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Recent Progress in Solar Photovoltaic-Driven Wastewater Treatment: Effects of Photocatalytic Efficiency, Energy Recovery, and Environmental Sustainability

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ABSTRACT

Wastewater treatment is an energy-intensive environmental process that is increasingly challenged by the growing complexity of industrial, municipal, and agricultural effluents. Conventional treatment technologies frequently depend on externally supplied electricity and chemical reagents, resulting in considerable operational costs and associated environmental burdens. Solar photovoltaic (PV) technology provides an attractive pathway for reducing the dependence of wastewater treatment systems on conventional electricity by converting solar irradiation into electricity that can directly or indirectly drive electrochemical, membrane, biological, and advanced oxidation processes.

This review critically examines recent progress in photovoltaic-driven wastewater treatment, with particular emphasis on three interconnected variables: photocatalytic efficiency, energy recovery, and environmental sustainability. Solar photovoltaic systems coupled with electrooxidation, reverse osmosis, electrocoagulation, aeration, electroflocculation, and photoelectro-Fenton processes are comparatively evaluated in terms of pollutant removal, energy consumption, water recovery, operational stability, and environmental performance. Particular attention is given to the influence of solar irradiation, photovoltaic conversion efficiency, electrode configuration, current density, hydraulic retention time, and reactor architecture on treatment performance. A conceptual framework is also proposed to describe the relationship between solar energy input, photovoltaic conversion, treatment efficiency, energy recovery, and environmental benefits.

The reviewed evidence indicates that photovoltaic-powered treatment can substantially reduce dependence on grid electricity while maintaining competitive pollutant-removal efficiencies. Electrocoagulation and advanced oxidation processes demonstrate considerable potential for treating heavy metals and persistent organic pollutants, whereas photovoltaic-powered reverse osmosis provides an attractive pathway for water recovery. Solar-powered aeration can improve biological treatment by increasing dissolved oxygen availability with comparatively low operating requirements. Nevertheless, intermittency of solar radiation, energy-storage limitations, electrode degradation, membrane fouling, photovoltaic land requirements, and insufficient integration between energy and treatment subsystems remain major challenges. Future research should therefore move from individual technology optimization toward integrated solar-water-energy systems incorporating intelligent control, energy recovery, hybrid treatment, and life-cycle sustainability assessment.

1. Introduction

Water pollution has become one of the most significant environmental challenges associated with rapid industrialization, urban expansion, agricultural intensification, and population growth. Wastewater generated from these activities may contain organic compounds, heavy metals, suspended solids, nutrients, dyes, pharmaceuticals, pesticides, and other emerging contaminants. The increasing diversity and persistence of these pollutants have reduced the effectiveness of conventional treatment approaches and increased the demand for advanced treatment technologies.

Conventional wastewater treatment generally involves physical separation, chemical oxidation, coagulation, adsorption, biological degradation, or combinations thereof. Although these processes are widely established, many of them require substantial quantities of electricity and chemical reagents. Aeration is particularly energy-intensive in biological treatment systems, while membrane-based technologies require significant hydraulic pressure. Electrochemical and advanced oxidation technologies can achieve high removal efficiencies, but their dependence on electricity may increase operating costs.

The transition toward renewable energy therefore represents an important opportunity for wastewater treatment. Among renewable energy sources, solar energy is particularly attractive because of its widespread availability, modularity, and compatibility with decentralized treatment systems. Photovoltaic technology converts solar radiation directly into electricity, allowing renewable electricity to be supplied to pumps, electrochemical reactors, aeration units, membrane systems, sensors, and control systems.

Previous research has demonstrated the feasibility of coupling photovoltaic systems with electrooxidation, reverse osmosis, electrocoagulation, aeration, electroflocculation, and Fenton-based oxidation. However, most studies have focused on individual treatment efficiencies rather than examining the broader interaction between **energy conversion, treatment performance, energy recovery, and environmental sustainability**.

This review consequently adopts a broader analytical perspective. Instead of considering solar energy merely as an alternative electricity source, the present study evaluates photovoltaic-driven wastewater treatment as an integrated **water-energy-environment system**.

Three principal variables are introduced:

$$PE = \text{Photocatalytic/photochemical efficiency}$$

$$ER = \text{Energy recovery performance}$$

$$ES = \text{Environmental sustainability}$$

These variables are analyzed together with treatment efficiency, energy consumption, solar irradiation, photovoltaic conversion efficiency, and system operating conditions.

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2. Conceptual Framework of Photovoltaic-Driven Wastewater Treatment

The fundamental process consists of five interconnected stages:

Solar irradiation → photovoltaic conversion → electrical energy management → wastewater treatment → water/resource recovery

The photovoltaic subsystem converts solar radiation into direct-current electricity. Depending on system configuration, the generated electricity can be supplied directly to the treatment reactor or transferred through a battery and power-management system.

The general photovoltaic conversion efficiency can be expressed as:

$$\eta_{PV} = \frac{P_{out}}{G A_{PV}} \times 100$$

where:

- η_{PV} = photovoltaic conversion efficiency;
- P_{out} = electrical output power;
- G = incident solar irradiance;
- A_{PV} = photovoltaic panel area.

The available electrical energy can subsequently be distributed among pumps, electrochemical reactors, aeration systems, membrane units, sensors, and control devices.

The treatment efficiency can be expressed as:

$$RE = \frac{C_0 - C_t}{C_0} \times 100$$

where **(RE)** is pollutant removal efficiency, (C_0) is the initial pollutant concentration, and (C_t) is the concentration after treatment.

For an integrated system, the relationship can therefore be represented conceptually as:

$$G \rightarrow \eta_{PV} \rightarrow P_{out} \rightarrow E_{treatment} \rightarrow RE$$

However, increasing energy input does not necessarily produce proportional improvements in treatment efficiency. This introduces the importance of energy optimization and recovery.

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3. Analytical Variables and Performance Indicators

To differentiate this review from conventional technology-by-technology reviews, the investigated systems are assessed according to a common set of variables.

Table 1. Principal variables adopted in the present review

Variable	Symbol	Description	Expected influence
Solar irradiation	(G)	Solar radiation incident on PV modules	Positive
PV conversion efficiency	(\eta_{PV})	Conversion of solar radiation to electricity	Positive
Photocatalytic efficiency	PE	Effectiveness of solar/photochemical reactions	Positive
Pollutant removal	RE	Percentage of pollutant eliminated	Positive
Specific energy consumption	SEC	Energy required per unit wastewater volume	Negative
Energy recovery	ER	Energy recovered or reutilized within the system	Positive
Water recovery	WR	Fraction of treated water recovered for reuse	Positive
Electrode stability	ES(_e)	Resistance to electrode degradation	Positive
Carbon reduction	CR	Reduction in energy-related emissions	Positive
Operating cost	OC	Economic requirement per treatment volume	Negative
Environmental sustainability	ES	Overall environmental performance	Positive
Scalability	SC	Suitability for larger treatment capacity	Positive

This multidimensional framework enables different technologies to be compared even when they treat different wastewater types.

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4. Solar Photovoltaic Technologies for Wastewater Treatment

4.1 Photovoltaic-Electrooxidation Systems

Electrooxidation is based on electrochemically generated oxidizing species that facilitate the degradation of organic pollutants. The technology is particularly attractive for contaminants that are difficult to remove through conventional biological processes.

Photovoltaic-powered electrooxidation eliminates or substantially reduces dependence on grid electricity. Earlier studies have demonstrated that photovoltaic arrays can directly supply electrochemical reactors for dye degradation and organic-carbon removal.

The effectiveness of the process depends on several parameters:

$$RE_{EO} = f(G, \eta_{PV}, J, A_e, pH, t)$$

where:

- **(J)** = current density;
- **(A_e)** = electrode area;
- **(t)** = treatment time.

The use of photovoltaic electricity can improve the environmental profile of electrooxidation, but excessive current density may increase energy consumption without producing a proportional improvement in pollutant removal.

Table 2. Major factors controlling photovoltaic electrooxidation

Factor	Low condition	Intermediate condition	High condition	General effect
Solar irradiance	Limited electrical output	Stable operation	High output	Increases available power
Current density	Low oxidation rate	Improved oxidation	Possible excessive energy use	
Electrode area	Limited reaction surface	Improved contact	Higher capital requirement	
Treatment time	Incomplete degradation	High removal	Diminishing returns	
pH	May restrict oxidation	Optimum range	May reduce process efficiency	

A key research direction is therefore the development of adaptive current control according to real-time photovoltaic output.

5. Photovoltaic Reverse Osmosis and Water Recovery

Reverse osmosis is fundamentally different from electrochemical oxidation because it relies on membrane separation rather than chemical destruction of contaminants.

The major advantage of photovoltaic-powered RO is the possibility of coupling renewable electricity with **water recovery**.

The water-recovery ratio can be defined as:

$$WR = \frac{V_p}{V_f} \times 100$$

where (V_p) is permeate volume and (V_f) is feed volume.

Specific energy consumption is given by:

$$SEC = \frac{E_{PV}}{V_p}$$

where (E_{PV}) represents electrical energy supplied to the RO system.

Previous studies have demonstrated high contaminant removal while maintaining relatively low energy requirements under optimized operating conditions. However, membrane fouling remains one of the principal limitations.

Table 3. Comparison of major photovoltaic-RO performance indicators

Indicator	Conventional RO	PV-assisted RO	Desired development
Grid dependence	High	Reduced	Near-zero
Energy source	Electricity	Solar electricity	Renewable hybrid
Water recovery	Moderate–high	Moderate–high	Increased
Carbon emissions	Relatively high	Lower	Minimized
Membrane fouling	Present	Present	Intelligent control
Storage requirement	Low	Variable	Optimized
Remote applicability	Limited	High	Expanded

The major limitation is that large RO installations require substantial photovoltaic capacity and therefore significant physical space.

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6. Photovoltaic Electrocoagulation

Electrocoagulation combines electrochemical dissolution of sacrificial electrodes with coagulation and precipitation mechanisms.

Aluminum and iron electrodes are commonly used because they can generate hydroxide species capable of capturing suspended particles, heavy metals, dyes, and organic compounds.

The removal efficiency may be expressed as:

$$RE_{EC} = f(J, t, pH, E_{PV}, C_0)$$

Experimental evidence summarized in the supplied literature indicates that photovoltaic-powered electrocoagulation can achieve substantial removal of turbidity and heavy metals while reducing dependence on conventional electricity.

Table 4. Principal operating variables in PV-electrocoagulation

Parameter	Effect on treatment
Current density	Controls coagulant generation
pH	Controls hydroxide formation and precipitation
Electrode material	Determines coagulation chemistry
Electrode spacing	Influences electrical resistance
Treatment time	Determines pollutant removal
Solar irradiance	Determines available electrical power
Initial pollutant concentration	Determines treatment demand

A major challenge is balancing treatment efficiency against electrode consumption. Excessive current density may improve removal but accelerate electrode degradation.

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7. Solar-Powered Aeration

Aeration represents one of the most important energy-consuming processes in biological wastewater treatment. Solar photovoltaic systems can directly drive blowers, surface aerators, or submerged aeration devices.

The principal mechanism is the increase in dissolved oxygen:

$$DO_{out} > DO_{in}$$

which enhances microbial activity and facilitates the biological oxidation of organic matter and nitrification.

Table 5. Effects of solar-powered aeration

Parameter	Expected response
Dissolved oxygen	Increase
COD removal	Increase
Ammonia removal	Increase

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Microbial activity	Increase
Grid electricity consumption	Decrease
Carbon emissions	Decrease
Operating flexibility	Dependent on solar availability

The major challenge is temporal mismatch between solar availability and oxygen demand. Battery storage or intelligent intermittent aeration can address this problem.

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8. Photovoltaic Electroflocculation

Electroflocculation promotes aggregation of fine particles and dissolved contaminants through electrochemically generated coagulants.

Its principal advantages include:

- low chemical requirement;
- effective turbidity reduction;
- heavy-metal removal;
- color removal;
- compatibility with renewable electricity.

Table 6. Representative treatment characteristics reported for solar-powered EC systems

Application	Main pollutant	Important operating variable	Reported performance
Synthetic wastewater	Turbidity	Treatment time	~72%
Nickel-containing wastewater	Ni^{2+}	Current and irradiance	Up to ~100%
Domestic wastewater	COD	Current density	~85%
Domestic wastewater	TDS	Current density	~70%
Domestic wastewater	Turbidity	Retention time	~87%
Lead-containing water	Pb^{2+}	Current density	~99.9%
Textile wastewater	COD	Electrolysis time	>50%
Surface water	Turbidity	Current density/time	~97%

These values are retained as **reported values from the literature supplied by the user**, rather than being presented as new experimental results.

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9. Solar Photoelectro-Fenton Treatment

Photoelectro-Fenton represents one of the most promising photovoltaic-assisted advanced oxidation technologies.

The Fenton reaction can be simplified as:

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + \cdot OH$$

The hydroxyl radical (\cdot OH) has a high oxidation potential and can attack persistent organic compounds.

Solar integration provides two potential benefits:

1. photovoltaic electricity supplies the electrochemical process;
2. solar radiation may contribute directly to photochemical regeneration and oxidation.

Therefore, the overall process can be represented as:

$$Solar\ radiation + PV\ electricity + Fe^{2+} + H_2O_2 \rightarrow \cdot OH \rightarrow Organic\ pollutant\ degradatio$$

Table 7. Important parameters affecting solar photoelectro-Fenton

Variable	Increase may produce
Solar irradiance	Higher photochemical contribution
Current density	Increased electrochemical generation
Fe^{2+} concentration	Increased catalytic activity up to optimum
H_2O_2 availability	Increased radical generation
Reaction time	Greater pollutant degradation
pH	Strong influence on Fenton chemistry
NaCl concentration	Modified conductivity and oxidation pathways

The principal disadvantage is the need for careful control of chemical conditions and the potential cost associated with reagent consumption.

10. Comparative Evaluation of the Six Solar-Driven Technologies

The six technologies considered in the original literature can be reclassified according to their principal function.

Table 8. Functional classification

Technology	Primary function	Main target	Energy demand	Main limitation
PV-EO	Oxidation	Organic pollutants	Medium–high	Electrode degradation
PV-RO	Separation	Dissolved contaminants	High	Membrane fouling
PV-EC	Coagulation	Metals/turbidity	Low–medium	Electrode consumption
PV-aeration	Biological enhancement	COD/NH_3-N	Low–medium	Solar intermittency
PV-electroflocculation	Particle separation	Suspended solids/metals	Medium	Sludge generation
PV-SPEF	Advanced oxidation	Persistent organics	Medium–high	Chemical control

This classification demonstrates that there is no universally superior photovoltaic wastewater treatment technology. Instead, technology selection should depend on wastewater composition, treatment objectives, solar resource, available land, required water-recovery rate, and energy-storage capacity.

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11. Photocatalytic Efficiency as a New Evaluation Variable

Photocatalytic efficiency is introduced in this review as a major variable because solar energy may contribute to treatment through both photovoltaic electricity and direct photochemical processes.

A simplified efficiency indicator can be expressed as:

$$PE = \frac{\Delta C}{E_{solar}}$$

where ΔC) represents the contaminant concentration reduction and (E_{solar}) represents solar energy input.

A more comprehensive indicator can combine pollutant removal and energy utilization:

$$PE^* = \frac{RE}{SEC}$$

where (RE) is removal efficiency and (SEC) is specific energy consumption.

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This parameter enables comparison between systems that achieve similar removal efficiencies but require substantially different amounts of energy.

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12. Energy Recovery and Energy-Positive Treatment

Most studies evaluate energy consumption but do not adequately consider the possibility of energy recovery.

Wastewater contains chemical energy in organic matter. Consequently, future photovoltaic wastewater systems should be designed not simply to reduce electricity consumption but also to recover energy.

A generalized net-energy balance can be expressed as:

$$E_{net} = E_{PV} + E_{recovered} - E_{treatment}$$

where:

- (E_{PV}) = photovoltaic electricity generated;
- ($E_{recovered}$) = energy recovered from wastewater;
- ($E_{treatment}$) = electricity consumed by treatment.

When:

$$E_{net} > 0$$

the system may theoretically operate as an energy-positive treatment platform.

Table 9. Proposed energy-recovery framework

Energy component	Source	Potential utilization
Photovoltaic electricity	Solar radiation	Direct treatment
Battery storage	Excess PV electricity	Night operation
Biogas	Organic wastewater	Electricity/heat
Hydrogen	Electrochemical treatment	Fuel
Waste heat	Equipment/processes	Thermal processes
Recovered chemical energy	Organic matter	Energy production

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13. Environmental Sustainability Assessment

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Environmental sustainability should not be evaluated solely through pollutant-removal efficiency.

A system may achieve very high removal efficiency while consuming substantial electricity, generating large quantities of sludge, or requiring frequent replacement of electrodes and membranes.

Therefore, a broader sustainability index is proposed:

$$ESI = w_1RE + w_2ER + w_3WR + w_4CR - w_5SEC - w_6OC$$

where (w_i) represent weighting coefficients.

Table 10. Proposed sustainability dimensions

Dimension	Indicator	Desired direction
Water quality	Pollutant removal	↑
Energy	Energy recovery	↑
Energy	Specific energy consumption	↓
Climate	Carbon emissions	↓
Water resources	Water recovery	↑
Materials	Electrode consumption	↓
Economics	Operating cost	↓
Reliability	System stability	↑
Scalability	Treatment capacity	↑

This multidimensional framework provides a stronger basis for comparing future systems.

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14. Interaction Between Solar Radiation and Treatment Performance

Solar radiation is not constant. It varies with:

- time of day;
- season;
- cloud cover;
- geographic location;
- panel orientation;
- temperature;
- dust accumulation.

Consequently, photovoltaic wastewater treatment should be designed around a dynamic energy supply.

Table 11. Expected effect of solar-resource conditions

Solar condition	PV output	Treatment response	Recommended strategy
Very low	Low	Reduced	Battery/grid support
Low	Limited	Partial operation	Reduced treatment load
Moderate	Stable	Normal	Standard operation
High	High	Enhanced	Maximum treatment
Highly variable	Fluctuating	Unstable	Intelligent control

15. Integrated Solar-Wastewater Treatment Architecture

A future system should not rely on a single treatment technology.

A more effective architecture may combine:

PV → energy management → pretreatment → electrochemical treatment → membrane separation → biological polishing → water reuse

An integrated configuration could include:

1. photovoltaic modules;
2. maximum-power-point tracking;
3. battery storage;
4. electrocoagulation;
5. electrooxidation;
6. membrane filtration;
7. solar-powered aeration;
8. water-quality sensors;
9. intelligent control;
10. energy-recovery unit.

Table 12. Proposed integrated architecture

Stage	Technology	Primary objective
1	Screening	Remove large solids

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2	PV-EC	Remove suspended solids/metals
3	PV-EO/SPEF	Degrade persistent organics
4	Biological treatment	Remove biodegradable organics/nutrients
5	PV-RO	Final separation and water recovery
6	Disinfection	Ensure reuse quality
7	Energy recovery	Recover useful energy
8	Monitoring	Real-time optimization

16. Economic and Operational Considerations

The economic feasibility of solar wastewater treatment depends on the relationship between capital expenditure and long-term electricity savings.

The simplified payback period can be expressed as:

$$PBP = \frac{C_{PV} + C_{storage}}{S_{energy}}$$

where:

- C_{PV} = photovoltaic investment;
- $C_{storage}$ = storage investment;
- S_{energy} = annual energy-cost savings.

Table 13. Economic factors affecting system feasibility

Factor	Economic effect
PV module price	Determines initial investment
Battery price	Strong effect on off-grid systems
Electricity price	Determines savings
Solar irradiation	Determines annual energy generation
Maintenance	Influences long-term cost
Electrode replacement	Important for EC/EO

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Membrane replacement	Important for RO
System lifetime	Determines return on investment
Water reuse value	Can improve economic feasibility

17. Major Research Gaps

The reviewed literature reveals several unresolved issues.

Table 14. Research gaps and proposed solutions

Research gap	Consequence	Proposed solution
Solar intermittency	Variable treatment capacity	Predictive energy management
Low storage efficiency	Night-time limitations	Advanced batteries
Electrode degradation	Increased operating cost	Durable electrode materials
Membrane fouling	Reduced RO efficiency	Electrochemical pretreatment
Limited energy recovery	Energy loss	Integrated recovery units
Large PV footprint	Land requirement	High-efficiency PV and floating PV
Lack of unified indicators	Difficult comparison	Standardized performance index
Limited pilot-scale studies	Poor scalability	Long-term field demonstrations
Weather dependence	Operational instability	Hybrid PV-storage systems
Insufficient life-cycle assessment	Uncertain environmental benefit	Full LCA analysis

18. Future Research Directions

Future studies should move toward **integrated photovoltaic-water-energy systems** rather than isolated photovoltaic-powered treatment units.

Particular attention should be given to five directions.

18.1 Intelligent energy management

Artificial intelligence and predictive control can estimate photovoltaic output and dynamically adjust current density, aeration intensity, membrane pressure, and treatment time.

18.2 Energy recovery

Photovoltaic generation should be integrated with biogas, hydrogen, and other energy-recovery technologies.

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18.3 Resource recovery

Wastewater should increasingly be viewed as a resource rather than merely a waste stream. Nitrogen, phosphorus, metals, hydrogen, and organic energy can potentially be recovered.

18.4 Hybrid treatment

Combining PV-electrocoagulation, PV-electrooxidation, biological treatment, and membrane processes may reduce the energy requirements of individual technologies.

18.5 Life-cycle sustainability

Future evaluations should include:

- embodied carbon of PV modules;
- battery manufacturing;
- electrode production;
- membrane replacement;
- sludge management;
- transportation;
- end-of-life disposal.

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19. Proposed Comprehensive Performance Index

To facilitate future comparison, a normalized Solar Wastewater Sustainability Index (SWSI) can be proposed:

$$SWSI = w_1RE + w_2PE + w_3ER + w_4WR + w_5CR - w_6SEC - w_7OC$$

where:

- **(RE)** = pollutant-removal efficiency;
- **(PE)** = photocatalytic efficiency;
- **(ER)** = energy recovery;
- **(WR)** = water recovery;
- **(CR)** = carbon reduction;
- **(SEC)** = specific energy consumption;
- **(OC)** = operating cost.

This index is proposed as a **conceptual framework for future research**, not as an experimentally validated index.

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20. Overall Comparative Matrix

Table 15. Overall assessment of photovoltaic-driven wastewater technologies

Technology	Pollutant removal	Energy efficiency	Water recovery	Sustainability	Scalability
PV-EO	High	Moderate	Low	High	Moderate
PV-RO	Very high	Moderate	Very high	High	High
PV-EC	High	High	Moderate	High	High
PV-aeration	Moderate	High	Moderate	Very high	Very high
PV-electroflocculation	High	Moderate	Moderate	High	High
PV-SPEF	Very high	Moderate	Low	High	Moderate
Integrated hybrid system	Very high	High potential	Very high	Very high	High potential

21. Conclusions

Solar photovoltaic technology provides an increasingly attractive pathway for reducing the energy and environmental burdens associated with wastewater treatment. Unlike conventional treatment systems that depend predominantly on grid electricity, photovoltaic-driven systems can utilize locally available renewable energy to power electrochemical reactors, membrane units, aeration systems, and advanced oxidation processes.

The present review extends conventional assessments by introducing three interconnected variables: **photocatalytic efficiency, energy recovery, and environmental sustainability**. These variables provide a broader framework for evaluating the performance of solar wastewater-treatment systems beyond conventional pollutant-removal efficiency.

Photovoltaic-electrooxidation systems are particularly promising for persistent organic contaminants, whereas photovoltaic reverse osmosis offers substantial potential for water recovery. Photovoltaic electrocoagulation and electroflocculation are attractive for heavy metals, turbidity, and suspended pollutants. Solar-powered aeration can substantially improve biological treatment while reducing electricity requirements. Photoelectro-Fenton systems provide strong oxidation capacity for difficult-to-degrade organic contaminants.

Nevertheless, the widespread implementation of these systems remains constrained by solar intermittency, energy-storage limitations, electrode degradation, membrane fouling, photovoltaic land requirements, and differences between laboratory and full-scale operating conditions.

Future development should therefore focus on **hybrid photovoltaic-water-energy systems** capable of simultaneously achieving pollutant removal, water recovery, energy recovery, and carbon reduction. Intelligent control systems, high-efficiency photovoltaic materials, durable electrodes, advanced membranes, and integrated energy-storage technologies will be critical to achieving reliable operation.

Ultimately, the transition from conventional wastewater treatment toward solar-powered circular water systems requires a shift from evaluating individual treatment technologies to evaluating the entire **water-energy-environment nexus**. Such an approach can improve the technical efficiency, economic feasibility, and environmental sustainability of wastewater treatment, particularly in remote and energy-constrained regions with abundant solar resources.

Ethical Considerations

Not applicable. This study did not require ethical approval because it does not include human or animal subjects and does not involve any personal or sensitive data.

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All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

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References

1. Zhang Z Z, Zhang Q. Analysis of water pollution and analysis of water environment protection strategies. *Leather Manufacturing and Environmental Technology*. 2023;4(4):81–83.
2. Chala G T, Al Alshaikh S M. Solar photovoltaic energy as a promising enhanced share of clean energy sources in the future—A comprehensive review. *Energies*. 2023;16(24):7919.
3. Elfaqih A K, Elbaz A, Akash Y M. A review of solar photovoltaic-powered water desalination technologies. *Sustainable Water Resources Management*. 2024;10(3):123.
4. Anand B, Shankar R, Murugavelh S, et al. A review on solar photovoltaic thermal integrated desalination technologies. *Renewable and Sustainable Energy Reviews*. 2021;141:110787.
5. Liu G, Zhen C, Kang Y Y, et al. Unique physicochemical properties of two-dimensional light absorbers facilitating photocatalysis. *Chemical Society Reviews*. 2018;47(16):6410–6444.
6. Wang X X. Application and maintenance of photovoltaic grid-connected inverters in photovoltaic power stations. *Lamps & Lighting*. 2021;(4):70–71.
7. Wang G, Liang S, Ma X L, et al. Study on solar concentrating photovoltaic–membrane distillation hybrid seawater desalination system. *Acta Energiae Solaris Sinica*. 2022;43(11):94–99.
8. Valero D, García-García V, Expósito E, et al. Electrochemical treatment of wastewater using photovoltaic energy. *Environmental Science and Technology*.
9. Dominguez-Ramos A, Aldaco R, Irabien A. Environmental assessment of electrochemical wastewater treatment powered by photovoltaic energy. *Journal of Cleaner Production*.

10. Kargi F. Photovoltaic-powered electrochemical treatment of wastewater and simultaneous hydrogen production. *Journal of Chemical Technology and Biotechnology*.
11. Salmerón I, et al. Solar-assisted electrochemical treatment of landfill leachate: energy consumption and pollutant removal performance. *Journal of Environmental Management*.
12. Salmerón I, et al. Solar photoelectro-Fenton treatment of emerging organic micropollutants in wastewater. *Water Research*.
13. Jbari M, et al. Photovoltaic-powered reverse osmosis for wastewater treatment and water recovery. *Desalination*.
14. Sundaramoorthy S, et al. Modeling and performance analysis of spiral-wound reverse osmosis systems for wastewater treatment. *Desalination*.
15. De Jesus A, et al. Solar photovoltaic-powered electrocoagulation for industrial wastewater treatment. *Journal of Environmental Chemical Engineering*. 2021.
16. Zhang Y, et al. Photovoltaic-powered electrocoagulation for nickel removal from wastewater. *Separation and Purification Technology*.
17. Louhichi B, et al. Solar photovoltaic-assisted electrocoagulation and electro-Fenton processes for textile wastewater treatment. *Process Safety and Environmental Protection*.
18. Dos Santos A J, et al. Solar photoelectro-Fenton treatment of greywater containing linear alkylbenzene sulfonates. *Chemosphere*.
19. Khaleel M, et al. Solar photoelectro-Fenton treatment of petroleum refinery wastewater: optimization of operational parameters. *Environmental Technology & Innovation*.
20. Muniasamy S, et al. Solar-powered electrocoagulation for domestic wastewater treatment: optimization of current density and retention time. *Environmental Technology*.
21. Hussin A, et al. Solar photovoltaic electrocoagulation using perforated zinc electrodes for lead removal from aqueous solutions. *Journal of Environmental Chemical Engineering*.
22. Mohamad M, et al. Integrated photovoltaic electrocoagulation for treatment of palm oil mill effluent. *Journal of Water Process Engineering*.
23. Karmankar S, et al. Photovoltaic-driven electrocoagulation for treatment of rice-stillages biogas effluent. *Environmental Science and Pollution Research*.
24. St-Onge M, et al. Battery-free photovoltaic electrocoagulation for surface-water treatment. *Water Research*.
25. Valero D, et al. Direct coupling of photovoltaic modules and electrocoagulation for textile dye removal. *Electrochimica Acta*.

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26. Mohamada M, et al. Photovoltaic-powered electrocoagulation for textile wastewater treatment: optimization of operating conditions. *Journal of Environmental Management*.
27. Louhichi B, et al. Solar photovoltaic-driven electrochemical treatment of textile wastewater: comparison between electrocoagulation and electro-Fenton processes. *Separation and Purification Technology*.
28. 28.楼佳俊. Solar-powered aeration combined with biological treatment for wastewater remediation. *Environmental Engineering*.
29. 吴薇, 等. Solar aeration-enhanced constructed wetlands for treatment of swine wastewater. *中国给水排水*.