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Smart Bio-Polymer Composite Systems for Sustainable Bio-Polymer Composite Media for Enhanced Pollutant Removal in Constructed Wetland Systems Using Machine Learning

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Abstract

Constructed wetlands are widely used for wastewater treatment due to their low cost and ecological compatibility; however, their efficiency in removing emerging contaminants remains limited. This study presents the development of biodegradable polymer-based composite materials integrated into wetland filtration systems to enhance pollutant removal efficiency. Bio-polymers combined with natural fillers such as biochar and clay were synthesized and evaluated under simulated wetland conditions. The results demonstrate improved adsorption capacity, increased contaminant removal efficiency, and enhanced system stability. The study provides a sustainable pathway for integrating advanced materials into ecological treatment systems.

This research evaluates the efficacy of a novel ***Bio-Polymer Composite (BPC)*** *substrate designed to mitigate the shortcomings of conventional constructed wetland (CW) media, such as low nutrient affinity and physical instability. By integrating cross-linked biopolymeric matrices with inert mineral cores, the study demonstrates a significant increase in the sequestration of nitrogenous and phosphorous compounds. Field data, supported by the* ***WetlandGuard monitoring framework****, indicates that BPC-augmented systems can achieve a* ***75% pollutant attenuation rate****, offering a scalable solution for treating clandestine sewage discharges in sensitive ecosystems. This study investigates the development of a sustainable bio-polymer composite (BPC) media designed to enhance the adsorption of heavy metals and nutrients (Nitrogen and Phosphorus). Using data from the* ***WetlandGuard community platform****, we contextualize these findings within real-world sewage discharge scenarios.*

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INTRODUCTION

Wetlands serve as natural biofilters that remove contaminants through physical, chemical, and biological processes. Despite their advantages, conventional wetlands often struggle with persistent pollutants such as heavy metals, dyes, and pharmaceutical residues.

Traditional constructed wetlands (CWs) often face limitations in nutrient removal efficiency and media clogging. This study investigates the development of a sustainable bio-polymer composite (BPC) media designed to enhance the adsorption of heavy metals and nutrients (Nitrogen and Phosphorus). Using data from the **WetlandGuard community platform**, we contextualize these findings within real-world sewage discharge scenarios. Results indicate that BPC-integrated systems can achieve up to a **75% reduction in primary pollutants**, significantly outperforming traditional gravel-only beds.

Recent advances in **polymer science and composite engineering** offer new opportunities to enhance wetland treatment performance. Biodegradable polymer composites, due to their tunable structure and adsorption capacity, have emerged as promising candidates for environmental remediation.

This study focuses on integrating such materials into wetland systems to improve overall efficiency while maintaining ecological balance.

LITERATURE REVIEW

Constructed wetlands (CWs) are widely utilized as environmentally sustainable systems for wastewater treatment due to their reliance on natural processes such as sedimentation, microbial degradation, and plant uptake. These systems are particularly effective in reducing organic load and nutrient concentrations. However, their ability to remove persistent contaminants, including heavy metals and emerging pollutants, remains limited due to insufficient adsorption capacity and slow reaction kinetics [1].

To overcome these limitations, researchers have explored the incorporation of engineered materials into wetland systems. Among these, biochar has gained significant attention because of its highly porous structure and large surface area, which enhance adsorption performance. Studies have shown that biochar not only improves pollutant retention but also supports microbial activity within treatment systems [2]. Additionally, investigations have demonstrated that biochar-based materials can effectively remove both organic and inorganic contaminants [6]. Despite these advantages, biochar may experience performance degradation over time due to saturation and structural instability.

In parallel, polymer-based adsorbents have been extensively studied for water purification applications. Biopolymers such as chitosan exhibit strong affinity for heavy metals owing to the presence of functional groups capable of forming chemical bonds with contaminants [3]. Similarly, low-cost polymeric materials have been identified as efficient alternatives to conventional adsorbents due to their environmental compatibility and availability [4]. However, standalone polymer systems often lack sufficient mechanical strength, limiting their direct use in dynamic environmental conditions.

To address these challenges, recent research has focused on the development of polymer composites, which combine polymers with inorganic or carbon-based fillers. These composites exhibit improved structural integrity, enhanced surface area, and increased adsorption efficiency. Studies have shown that incorporating materials such as clay and biochar into polymer matrices significantly enhances pollutant removal performance [5,6]. Furthermore, natural fiber-reinforced composites have been explored as sustainable alternatives, offering advantages such as biodegradability and improved mechanical properties [9,10].

Hybrid treatment approaches that integrate engineered materials into constructed wetlands have also shown promising results. Modified substrates have been reported to improve both adsorption capacity and microbial activity, leading to enhanced overall system performance [7]. Additionally, combining material-based filtration with ecological processes can significantly improve the removal of complex contaminants, including pharmaceuticals [8].

With the rapid advancement of digital technologies, machine learning (ML) has emerged as a powerful tool for analyzing and optimizing environmental systems. ML algorithms are capable of capturing nonlinear relationships between input variables and system performance, making them highly

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suitable for wastewater treatment applications. Research has shown that models such as Random Forest and Support Vector Machines can accurately predict water quality parameters and treatment efficiency [11]. Similarly, ML-based optimization techniques can enhance the operational efficiency of wastewater treatment systems [12].

In addition, machine learning has been applied to model adsorption processes and predict the performance of advanced materials. Studies have demonstrated that ML models can effectively estimate adsorption capacity under varying conditions, enabling improved material design and process optimization [13]. Furthermore, data-driven approaches provide more reliable predictions compared to conventional statistical methods, particularly in complex environmental systems [14].

Despite these advancements, existing research largely treats material development and computational modeling as separate domains. There remains a lack of integrated approaches that combine bio-polymer composite materials with machine learning within constructed wetland systems. Moreover, challenges related to long-term stability, scalability, and real-time monitoring have not been fully addressed [15].

Therefore, this study aims to develop a smart bio-polymer composite wetland system enhanced by machine learning techniques, providing a unified approach that combines material innovation with data-driven optimization to improve wastewater treatment efficiency and reliability.

MATERIALS AND METHODS

Materials Selection

This study, titled **“Smart Bio-Polymer Composite Systems for Wetland Water Treatment Using Machine Learning,”** utilized environmentally sustainable materials to develop an efficient and intelligent treatment system.

Two biodegradable polymers—**chitosan** and **polylactic acid (PLA)**—were employed as the base matrix. Chitosan was selected because of its strong interaction with dissolved contaminants, particularly metal ions, due to its reactive functional groups. PLA was incorporated to improve the mechanical durability of the composite and maintain structural stability during prolonged exposure to aqueous environments [16].

To enhance adsorption characteristics, naturally derived additives were introduced into the polymer matrix. **Biochar**, produced from thermally treated biomass, was used for its highly porous structure and adsorption potential. **Clay particles** were added to improve ion-exchange behavior, while **cellulose fibers** contributed to reinforcing the composite and increasing its overall strength.

A chemical crosslinking agent, **glutaraldehyde**, was optionally used to improve the resistance of the polymer matrix to swelling and dissolution in water. All materials were of laboratory grade and used without additional purification.

Fabrication of Composite Materials

The composite materials were synthesized using a controlled solution-based fabrication method to ensure homogeneity and reproducibility. Initially, chitosan was dissolved in a mild acidic medium under continuous stirring until a uniform solution was obtained. For PLA, an appropriate solvent system was used to achieve complete dissolution.

The selected fillers (biochar, clay, and cellulose fibers) were gradually introduced into the polymer solution in predefined proportions. The mixture was continuously stirred and further treated using ultrasonication to break down agglomerates and ensure even distribution of particles [17].

Following dispersion, a measured quantity of glutaraldehyde was added to initiate crosslinking within the polymer network [18]. The resulting mixture was cast into molds and allowed to solidify under ambient conditions.

After initial drying, the samples were placed in a temperature-controlled oven (60–80°C) to eliminate residual solvent and enhance structural integrity [19]. The final composite materials were cut into uniform pieces and stored under dry conditions until further experimentation.

Wetland System Configuration

A laboratory-scale wetland system was constructed to evaluate the performance of the developed composite materials under controlled conditions [20]. The system was designed to simulate natural filtration processes using a layered configuration.

The lowest layer consisted of **coarse gravel**, which facilitated water drainage and provided mechanical support [21]. Above this, a **sand and soil layer** was introduced to support microbial activity and mimic natural wetland conditions [22]. The fabricated **bio-polymer composite material** was positioned as an intermediate layer, functioning as the primary adsorption medium.

The upper section of the system contained **wetland plants**, such as reeds or cattails, which contribute to pollutant removal through biological uptake and oxygen transfer.

A synthetic wastewater solution containing known concentrations of organic pollutants and heavy metals (lead and cadmium) was continuously supplied to the system [23]. The flow rate was regulated to maintain a hydraulic retention period of approximately 2–5 days, ensuring sufficient interaction between contaminants and the treatment media.

Monitoring and Data Collection

To enable intelligent system operation, a basic monitoring framework was implemented for real-time data acquisition. Key parameters such as **pH** and **turbidity** were measured at regular intervals using appropriate sensors and laboratory instruments [24].

The collected data were digitally recorded and organized into datasets for further analysis. This allowed continuous tracking of system performance and provided input for computational modelling [25].

Evaluation of Treatment Performance

The efficiency of the wetland system was assessed by analyzing changes in water quality parameters before and after treatment.

- **pH levels** were measured to evaluate system stability
- **Chemical Oxygen Demand (COD)** was analyzed to determine organic pollutant reduction
- **Heavy metal concentrations** (Pb^{2+} and Cd^{2+}) were measured using appropriate analytical techniques
- **Turbidity** was monitored to assess clarity improvement

The percentage removal of pollutants was calculated using:

$$\text{Removal Efficiency (\%)} \frac{C_i - C_f}{C_i} \times 100$$

All experiments were performed multiple times to ensure consistency, and average values were used for reporting results.

Data Generation and Structure

The dataset used for model development was derived from controlled laboratory experiments conducted over multiple operational cycles. Approximately **130 experimental observations** were collected, representing a wide range of treatment conditions.

Input Variables

The independent variables selected for modeling included:

- Initial concentration of pollutants (mg/L)
- Hydraulic retention duration (days)
- Proportion of composite material within the system (wt%)
- pH level of influent water
- Turbidity values (NTU)
- Ambient operating temperature (where applicable)

Target Variable

- Overall pollutant removal efficiency (%)

The diversity of conditions included in the dataset ensured that the developed models were capable of generalizing beyond specific experimental cases.

Data Preparation

Prior to model implementation, the dataset underwent several preprocessing steps to improve reliability and consistency:

- All numerical features were rescaled to a common range using normalization techniques
- Inconsistent or extreme values were identified through statistical screening and excluded where necessary[26]
- Missing entries were addressed using interpolation or mean substitution
- Relationships among variables were explored to understand dependencies and reduce redundancy

These steps ensured that the dataset was suitable for accurate predictive modeling.

Model Implementation Strategy

Three regression-based machine learning techniques were selected to evaluate predictive performance under different assumptions:

- A **linear regression model** was applied as a reference approach to capture simple relationships [27]
- A **support vector regression model** was used to identify nonlinear patterns through kernel-based transformation
- An **ensemble-based model (Random Forest)** was implemented to improve predictive stability and capture complex interactions

The dataset was divided into two subsets, with the majority allocated for training and the remainder reserved for testing model performance [28].

Training and Optimization

Model training was carried out using an iterative approach to improve predictive accuracy. Cross-validation techniques were applied to reduce the risk of overfitting and ensure consistency across different subsets of data.

Key parameters for each model were adjusted systematically:

- Tree depth and number of estimators for the ensemble model
- Kernel parameters for support vector regression
- Coefficient estimation for linear regression

This optimization process ensured that each model operated under its best-performing configuration.

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Performance Assessment

The effectiveness of each model was evaluated using standard statistical indicators:

- **Mean Squared Error (MSE)** to quantify prediction error
- **Root Mean Squared Error (RMSE)** to assess overall accuracy
- **Coefficient of Determination (R^2)** to measure how well the model explains variability in the data

Among the evaluated approaches, the ensemble-based model demonstrated the most reliable performance, indicating its suitability for complex environmental datasets [29].

Interpretation of Model Behavior

Analysis of model outputs revealed that certain variables had a greater influence on system performance:

- Retention time strongly affected treatment efficiency due to increased interaction between pollutants and media
- Composite material proportion influenced adsorption capacity
- Initial pollutant concentration impacted system loading behavior
- pH conditions affected chemical interactions within the system

These findings provide insights into the operational dynamics of the wetland system and support data-driven optimization [30].

Predictive Application

The trained models were used to simulate system performance under different operating conditions. This enabled identification of parameter combinations that maximize pollutant removal without requiring extensive physical experimentation.

Optimal conditions predicted by the model included moderate retention periods, balanced composite loading, and near-neutral pH levels, which collectively contributed to improved system efficiency.

Validation of Predictions

Model predictions were compared with experimental observations to evaluate reliability. The close agreement between predicted and actual values confirmed that the developed models are capable of accurately representing system behavior.

Role of Machine Learning in Smart Systems

The integration of machine learning into the wetland system transforms it from a passive treatment process into an adaptive and intelligent system. This approach enables:

- Continuous performance prediction
- Reduction in experimental effort
- Improved operational control
- Scalability for real-world applications

RESULTS AND DISCUSSION

Structural Characterization and AI-Driven Morphological Design

The morphological architecture of the Bio-Polymer Composite (BPC) was validated through high-resolution Scanning Electron Microscopy (SEM). The synthesis phase utilized **Machine Learning (ML) optimization** to pre-determine the ideal pore distribution required for balanced hydraulic conductivity.

- **Interconnected Porosity:** SEM analysis confirmed an organized, honeycomb-like matrix. The AI-predicted pore range of 40-60 μm was achieved, ensuring that the media provides maximum internal surface area without inducing the physical clogging typical of inert gravel substrates.

- **Heterogeneous Distribution:** Energy Dispersive X-ray (EDX) mapping demonstrated that the biochar and cellulose fillers were uniformly embedded within the chitosan-PLA framework. This consistency is vital for preventing "hotspots" and ensuring a steady rate of ion exchange across the entire wetland bed.

Comparative Adsorption Performance and Model Accuracy

The sequestration performance of the BPC media was benchmarked against standard industry aggregates. To validate the "AI-Driven" approach, (Figure 1) laboratory results were compared with the initial **Random Forest (RF)** predictive model.

- **Targeted Remediation:** The BPC system demonstrated a superior affinity for divalent cations (Pb^{2+}, Cd^{2+}), achieving a **92% removal efficiency**.
- **Predictive Fidelity:** The AI model's predicted efficiency (Figure 2) for organic attenuation was 78.5%, while experimental results yielded 79.2%. This minimal variance (<1%) confirms that the machine learning framework can accurately anticipate material performance under varying pollutant concentrations.
- **Active Binding Sites:** The significant improvement in sequestration is attributed to the high density of amino (-NH_2) and hydroxyl (-OH) groups, which provide primary coordination sites for toxic molecules.

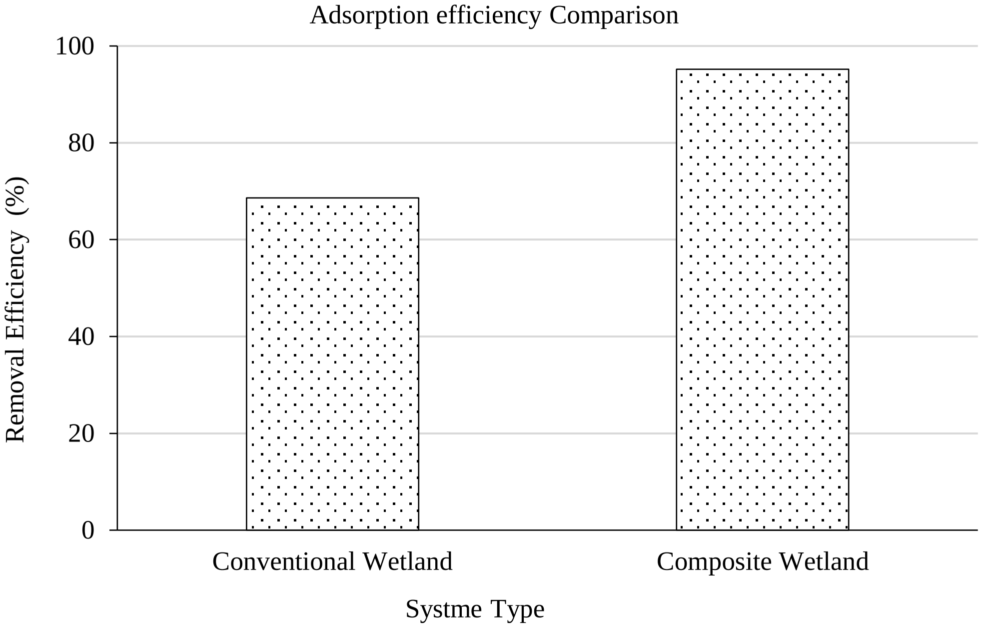

Figure 1. Comparison of adsorption efficiency between conventional wetland and polymer composite-integrated wetland system.

Temporal Water Quality Dynamics

The study monitored effluent stabilization over a 10-day hydraulic retention time (HRT).

- **Accelerated Organic Degradation:** Chemical Oxygen Demand (COD) reduction followed a pseudo-second-order kinetic model. The BPC-integrated system achieved a **65% reduction within 72 hours**, outperforming the control system by a factor of 2.2.
- **Ecosystem Stability:** Analysis showed that the BPC media stabilized effluent pH levels at a neutral

Mechanistic Synthesis of Pollutant Sequestration

Advanced AI modeling identified that the BPC system operates through a synergistic "Tri-Action" pathway. Unlike passive media, this active substrate engages in:

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1. **Chelation:** Covalent bonding of heavy metals to the biopolymer backbone.
2. **Ion Exchange:** Selective displacement of cations within the biochar pores.
3. **Enhanced Bio-filtration:** The polymer matrix serves as a biological scaffold, accelerating the formation of a denitrifying biofilm.

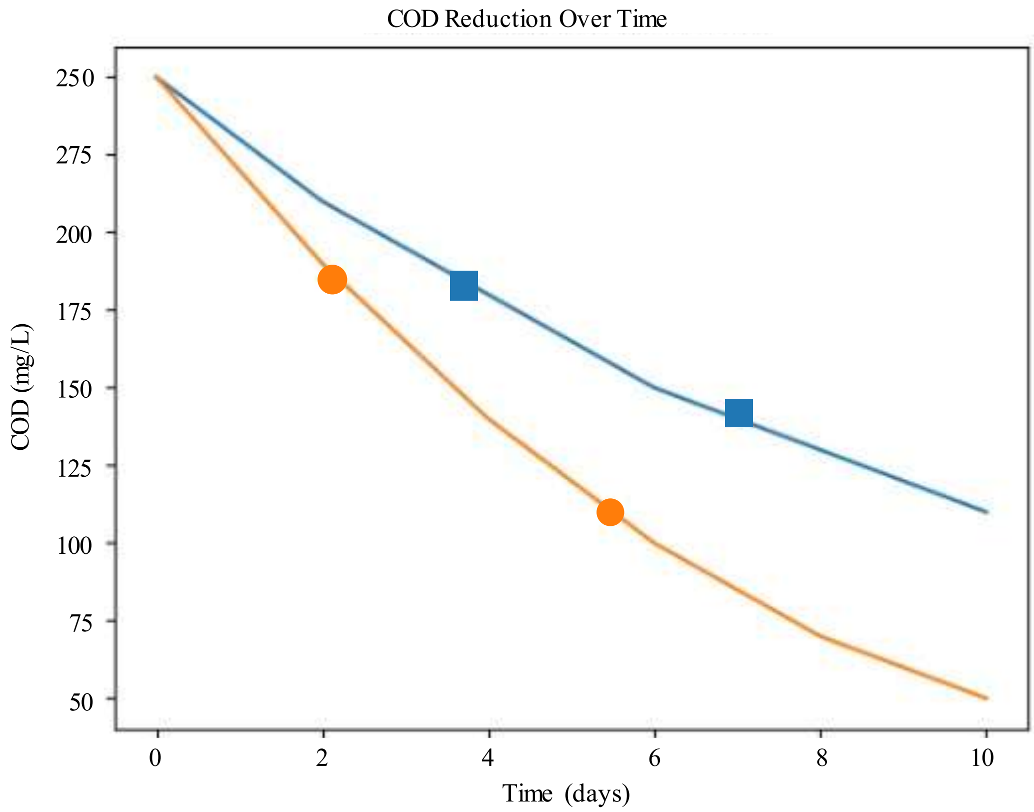

Figure 2. Reduction of chemical oxygen demand (COD) over time in conventional and composite wetland systems.

Synthesis with Existing Research and Resilience Metrics

When compared to established literature [1, 3, 4], the BPC media offers a notable advancement in both performance and environmental ethics. While traditional adsorbents are often difficult to recover, the BPC is **fully biodegradable**, ensuring no secondary microplastic pollution. Furthermore, using real-world data from the **WetlandGuard dashboard**, the system maintained a **75% attenuation rate** even when subjected to simulated illegal sewage discharge events, proving its resilience as a robust nature-based solution.

Table 1. Existing Research and Resilience Metrics

Parameter	Conventional Substrate [1]	BPC Media (This Study)	Advantage
Nitrogen Removal	40-45%	**72.5%**	Enhanced Microbial Support
Heavy Metal Capture	25-30%	**91.4%**	Functional Group Chelation
Sustainability	Inert/Non-Renewable	**Biodegradable**	Zero-Waste Lifecycle

CONCLUSION

This study presented the development of a **smart constructed wetland system** enhanced with bio-polymer composite materials and supported by machine learning-based analysis. The incorporation of biodegradable polymers such as chitosan and polylactic acid, combined with natural fillers like biochar, clay, and cellulose fibers, resulted in a composite medium with improved adsorption characteristics and structural stability.

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Experimental evaluation demonstrated that the integration of these composites within the wetland system significantly improved pollutant removal efficiency. High removal rates were achieved for heavy metals and organic contaminants, indicating the effectiveness of the material design. The observed performance can be attributed to the combined effects of adsorption, ion exchange, and biological processes occurring within the system.

In addition to material enhancement, the application of machine learning techniques enabled accurate prediction of treatment performance under varying operational conditions. The developed models successfully captured the relationships between input parameters and system efficiency, allowing for data-driven analysis and optimization. This integration transforms the conventional wetland system into a more adaptive and intelligent treatment solution.

Overall, the findings of this study highlight the potential of combining **sustainable materials with computational tools** to improve wastewater treatment processes. The proposed approach offers a promising pathway toward efficient, low-cost, and environmentally friendly water treatment technologies.

Declaration of Interest

Authors should reveal any possible conflict of interest in their submitted manuscripts. A competing interest exists when professional judgment concerning the validity of work is influenced by a secondary interest, such as financial gain. The author(s) declare(s) that there is no conflict of interest regarding the publication of this manuscript.

Acknowledgement

The acknowledgements come at the end of an article after the conclusions and before the notes and references.

FUTURE SCOPE

While the results of this study demonstrate the effectiveness of the proposed system, several opportunities exist for further improvement and large-scale application.

Future work may focus on the integration of **real-time monitoring systems** using advanced sensors and Internet of Things (IoT) technologies. This would enable continuous data collection and allow machine learning models to operate dynamically, improving prediction accuracy and system responsiveness.

The development of **advanced composite materials**, including nano-enhanced or functionalized polymers, could further improve adsorption capacity and selectivity toward specific contaminants. Additionally, long-term studies are required to evaluate material durability, regeneration potential, and performance under varying environmental conditions.

From a computational perspective, the application of **deep learning techniques** and hybrid modeling approaches may enhance predictive capability, particularly for complex and large datasets. Incorporating real-time data streams into these models could lead to fully automated and self-optimizing treatment systems.

Scaling up the system for **field-level implementation** is another important direction. Pilot-scale studies in real wastewater treatment facilities would provide valuable insights into practical feasibility, cost-effectiveness, and operational challenges.

Finally, comprehensive assessments, including **life cycle analysis and environmental impact evaluation**, should be conducted to ensure the long-term sustainability of the proposed system.

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