FUNCTIONAL-TECHNOLOGICAL ARCHITECTURE AND ADAPTIVE CONTROL CONCEPT OF AN INTELLIGENT SOLAR-ELECTROBIOMEMBRANE SYSTEM

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Abstract The increasing occurrence of micropollutants in municipal and industrial wastewater requires treatment platforms capable of combining contaminant destruction, biological transformation, membrane separation, and energy-efficient operation. This paper develops a functional-technological concept for an intelligent solar-electrobiomembrane system in which photovoltaic energy supply, electrochemical treatment, biological degradation, membrane separation, sensing, and adaptive control are integrated into a coordinated technological architecture. The study is based on a structured analysis of the scientific materials supplied for the research topic and does not introduce unsupported experimental measurements. The principal energetic, thermal, electrochemical, biological, and membrane-related parameters were classified according to their role in system control. Previously reported operating indicators, including a temperature interval of 25–35 °C, current density of 5–15 A/m², micropollutant degradation of up to 92.4%, a 38% reduction in biofouling formation rate, and a 28.5% reduction in the overall energy budget, were used as reference values for establishing the technological operating domain. The resulting framework emphasizes state-dependent control rather than fixed operating conditions. Such an architecture creates a methodological basis for real-time monitoring, digital-twin implementation, machine-learning-assisted prediction, and multi-objective optimization of wastewater treatment performance.

1. INTRODUCTION

Water pollution is increasingly characterized by the simultaneous presence of conventional pollutants and emerging contaminants. Organic matter, nutrients, suspended solids, pharmaceuticals, antibiotics, endocrine-active substances, pesticides, and other micropollutants may occur at different concentrations and exhibit substantially different physicochemical and biological characteristics. Consequently, a single treatment mechanism is often insufficient for achieving stable removal across a broad contaminant spectrum. Advanced wastewater treatment therefore increasingly relies on process integration, in which complementary separation and transformation mechanisms are combined within a coordinated technological platform.

Membrane bioreactor technology is particularly relevant to this development because biological treatment and membrane-based solid-liquid separation can be implemented within one compact process configuration. The membrane barrier produces a clarified permeate while retaining suspended biomass and particulate material. This configuration can provide high-quality treated water and a smaller footprint than treatment schemes relying on conventional secondary clarification. Nevertheless, membrane operation is constrained by biofouling, concentration polarization, declining permeability, hydraulic resistance, and the energy required for aeration, circulation, and membrane scouring. The energy dimension becomes especially important when membrane processes are coupled with electrochemical treatment. Electrochemical oxidation and related processes can improve the transformation of persistent or biologically recalcitrant compounds, but their performance depends on electrical input, electrode conditions, current density, solution composition, and mass transfer. If these variables are maintained without considering the instantaneous energy availability and biological state of the reactor, the resulting system may exhibit unnecessary energy consumption or unstable operating conditions.

Solar energy offers an alternative pathway for reducing dependence on external electricity. A photovoltaic-thermal configuration can provide electrical energy for electrochemical treatment and auxiliary equipment while simultaneously supplying useful thermal energy for temperature management. The resulting integration is particularly attractive for decentralized treatment, remote facilities, and applications in which local renewable energy availability can be coordinated with treatment demand. The scientific challenge is therefore not simply the substitution of grid electricity with photovoltaic electricity. The central challenge is the development of an integrated control architecture capable of continuously reconciling three interacting states: the availability of renewable energy, the biological and electrochemical state of the reactor, and the operational state of the membrane. This perspective shifts the treatment system from a collection of independently controlled units toward a dynamic, information-driven process.

Previous research supplied for the present study provides several technologically important reference indicators. In a photovoltaic-thermal electrobiomembrane configuration, a temperature range of 25–35 °C and a current-density range of 5–15 A/m² were associated with improved treatment performance. The reported maximum micropollutant degradation reached 92.4%, while the biofouling formation rate was reported to decrease by 38%. The same body of material indicated a 28.5% reduction in the overall energy budget. These values are treated here as source-derived reference indicators rather than as newly generated experimental results. The research gap addressed in this paper concerns the system-level organization of these variables. Existing treatment components can be individually optimized, but the scientific value of the proposed architecture lies in their coordinated operation. An intelligent control layer can use sensor information to identify the current system state and select an operating regime that balances contaminant removal, biological activity, membrane stability, and energy consumption.

Accordingly, the objective of this study was to formulate a scientifically grounded functional-technological architecture for an intelligent solar-electrobiomembrane system and to establish the hierarchy of parameters required for adaptive control. The specific objectives were to define the functional roles of the major subsystems, classify the principal control variables, organize previously reported performance indicators into a coherent operating framework, formulate an adaptive control concept, and identify methodological directions for subsequent digital-twin and machine-learning implementation.

2. MATERIALS AND METHODS

2.1. Research design

The present work employed a structured analytical design based on the scientific materials supplied for the development of the solar-electrobiomembrane research topic. The methodological procedure consisted of four consecutive stages: identification of technological subsystems; classification of controllable and observable parameters; synthesis of reported performance indicators; and formulation of an adaptive control architecture. Because the supplied materials do not provide a complete raw experimental dataset, statistical re-analysis, uncertainty estimation, or independent replication was not performed. This methodological limitation is important for the interpretation of the paper. The numerical indicators reported in the Results section originate from the supplied research material and are not presented as measurements newly obtained in the present work. The analytical contribution of this paper is the organization of those indicators within a unified control-oriented framework.

2.2. Functional decomposition of the treatment system

The proposed system was decomposed into five functional subsystems. The first is the photovoltaic-thermal energy subsystem, which converts incident solar radiation into electrical and useful thermal energy. The second is the energy-management subsystem, which distributes available electrical power among electrochemical treatment, pumping, sensing, control, and auxiliary equipment. The third is the hybrid electrobiomembrane reactor, where electrochemical transformation, biological degradation, and membrane separation are coupled. The fourth is the sensing and monitoring subsystem, which provides information on the current state of the process. The fifth is the intelligent control subsystem, which converts monitored state information into adaptive operating decisions. This decomposition was selected because each subsystem contributes a different class of state variables. Solar irradiance and photovoltaic output characterize the energy state; temperature, current density, flow regime, and biological activity characterize the process state; and permeate behavior and biofouling indicators characterize membrane condition. The control system must therefore process heterogeneous information rather than relying on a single measured variable.

2.3. Classification of monitored and controlled parameters

Energy variables include solar irradiance, photovoltaic output, thermal output, and electrical demand. Thermal variables include reactor temperature, heat input, and heat loss. Electrochemical variables include current density, electrical load, and electrode condition. Biological variables include biomass activity, organic loading, and process stability. Hydrodynamic variables include flow rate, recirculation, and hydraulic loading. Membrane variables include permeate behavior, fouling state, and membrane stability. Intelligent-control variables include sensor signals, estimated states, and predicted states.

2.4. Analytical synthesis of source-derived indicators

The reported numerical indicators were not pooled statistically because the supplied source materials do not establish a common experimental protocol, sample composition, reactor geometry, replication scheme, or uncertainty structure sufficient for formal meta-analysis. Instead, the values were mapped to the parameter domains described above. This procedure allows the indicators to be interpreted as operating references without creating an unsupported claim of statistical equivalence. The 25–35 °C temperature interval was assigned to the thermal-biological domain. The 5–15 A/m² current-density interval was assigned to the electrochemical control domain. The 92.4% micropollutant degradation indicator was treated as a treatment-performance outcome. The 38% reduction in biofouling formation rate was associated with membrane stability, while the 28.5% reduction in overall energy budget was assigned to system-level energy performance.

2.5. Adaptive control logic

The proposed control logic is state-dependent. First, the sensing layer acquires information describing energy availability, reactor conditions, and membrane state. Second, the monitoring layer performs state identification and detects deviation from the preferred operating domain. Third, the supervisory controller prioritizes the most critical constraint. For example, a reduction in solar availability may require energy allocation to be reconfigured, whereas an increase in membrane fouling tendency may require modification of electrochemical or hydrodynamic conditions. Finally, the actuator layer implements the selected adjustment. The control objective is deliberately formulated as a multi-criteria problem. Maximization of contaminant removal alone may result in excessive electrical demand, while minimizing energy consumption alone may compromise treatment quality. Likewise, aggressive membrane operation can increase productivity in the short term but accelerate fouling. The adaptive architecture therefore seeks a balanced state in which treatment efficiency, membrane stability, biological activity, and energy performance are simultaneously considered.

3. RESULTS

3.1. Integrated functional architecture

The analysis resulted in an integrated functional architecture in which energy conversion and wastewater treatment are linked through an intelligent supervisory layer. Solar radiation is converted by the photovoltaic-thermal subsystem into electrical and thermal energy. Electrical energy is directed toward electrochemical treatment and auxiliary equipment, whereas useful thermal output can be applied to temperature management. The wastewater stream then passes through the hybrid electrobiomembrane reactor, where electrochemical transformation, biological degradation, and membrane separation operate as interconnected mechanisms. A central result of the analysis is the recognition that the membrane should not be treated as an isolated polishing unit. Its operating state is directly influenced by upstream biological activity, electrochemical conditions, hydraulic loading, and the energy available for control actions. Conversely, membrane behavior provides information about the overall process state. A rise in fouling tendency may indicate excessive biological accumulation, unfavorable hydrodynamic conditions, or insufficient control of upstream transformations.

3.2. Parameter hierarchy for intelligent operation

The resulting parameter hierarchy consists of three principal control levels. The first level is the energetic state, represented by solar-resource availability and the electrical and thermal outputs of the photovoltaic-thermal subsystem. The second level is the technological state, represented primarily by temperature, electrochemical intensity, hydraulic conditions, and biological activity. The third level is the membrane state, represented by separation behavior and fouling tendency. The hierarchy allows the control system to distinguish between the source of a disturbance and its technological consequence. The hierarchical structure also supports fault-oriented reasoning. For example, a decline in treatment performance accompanied by stable energy availability but increasing membrane fouling would be interpreted differently from a decline occurring simultaneously with a substantial reduction in photovoltaic output. In the first case, membrane or process conditions would become the dominant control concern; in the second case, energy management would become more important.

3.3. Source-derived operating indicators

The source-derived indicators establish a coherent set of reference values for the proposed architecture. The reactor temperature was reported in the 25–35 °C range; current density was reported in the 5–15 A/m² range; maximum micropollutant degradation was reported as 92.4%; biofouling formation rate was reported to decrease by 38%; and the overall energy budget was reported to decrease by 28.5%. These values define a source-derived technological envelope rather than universally optimal values for all wastewater compositions or reactor configurations.

3.4. Energy-process coordination

The integrated architecture indicates that energy availability should be considered a dynamic process variable. Under favorable solar conditions, available photovoltaic power can support electrochemical treatment and auxiliary loads while thermal output contributes to temperature regulation. Under reduced solar availability, the supervisory controller can prioritize essential process functions and reduce non-critical energy demand. Such prioritization is especially relevant for decentralized installations where energy storage or grid backup may be limited. The reported 28.5% reduction in the overall energy budget provides an important source-derived indication that integrated energy management may have a measurable effect on system performance. However, the available materials do not provide sufficient information to attribute this reduction to a single mechanism or to establish its statistical uncertainty. Therefore, the value is used here as a performance reference rather than as a generalized prediction.

3.5. Membrane-state integration

The membrane-related findings demonstrate the importance of incorporating fouling state into the supervisory control architecture. The reported 38% reduction in biofouling formation rate suggests that electrochemical operating conditions can influence membrane stability. From a control perspective, this means that membrane protection can become an active objective rather than a passive consequence of reactor operation. The resulting architecture consequently treats membrane state as a feedback variable. When fouling indicators remain within an acceptable range, the system can maintain the prevailing operating regime. When fouling tendency increases, the controller can initiate a corrective response through appropriate modification of electrochemical intensity, hydraulic conditions, or cleaning-related actions. The precise control law requires experimental calibration and is not claimed to have been validated in the present analytical study.

4. DISCUSSION

4.1. Scientific significance of system integration

The main scientific implication of the proposed architecture is that wastewater treatment performance should be considered as the outcome of coupled energy, reaction, biological, transport, and separation phenomena. Conventional control strategies often regulate individual variables independently. Such an approach is less suitable for a renewable-energy-driven system because the energy input itself is variable. The intelligent solar-electrobiomembrane concept addresses this limitation by making energy availability an explicit component of the process state. The integration of electrochemical and biological mechanisms is also significant from the perspective of micropollutant treatment. Electrochemical transformation can contribute to the degradation of compounds that may be relatively persistent under biological treatment, while biological processes can further transform biodegradable fractions and reaction intermediates. Membrane separation then provides a physical barrier for retaining biomass and particulate matter. The combined architecture therefore provides complementary treatment mechanisms rather than relying on a single removal pathway.

4.2. Relationship between thermal and electrochemical regimes

Temperature and current density represent two particularly important operating dimensions because they affect different but interacting parts of the treatment mechanism. Temperature influences biological kinetics, microbial activity, mass-transfer characteristics, and the physicochemical properties of the wastewater. Current density directly affects electrochemical reaction intensity and electrode-associated processes. The source-derived ranges of 25–35 °C and 5–15 A/m² therefore provide a rational starting point for adaptive control, while their exact optimum remains dependent on wastewater composition and reactor configuration. The reported degradation performance of up to 92.4% should be interpreted in this context. High removal does not necessarily imply that all compounds follow the same degradation pathway or that complete mineralization has occurred. In an integrated electrobiological system, apparent contaminant removal can involve electrochemical transformation, biodegradation, adsorption, retention, and other mechanisms. Detailed pathway identification would require compound-specific analytical measurements that are not available in the supplied material.

4.3. Biofouling as a control variable

Biofouling remains one of the most consequential limitations of membrane-based wastewater treatment because the development of a biological layer can alter membrane permeability and increase operational demand. Treating fouling as a feedback variable is therefore more scientifically appropriate than considering it solely as an end-of-process maintenance problem. The reported 38% reduction in biofouling formation rate provides evidence supporting the potential role of electrochemical conditions in membrane protection. Nevertheless, a rigorous interpretation requires information on biomass characteristics, extracellular polymeric substances, membrane material, hydrodynamic shear, aeration intensity, and cleaning frequency. These variables were not sufficiently specified in the supplied materials and therefore require dedicated experimental investigation.

4.4. Implications for digital-twin development

The parameter hierarchy developed in this study is compatible with a digital-twin framework. A digital twin for the solar-electrobiomembrane system would continuously receive sensor information, estimate latent process states, compare observed conditions with a virtual process representation, and generate predictive information for the supervisory controller. The most valuable variables for such a model would include solar availability, energy demand, temperature, electrochemical intensity, hydraulic state, biological indicators, and membrane condition. Machine learning can subsequently be introduced at several levels. Regression models can estimate treatment performance; anomaly-detection models can identify deviations from normal operation; time-series models can forecast energy availability and membrane-state evolution; and adaptive optimization strategies can support decision-making under changing operating conditions. However, reliable deployment requires a sufficiently large, diverse, and experimentally validated dataset. The present paper establishes the conceptual parameter structure but does not claim validation of a machine-learning model.

4.5. Energy efficiency and operational resilience

The reported 28.5% reduction in overall energy budget suggests that the integration of renewable energy conversion and adaptive process control can contribute to improved energy performance. The underlying mechanism is likely to involve both energy substitution and better matching between available energy and treatment demand. Yet, the precise contribution of photovoltaic generation, thermal integration, electrochemical optimization, and auxiliary-load management cannot be separated from the supplied evidence. Operational resilience is another important implication. A system that can adapt its operating regime to changes in solar availability may remain functional under conditions that would challenge a fixed-parameter process. This is particularly relevant to decentralized wastewater treatment, where access to stable grid electricity can be limited. Nevertheless, resilience should be assessed through long-duration experiments that include cloud transients, seasonal variation, wastewater-load fluctuations, sensor faults, and membrane aging.

4.6. Limitations and future experimental requirements

The present study has several limitations. First, it is an analytical synthesis of supplied scientific materials rather than a new experimental campaign. Second, the available information does not provide a complete description of reactor dimensions, membrane area and material, wastewater composition, replicate number, uncertainty, or statistical significance. Third, the reported performance indicators originate from prior material and therefore should not be generalized beyond their original experimental context.

Future experimental work should establish a controlled pilot-scale platform with continuous measurement of solar irradiance, photovoltaic output, thermal state, current density, flow regime, biological indicators, permeate behavior, and membrane fouling. Repeated experiments should be performed across representative wastewater compositions and solar conditions. The resulting dataset would allow development and validation of predictive models, quantitative uncertainty assessment, and rigorous multi-objective optimization.

Within this context, the present framework should be regarded as a bridge between component-level experimental findings and a system-level intelligent treatment platform. Its principal contribution is the organization of heterogeneous process variables into an integrated control architecture that can subsequently be tested, calibrated, and validated experimentally.

CONCLUSION

1. The integration of photovoltaic energy, electrochemical treatment, biological degradation, and membrane separation into a unified technological platform provides a scientifically grounded approach to integrated wastewater treatment.
2. The structural and functional architecture of the intelligent solar-electrobiomembrane system is based on the synergistic integration of energetic, technological, membrane, monitoring, and control subsystems.
3. Maintaining the reactor temperature within the 25–35 °C range can provide favorable thermal and biological conditions for intensified biodegradation and enhanced removal of micropollutants.
4. Regulation of the electrochemical process within the 5–15 A/m² current-density range represents an important technological factor for controlling membrane biofouling and maintaining stable membrane performance.
5. Integration of photovoltaic-thermal energy supply with the electrobiomembrane reactor demonstrates potential for reducing external energy requirements and improving the overall energy efficiency of the treatment system.
6. The proposed adaptive control concept enables real-time adjustment of technological operating conditions according to the current energetic, thermal, electrochemical, biological, and membrane states of the system.
7. The developed conceptual framework provides a methodological basis for further implementation of digital twin technologies, machine learning, real-time monitoring, and multi-objective optimization in intelligent solar-electrobiomembrane wastewater treatment systems.

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