treatment plants

Traditional wastewater treatment plants (WWTPs) are energy-intensive, with an average consumption of about 0.3-0.6 kWh per cubic meter of treated wastewater depending on the treatment type (aeration, filtration, disinfection, and others) (Sarpong and Gude., 2021; Chatzisymeon., 2020; Dhara et al., 2023; Batool et al., 2023). Solar-powered wastewater treatment systems harness solar energy to reduce reliance on grid electricity or fossil fuels. The energy saved depends on the size of the solar installation and local solar radiation levels. A typical solar wastewater treatment plant can reduce energy consumption by 30-50%, depending on the efficiency of the solar panels and the specific technology used (electrocoagulation, photocatalysis, and others) (Gu et al., 2017; Maktabifard et al., 2018).

A conventional wastewater treatment plant can treat 10,000 cubic meters of wastewater per day (assumption), and Energy consumption per cubic meter (based on averages) is 0.5 kWh. Thus, the Total energy consumed per day is 10,000 m^3 × 0.5 kWh/m^3 = 5,000 kWh/day. Solar energy can typically reduce energy consumption by 30-50%, so considering an average 40% reduction for this scenario, energy saved per cubic meter is 0.5 kWh/m^3 x 0.4= 0.2 kWh/m^3, so, energy consumed using solar power is 0.5 kWh/m^3-0.2 kWh/m^3= 0.3 kWh/m^3. Energy saved per day is 5,000 kWh × 0.4 = 2,000 kWh/day. Thus, energy consumed after using solar: 5,000 kWh/day − 2,000 kWh/day = 3,000 kWh/day. Subsequently, energy consumed throughout the year is 5000 kWh/year x 365 days= 1825000 kWh/year and energy consumed by solar powered plants is 1825000 kWh/year - 0.4*(1825000) kWh/year = 1095000 kWh/year. Therefore, the total annual saved electric power is 1825000 kWh/year - 1095000kWh/year = 730,000 kWh/year. The literature further suggests that 1 kWh of electricity from fossil fuel-based sources typically generates around 0.92 kg of CO_2 (Feron et al., 2019; Modi et al., 2017), thus reducing 730,000 kWh × 0.92 kg-CO_2/kWh = 671,600 kg CO_2 per year.

In addition to energy savings, solar-powered wastewater treatment systems offer significant cost reductions. The operational costs for conventional wastewater treatment plants are heavily influenced by electricity costs, with an average cost of electricity at approximately $0.10 per kWh. For a conventional plant consuming 0.5 kWh per cubic meter, the total cost per cubic meter would be 0.5 kWh/m^3 x $0.10 /kWh= $0.05 /$m^3$. A typical plant consumes 5,000 kWh per day, the total daily energy cost would be 5,000 kWh/day × $0.10 /kWh = $500 /day. Over the course of a year, this amounts to $500 /day × 365 days = $182,500 /year in energy expenses. With solar power reducing energy consumption by 40%, the energy cost savings are substantial. The cost per cubic meter to run the solar power plant will be 0.3 kWh/m^3 x $0.10 /kWh= $0.03 /$m^3$, thus, the per cubic meter cost savings would be $0.05 /m^3 - $0.03 /$m^3$= $0.02 /$m^3$. The daily cost for running a solar powered plant would be 3000 kWh/day x $0.10 /kWh= $300 /day, therefore, the daily savings would be $500 /day- $300 /day = $200 /day. Consequently, the total annual cost for a solar powered plant would be 1095000 kWh /year x $0.10 /kWh = $109500 /year, leading to an annual saving of $182500 /year - $109500 /year = $73,000 /year. Therefore, by incorporating solar energy into the wastewater treatment process, the plant would save $73,000 annually in electricity costs, in addition to the environmental benefits of reduced CO_2 emissions. While the initial investment in solar panels and infrastructure is significant, the long-term cost savings, coupled with environmental benefits, make solar-powered wastewater treatment systems a financially viable and sustainable solution.

Table 2: Energy and Cost Comparison per Cubic Meter, Day, and Year Between Solar-Powered and Conventional Wastewater Treatment Techniques.

Wastewater treatment technique	Energy consumption			Cost		
	Energy/ m^3	Energy/ day	Energy/ year	Cost/m^3	Cost/day	Cost/year
Conventional	0.5 kWh/m^3	5000 kWh/day	1825000 kWh/year	\$0.05 /m^3	\$500 /day	\$182500 /year
Solar powered	0.3kWh/m^3	3000 kWh/day	1095000 kWh/year	\$0.03 /m^3	\$300 /day	\$109500 /year

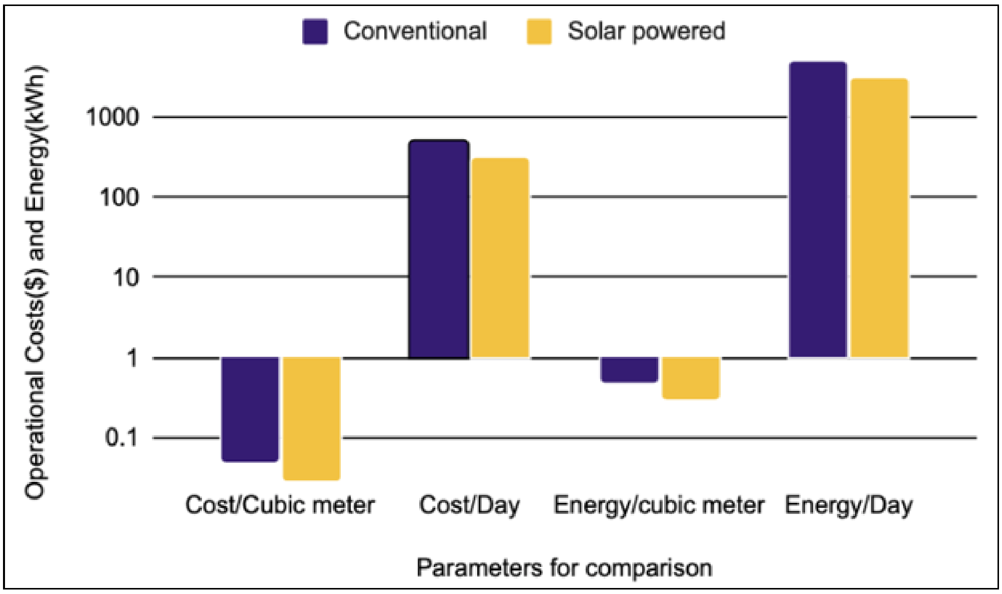

Figure 3: Comparison of Energy Consumption and Costs of Conventional and Solar-Powered Wastewater Treatment Plants Based on Parameters: Per Cubic Meter and Per Day.

4.2 Solar Power and Wastewater Plants - An Indian Perspective

India has made substantial progress in solar energy development, as evidenced by the nation's cumulative solar power capacity of 81.81 GW as of March 31, 2024 (MNRE, 2024). This figure includes 64.41 GW from ground-mounted solar installations, 11.89 GW from rooftop solar systems, 2.57 GW from hybrid solar projects, and 2.95 GW from off-grid solar systems. Additionally, the country is actively expanding its renewable energy base, with 95.69 GW of solar power capacity under implementation and 78.29 GW of solar/hybrid/RTC/FDRE projects in the tendering stage. The fiscal year 2023-24 alone saw the commissioning of 15.03 GW of solar power, demonstrating the nation's commitment to clean energy transition (MNRE, 2024). However, the challenge now lies in aligning these efforts with India's critical need for wastewater management and ensuring the sustainable use of water resources. The integration of solar energy into wastewater treatment plants offers a promising solution for this dual challenge. The Indian government has already recognized the critical importance of wastewater treatment in urban and rural areas. Wastewater treatment is energy-intensive, with treatment plants often relying on traditional energy sources, leading to significant operational costs and carbon emissions. As wastewater generation continues to rise with urbanization and industrial growth, sustainable energy solutions are essential for managing these facilities.

The geographic distribution of solar potential and wastewater treatment infrastructure, as illustrated in Figure 4, offers a clear pathway for the integration of solar energy into wastewater treatment plants. States like Rajasthan, Madhya Pradesh, and Maharashtra have considerable installed solar power capacities and a large number of wastewater treatment plants, as indicated by the green circles. Rajasthan, for example, already has 64.41 GW of ground-mounted solar capacity, making it a prime candidate for solar-powered wastewater treatment. Similarly, Madhya Pradesh and Maharashtra, which are leaders in both solar installations and wastewater treatment infrastructure, can benefit from using solar energy to power these facilities, thereby reducing reliance on fossil fuels and lowering operational costs. These regions should prioritize using the energy from their installed solar capacity for wastewater treatment operations, thereby aligning with the goals of both energy sustainability and efficient water management.

On the other hand, the red circles in the figure highlight areas such as Punjab, West Bengal, Tamil Nadu, and Uttar Pradesh, where there are a large number of wastewater treatment plants but relatively low levels of installed solar capacity. These regions present an opportunity for targeted solar infrastructure expansion. For instance, Tamil Nadu and Uttar Pradesh, despite their high energy demands, have yet to fully utilize their solar potential. In these areas, concerted efforts to expand solar installations would directly benefit wastewater treatment plants, reducing operational costs and minimizing environmental impacts. As the National Institute of Solar Energy (NISE) has assessed India's overall solar potential at around 750 GWp, there is ample scope to direct resources to these underutilized regions to promote sustainable energy use in wastewater management.

The integration of solar energy into wastewater treatment plants aligns with several of the United Nations Sustainable Development Goals (SDGs). Specifically, SDG 6 (Clean

Water and Sanitation) and SDG 7 (Affordable and Clean Energy) are directly impacted by this approach. SDG 6: Clean Water and Sanitation, access to clean water and sanitation is a fundamental human right, yet many regions in India still struggle with inadequate wastewater treatment infrastructure. By harnessing solar energy to power wastewater treatment plants, India can ensure a more sustainable and continuous supply of treated water, especially in rural and underdeveloped areas where energy availability is often a limiting factor. Solar-powered wastewater treatment plants can also contribute to water recycling and reuse, addressing water scarcity issues in drought-prone regions. SDG 7: Affordable and Clean Energy, solar energy is a clean, renewable source that reduces dependence on fossil fuels. By integrating solar power with wastewater treatment plants, India can make wastewater treatment more affordable and sustainable. This will not only reduce greenhouse gas emissions but also lower energy costs for municipalities and industries that operate these plants. Moreover, decentralized solar energy systems, such as rooftop solar panels or off-grid solar setups, can be particularly effective in rural areas, providing energy where the conventional grid is unavailable or unreliable. SDG 13: Climate Action, by transitioning wastewater treatment plants to renewable energy, India can significantly reduce the carbon footprint of these operations. The integration of solar energy aligns with SDG 13 (Climate Action), contributing to the country's commitment to reduce greenhouse gas emissions. In 2021, India pledged to achieve net-zero carbon emissions by 2070 at the COP26 Summit, and solar-powered wastewater treatment plants could be a key step in realizing this goal.

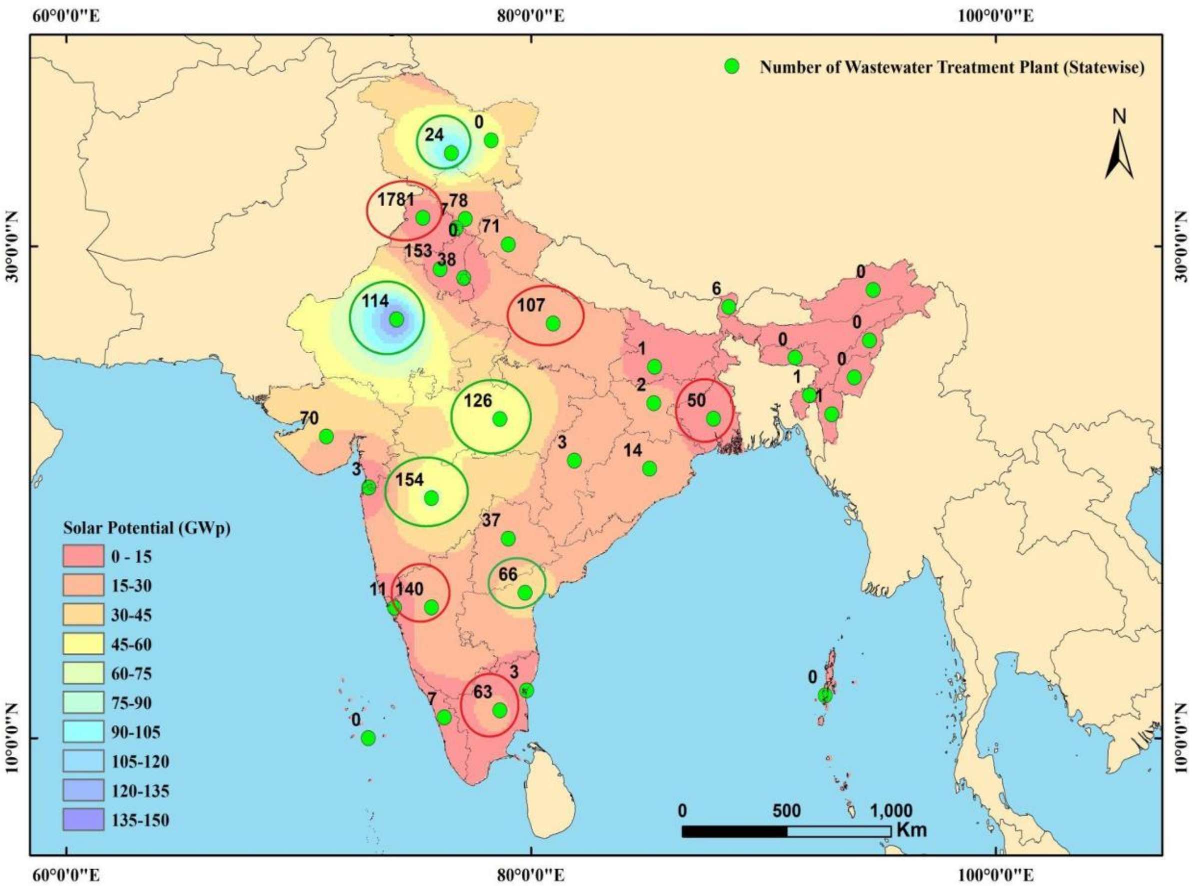

Figure 4: GIS Map Showing the Concentration of Wastewater Treatment Plants and Solar Potential Across India. The map highlights regions with varying solar energy potential (in GWp) and overlays the number of wastewater treatment plants, providing insights into areas where solar-powered wastewater treatment systems can be most effectively implemented.

4.3 Advanced Solar Solutions for Wastewater Treatment: Electrocoagulation and Photocatalytic Methods

Wastewater treatment encompasses a wide range of techniques, each with varying energy demands and applications. In this study, we focus on two energy-intensive methods: electrocoagulation and photocatalytic treatment. These techniques have been selected for their effectiveness in pollutant removal and their potential for integration with solar energy, offering more sustainable solutions for wastewater treatment. The following sections explore the mechanisms, applications, and benefits of these approaches, along with a comparative analysis of their performance when powered by solar energy.

4.3.1 Electrocoagulation

Electrocoagulation has garnered significant interest in recent years due to its simplicity, cost-effectiveness, rapid treatment capabilities, and minimal sludge generation, making it an environmentally friendly option for wastewater treatment. This method is highly effective in removing contaminants such as tannins, dissolved metals, dyes, and suspended solids (Shahedi et al., 2020). The process involves electrolysis, which produces colloidal particles known as flocs, which are later removed through sedimentation. The primary mechanisms responsible for pollutant removal include electro-oxidation, electro-flocculation, and electrocoagulation (Lin et al., 1998).

The electrocoagulation setup consists of two metallic electrodes, typically aluminum (Al) or iron (Fe), submerged in an electrolyte. When an electric current is applied, the anode dissolves, releasing metal ions (cations) into the solution, while hydrogen gas and hydroxyl ions are generated at the cathode. The released metal ions act as coagulants, attracting and neutralizing oppositely charged pollutants, leading to the formation of flocs. These flocs trap contaminants such as heavy metals, emulsified oils, and suspended solids, which either rise to the surface or settle to the bottom due to sedimentation and flotation caused by hydrogen gas bubbles formed at the cathode.

When aluminum electrodes are used, the flocs that form are referred to as "sweep flocs" ($Al(OH)_3$), known for their large surface area, which aids in the rapid adsorption of soluble organic compounds and the trapping of colloidal particles. These flocs can be easily removed from the treated water through filtration or sedimentation. Figure 5, summarises the process and the main electrochemical reactions occurring at the anode and cathode for both aluminum and iron electrodes are outlined in Table 3 below.

Table 3: Electrochemical Reactions for Aluminum (Al) and Iron (Fe) Anodes in Electrocoagulation.

	Aluminum (Al) Anode:	Iron (Fe) Anode:
Anode reaction	$Al(s) \rightarrow Al^{3+} + 3e^-$	$Fe(s) \rightarrow Fe^{2+} + 2e^-$
Cathode reaction	$3H_2O + 3e^- \rightarrow 1.5\ H_2(g) + 3OH^-$	$2H_2O + 2e^- \rightarrow H_2(g) + 2OH^-$
Overall reaction	$Al + 3H_2O \rightarrow Al(OH)_3 + 3H_2$	$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3(s) + 3H^+$

4.3.1.1 Evaluation of Research Findings on Solar-Driven Electrocoagulation

Integrating solar power into the electrocoagulation process cab be highly effective in reducing both operational costs and energy consumption. Nawarkar and Salkar (2019) demonstrated that using solar energy significantly lowered costs and made the electrocoagulation process more energy-efficient. Similarly, Al-zghoul et al. (2023) showed that combining chemical coagulation with solar-powered electrocoagulation reduced total costs by 22.1% when considering current density, and by 27% with optimized reaction times. This further reinforces the cost-efficiency of solar energy integration.

Marmanis et al. (2022) simulated the energy requirements for a solar-powered wastewater treatment system and found that solar radiation alone could meet the system's energy needs, allowing it to operate with minimal costs. The authors concluded that solar-powered systems are not only energy-efficient but also capable of being operated by communities with low operational expenses. Aryanti et al. (2024) also emphasized that integrating renewable energy into electrocoagulation technology can contribute significantly to sustainable and efficient water management practices, addressing both environmental and economic concerns.

Further studies by Rakhimol et al. (2024) and Zhang et al. (2018) advocated that solar-powered electrocoagulation is a cost-effective and environmentally friendly alternative to conventional wastewater treatment methods, particularly for regions with limited economic resources or serious environmental challenges. Their research highlighted that solar-powered electrocoagulation is an effective and affordable solution for removing heavy metals from wastewater. Karmankar et al. (2023) found that, conventional systems consumed 31.4 Wh/L, while the solar-powered system consumed only 15 Wh/L. Their findings showed that conventional systems required longer treatment times and higher voltage, while solar-powered electrocoagulation proved to be both cost and energy efficient. Overall, the integration of solar power into electrocoagulation offers significant advantages in terms of reducing both energy consumption and operational costs.

4.3.2 Photocatalytic treatment

Photocatalytic treatment has proven to be an effective method for wastewater purification, offering significant benefits across various industries such as pharmaceuticals, pesticides, textiles, tanneries, the food sector, and olive oil processing, as well as for municipal wastewater. The process begins with the activation of photocatalysts, typically semiconductors, through the absorption of light. This light can be natural sunlight or light from the visible or ultraviolet spectrum, provided it has a wavelength and energy level sufficient to generate electron-hole pairs within the photocatalyst's conduction and valence bands. To initiate this reaction, the photons must have an energy equal to or greater than the band gap of the photocatalyst.

Titanium dioxide (TiO_2) is one of the most widely used photocatalysts in heterogeneous photocatalysis due to its high reactivity, chemical stability, affordability, and low toxicity (Fujishima and Zhang., 2006). Once activated, the electrons and holes are separated and migrate to the surface of the photocatalyst, where they participate in redox reactions. Electrons reduce the acceptor molecules, while the holes oxidize donor molecules. If not quickly used, the electrons and holes can recombine, losing energy.

Subsequently, moisture and contaminant molecules are absorbed on the photocatalyst's surface. Electrons combine with oxygen to form superoxide anions, while holes interact with water molecules to generate hydroxyl ions (OH^-). These reactive species work together to degrade both organic and inorganic pollutants adsorbed on the photocatalyst’s surface through advanced oxidation processes. This technique, which involves five key steps, as illustrated in Figure 5, is known for being versatile, risk-free, non-toxic, and cost-effective, making it applicable in a variety of wastewater treatment scenarios.

4.3.2.1 Evaluation of Research Findings on Solar-Driven Photocatalytic Treatment

One challenge of photocatalytic treatment is the high energy demand of UV lamps or other light-emitting devices, which require a constant electricity supply and increase operational costs. However, substituting sunlight for artificial light has proven to be a successful strategy for reducing energy consumption. According to Kositzi et al. (2004), using sunlight in photocatalytic processes significantly reduced the organic content in municipal wastewater. His research group further demonstrated that combining solar light with simple, affordable technology offers economically viable solutions for liquid waste processing.

Borges et al. (2016) also confirmed that utilizing sunlight to degrade pollutants from wastewater is a promising approach, as they found that up to 95% of pollutants can be decomposed by sunlight within two hours. Spasiano et al. (2015) further concluded that solar photocatalytic wastewater treatment, particularly in sun-rich regions, provides an environmentally friendly alternative to conventional processes. In scenarios where continuous energy is required, solar-powered photovoltaic systems can be employed to provide the electricity needed for UV lamps or other light-emitting devices. This is particularly important for photocatalysts that demand substantial energy input over a specific period, which solar photons alone may not provide. Muscetta et al. (2024) proposed that small-scale solar photoreactors for water disinfection in rural areas would be highly cost-effective, noting that the operational costs of running photocatalytic reactors and lamps could be reduced by up to tenfold with the integration of solar power. Overall, the photocatalytic treatment, when combined with solar energy, offers an efficient, sustainable, and economically viable solution for wastewater treatment. The use of natural sunlight reduces energy costs, minimizes greenhouse gas emissions, and presents a practical alternative to conventional wastewater treatment methods, particularly in regions with high solar exposure.

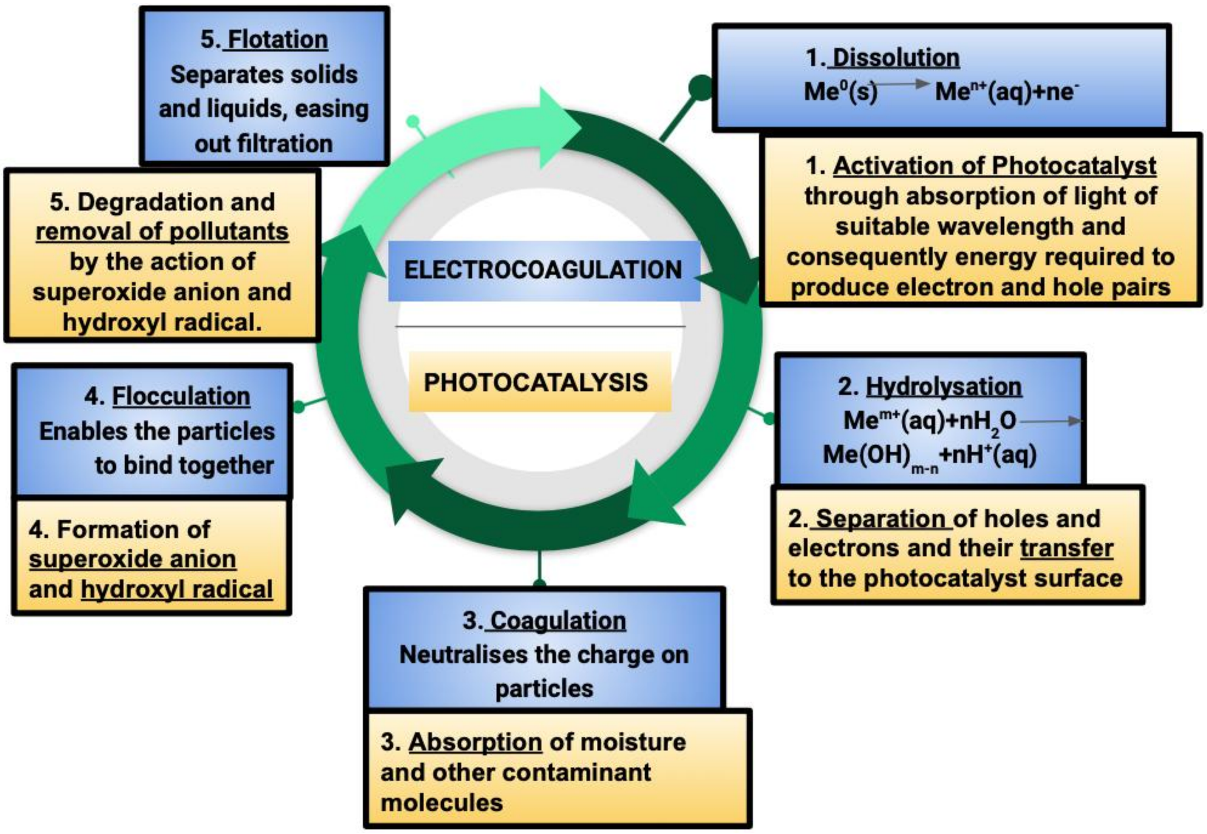

Figure 5: Mechanisms and Processes Involved in Electrocoagulation and Photocatalytic Wastewater Treatment. This diagram illustrates the key stages of both electrocoagulation and photocatalysis, highlighting the chemical reactions and physical processes responsible for pollutant removal.

4.4 Future Directions: Challenges and Opportunities

This study acknowledges several limitations, particularly its reliance on secondary data, which can introduce challenges such as inconsistencies in data quality, unclear data collection methods, and potential biases. However, efforts were made to mitigate these issues by using reliable and credible sources wherever possible. Furthermore, while the integration of Geographic Information Systems (GIS) provided valuable insights into the distribution of solar potential and wastewater treatment facilities, it did not capture the nuances of site-specific factors such as local infrastructure conditions or regional policy frameworks. Despite these limitations, we ensured that the data used for mapping was as current and accurate as could be verified.

The potential for integrating solar energy into wastewater treatment is promising, but several challenges must be addressed. One significant barrier is the high initial cost of installing solar panels and retrofitting existing wastewater treatment facilities with solar technology, especially in underdeveloped or resource-limited regions. Nevertheless, this challenge can be mitigated by leveraging government incentives, subsidies, and international financing initiatives aimed at supporting renewable energy infrastructure.

Another challenge lies in the operation and maintenance of solar-powered systems, which require specialized technical knowledge. In many areas, particularly rural or underdeveloped regions, this expertise may be lacking. To address this, capacity-building programs and training for plant operators will be essential to ensure the long-term success of solar-powered wastewater treatment systems. Additionally, the intermittent nature of solar power, limited by the availability of sunlight and potential power outages, poses a challenge for consistent operation. However, emerging technologies such as smart grids, advanced inverters, and hybrid systems that combine solar power with other renewable energy sources or backup generators can help mitigate these limitations and enhance reliability.

Despite these obstacles, the opportunities for scaling up solar-powered wastewater treatment are substantial. India, for instance, is experiencing rapid growth in solar energy capacity, with 95.69 GW currently under implementation and 78.29 GW in the tendering phase. This expanding solar infrastructure creates a significant opportunity to extend the use of solar power in wastewater treatment plants. By strategically targeting regions with a high demand for wastewater treatment but low solar energy penetration, there is immense potential to optimize renewable energy resources for water management. In areas with abundant sunlight and wastewater treatment needs, solar-powered systems could offer both energy savings and environmental benefits, contributing to a more sustainable future. Thus, while the road to widespread adoption of solar-powered wastewater treatment systems presents several challenges, the technological advances, financial mechanisms, and capacity-building initiatives available today provide a pathway toward overcoming these hurdles. As countries like India continue to invest in renewable energy, solar-powered wastewater treatment has the potential to play a critical role in reducing energy consumption, lowering operational costs, and minimizing environmental impacts, all while promoting sustainable water management practices.

5. Conclusion

This study highlights the promising potential of solar-powered wastewater treatment technologies, particularly through electrocoagulation and photocatalysis. These approaches not only offer significant energy and cost savings but also contribute to environmental sustainability by reducing greenhouse gas emissions and the reliance on fossil fuels. By integrating solar energy, wastewater treatment plants can significantly lower their operational costs and energy consumption, making these methods viable alternatives to conventional energy-intensive systems. The analysis of existing literature demonstrates that solar-powered electrocoagulation and photocatalytic treatment are effective in removing a wide range of pollutants, including heavy metals, organic compounds, and suspended solids. Additionally, these methods offer the flexibility of being implemented in various industrial and municipal wastewater treatment settings. However, challenges remain in scaling these technologies, particularly due to the high initial investment costs and the technical expertise required for operation and maintenance. Geographic Information System (GIS) mapping further emphasizes the potential of strategically deploying solar-powered wastewater treatment systems in regions with high solar potential and wastewater treatment demand. By aligning solar energy availability with wastewater treatment needs, regions like India have the opportunity to harness renewable energy for sustainable water management. Overall, while the integration of solar energy into wastewater treatment presents certain challenges, including costs and technical limitations, it also offers immense opportunities for enhancing sustainability in the sector. With the ongoing advancements in solar technology and the increasing availability of government incentives, solar-powered wastewater treatment systems have the potential to play a crucial role in addressing global water and energy challenges, paving the way for a cleaner and more sustainable future. Further research and innovation will be essential to overcome existing barriers and optimize these technologies for broader implementation.

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