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Enhancing process monitoring and control in novel carbon capture and utilization biotechnology through artificial intelligence modeling: An advanced approach toward sustainable and carbon-neutral wastewater treatment

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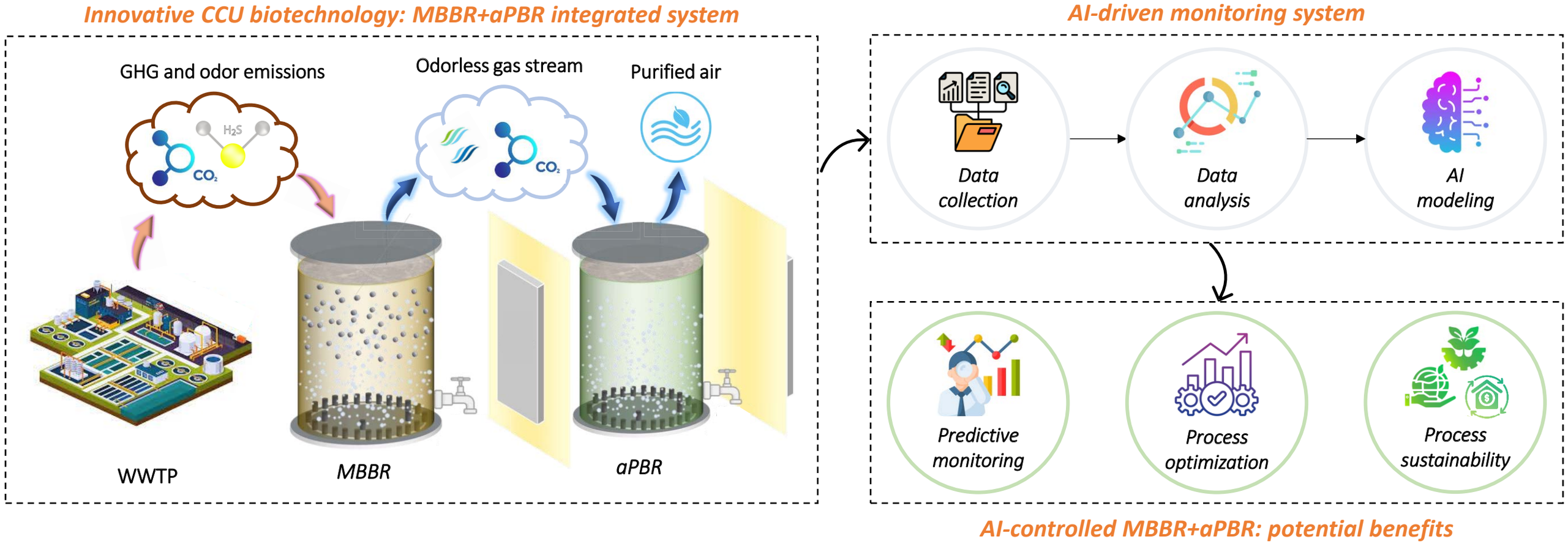
Highlights

- AI modeling can improve process monitoring and control of CCU biotechnologies.
- The novel MBBR+aPBR system can contribute to the carbon-neutrality of WWTPs.
- AI models were tested to predict CO_2 and H_2S emissions from MBBR+aPBR.
- LSBoost showed the highest prediction accuracy.
- Model selection and optimization are crucial for effective AI modeling.

Graphical Abstract



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Enhancing process monitoring and control in novel carbon capture and utilization biotechnology through artificial intelligence modeling: An advanced approach toward sustainable and carbon-neutral wastewater treatment

Abstract

Integrating carbon capture and utilization (CCU) technologies into wastewater treatment plants (WWTPs) is essential for mitigating greenhouse gas (GHG) emissions and enhancing environmental sustainability, but further advancements in process monitoring and control are critical to optimizing treatment performance. This study investigates the application of artificial intelligence (AI) modeling to enhance process monitoring and control in a novel integrated CCU biotechnology with a moving bed biofilm reactor (MBBR) sequenced with an algal photobioreactor (aPBR). This system reduces GHG and odour emissions simultaneously. Several machine learning (ML) models, including artificial neural networks (ANNs), support vector machines (SVM), random forest (RF), and least-squares boosting (LSBoost), were tested. The LSBoost was the most suitable for modeling the MBBR+aPBR system, exhibiting the highest accuracy in predicting CO_2 (R^2 = 0.97) and H_2S (R^2 = 0.95) emissions from the MBBR. LSBoost also achieved the highest accuracy for predicting CO_2 (R^2 = 0.85) and H_2S (R^2 = 0.97) outlet concentrations from the aPBR. These findings underscore the importance of aligning AI algorithms to the characteristics of the treatment technology. The proposed AI models outperformed conventional statistical methods, demonstrating their ability to capture the complex, nonlinear dynamics typical of processes in environmental technologies. This study highlights the potential of AI-driven monitoring and control systems to significantly improve the efficiency of CCU biotechnologies in WWTPs for climate change mitigation and sustainable wastewater management.

Keywords: advanced process control; bioprocess modeling; carbon neutrality; gaseous emission control; integrated algal biotechnology; supervised machine learning; odour treatment technology.

1. Introduction

Climate change is a critical global challenge requiring immediate action (Pahunang et al., 2021). Reducing greenhouse gas (GHG) emissions is a pressing goal across all industrial sectors, including wastewater treatment (Y. He et al., 2023), which accounts for about 1.6 % of global emissions and about 5 % of global non-CO_2 GHG emissions (Lu et al., 2018). This is compounded by the increase in global wastewater production (Qadir et al., 2020), which could further amplify the contribution of wastewater treatment plants (WWTPs) to GHG emissions.

GHG emissions from WWTPs can be direct or indirect. Direct emissions primarily arise from the biological degradation and biotransformation of carbonaceous and nitrogenous pollutants in water and sludge lines; while indirect emissions stem from energy consumption (often derived from non-renewable sources) and the production and transport of chemicals and fuels used in treatment (Lu et al., 2018; Mannina et al., 2018; Yu et al., 2022). Among indirect GHG emissions, electricity use during operation and maintenance represents the largest portion of conventional WWTPs' carbon footprint, emphasizing the need for strategies that improve energy efficiency and self-sufficiency (Guven et al., 2022; X. He et al., 2023; Rani et al., 2022). Advanced approaches for reducing direct GHG emissions are equally critical in the pursuit of carbon neutrality in WWTPs (Lancioni et al., 2024; Pasquarelli et al., 2024a). The growing research interest in these topics is evidenced by the rising number of publications over the past few years. A TITLE-ABS-KEY search using the terms «(“carbon neutral*” OR “carbon-neutral*” OR “self sufficie*” OR “self-sufficie*”) AND (“wastewater treatment” OR “waste water treatment”)» in the Scopus database revealed 849 documents, with 591 papers (around 70% of the total) published since 2021 (**Figure S1**). In particular, several studies have emphasized the urgent need to achieve multiple, sometimes competing objectives of advanced wastewater treatment and low GHG emissions, with a strong focus on achieving carbon neutrality in WWTPs (Cairone et al., 2024e, 2024d; Corpuz et al., 2024; Yang et al., 2022, 2023, 2024b, 2024a). Carbon-neutral wastewater treatment requires the adoption of state-of-the-art

technologies that ensure high contaminant removal while minimizing GHG emissions. One promising strategy is integrating carbon capture and utilization (CCU) in WWTPs to capture and convert CO_2 emissions into valuable resources while substantially reducing GHG emissions (Corpuz et al., 2021; Maselli et al., 2024; Senatore et al., 2022, 2021). CCU technologies not only mitigate the environmental impact of wastewater treatment but also align with circular economy principles by transforming CO_2 into valuable products. This dual functionality makes CCU particularly advantageous, offering environmental and economic benefits. Moreover, CCU addresses the growing global emphasis on resource recovery and the transition toward net-zero emissions, critical goals for sustainable wastewater management. These features make CCU an attractive and forward-thinking solution also for circular economy-driven WWTPs. Various CCU technologies have been proposed, including biological and enzymatic methods, chemical and electrochemical conversion processes, membrane-based separation, liquid absorption, and solid adsorption. Although many of these are energy- and material-intensive, biological technologies stand out for their efficiency, cost-effectiveness, and low energy requirements (Alli et al., 2024; Yang et al., 2024c).

Among the CCU biotechnologies proposed in the prior art, a particularly innovative approach involves combining a moving bed biofilm reactor (MBBR) with an algal photobioreactor (aPBR) in an integrated MBBR+aPBR system (Oliva et al., 2023; Pasquarelli et al., 2024a). This system not only reduces GHG emissions but abates odorous substances such as hydrogen sulfide (H_2S), which present serious social concerns for WWTPs. The effective management of odour emissions is essential given the elevated sensitivity of surrounding communities to odours (De Paola et al., 2024). In the MBBR+aPBR system, bacterial activity within the MBBR degrades and oxidizes undesirable compounds like H_2S, and produces CO_2, which is utilized by microalgae in the aPBR, thus forming a CCU system. This approach promotes carbon neutrality and aligns with circular economy principles because the harvested microalgae can be processed into biofuels and other high-value products (Oliva et al., 2024; Zarra et al., 2024).

Recent studies also highlight the importance of developing strategies for automation, optimization and the advanced control of treatment processes. Adapting operational conditions in real-time to the needs of the treatment process can enhance WWTP performance and optimize resource use (Cairone et al., 2024a). Integrating real-time monitoring with predictive modeling offers substantial benefits. Artificial intelligence (AI) is now emerging as a powerful tool for creating advanced models that can optimize WWTP operations, overcoming the limitations of conventional mechanical/mathematical models (Cairone et al., 2024b, 2024c; Kamali et al., 2021; Nam et al., 2023; Newhart et al., 2019; Zhang et al., 2023). While conventional models struggle with the manifold complexity and uncertainties of operating conditions, AI models can outperform them in identifying intricate data patterns and nonlinear relationships between inputs and outputs, leading to more accurate predictions (Li et al., 2019; Niu et al., 2022; Zhang et al., 2019). These predictions can, in turn, provide useful insights for real-time process optimization and control, even in the complex and dynamic environments typical of bioprocesses (Cheng et al., 2023). By optimizing operational conditions, AI-based process control can yield significant environmental, economic, and social benefits (Alhajeri et al., 2024; Cairone et al., 2024a; Serna-Carrizales et al., 2024). These benefits include increased contaminant removal, reduced GHG and odour emissions, optimized energy and chemical consumption, enhanced public health protection, and reduced operating costs (Cairone et al., 2024a).

This study explores the potential of AI modeling for process monitoring and control in the novel MBBR+aPBR integrated system, providing valuable insights for sustainable and carbon-neutral wastewater treatment. To the best of the authors' knowledge, no prior studies have investigated AI modeling to support the monitoring system of CCU biotechnologies implemented in WWTPs. Several AI models were tested and compared for their performance in predicting CO_2 and H_2S outlet concentrations from the MBBR+aPBR system. The potential benefits, challenges, and future perspectives of the proposed approach are discussed.

2. Materials and methods

2.1 Materials and experimental set-up

The laboratory-scale MBBR+aPBR integrated system consisted of an MBBR with an operating volume of 10 L, inoculated with activated sludge, and an aPBR with an operating volume of 26 L, inoculated with microalgae (**Figure 1**). This configuration provides complementary treatment capabilities. The MBBR degrades organic matter and odorous compounds efficiently, including H_2S. The aPBR abates these odorous compounds further while facilitating the fixation of CO_2 produced by bacterial activity in the MBBR, using it for metabolic processes during algal growth.

A synthetic solution simulating dairy wastewater (DWW) was fed continuously into the bioreactors. Pure H_2S was injected into the system using an automatic syringe pump (New Era Pump Systems, Inc., Model 300), its concentration regulated by dilution with ambient air using a compressor (Stanley DST 100/8/6) equipped with a flowmeter set to 2 L/min. One-third of the MBBR's operating volume was filled with plastic carriers (Kaldnes Ring, Amitec, Italy) to support biomass growth and increase the contact time between the raw gas and biomass. The aPBR was stirred continuously at 300 rpm and the temperature was maintained at 25 ± 1 °C. This promotes optimal growth conditions for the microalgae. In the aPBR, light plays a critical role in driving photosynthesis, which aids CO_2 sequestration and O_2 production, contributing to the overall efficiency of the treatment process (Guedes et al., 2023; Vergara et al., 2016). To promote photosynthesis in the algal biomass, artificial light was provided by four white LED bulbs (luminous intensity: 8258 LUX) arranged around the aPBR, with a 12-hour light/12-hour dark cycle. An extensive description of the system is available in previous studies (Oliva et al., 2023; Pasquarelli et al., 2024a).

2.2 AI modeling

Machine learning (ML) algorithms were implemented to predict the performance of the MBBR+aPBR integrated system. Specifically, artificial neural networks (ANNs), support vector

machine (SVM), random forest (RF), and least-squares boosting (LSBoost) were tested. These were selected for their suitability in regression tasks and their ability to effectively handle complex data patterns. Modeling was conducted using MATLAB® (Release 2024a, MathWorks, Inc., Natick, Massachusetts, USA). To enhance model accuracy and robustness, hyperparameter optimization was performed for each tested model using a grid search approach.

The modeling process began with separate analyses of the MBBR (Section 3.1) and aPBR (Section 3.2) to identify the best-performing supervised learning algorithm for each treatment unit. After selecting the optimal algorithms, the models were integrated by using the outputs (Section 2.2.1) from the MBBR model as inputs for the aPBR model (Section 3.3). This integration allowed for an accurate representation of the overall system by capturing the interactions between the two treatment units.

2.2.1 Data collection and preprocessing

Data quality and quantity are key factors in ML modeling. The current study relies on data from the laboratory-scale MBBR+aPBR integrated system described in Section 2.1. Key operational parameters, including pH, temperature, dissolved oxygen (DO), saturated oxygen, total suspended solids (TSS), and concentrations of CO_2 and H_2S at the inlet and outlet, were monitored to evaluate the performance of the MBBR+aPBR system. Temperature, pH, DO, and saturated O_2 were measured using a multi-parameter probe (Hanna Instruments), cleaned regularly, and calibrated following the manufacturer's guidelines. CO_2 and H_2S concentrations were measured using a multiparameter gas analyzer (MultiRAE, Recom Industriale S.r.l., Italy) and a gas chromatograph equipped with a thermal conductivity detector (GC–TCD, Thermo Fischer Scientific, USA). The standard method was applied to determine TSS content (APAT, 2003). All parameters were measured daily during the experimental period to ensure an accurate representation of system dynamics.

Data preprocessing involved multiple steps to improve dataset quality and enhance the accuracy of the AI models (Maharana et al., 2022; Rios Fuck et al., 2024). Outlier detection was performed using the interquartile range (IQR) method, with outliers defined as data points falling below $Q_1 - 1.5 \times$

IQR or above $Q_3 + 1.5 \times IQR$, where Q_1 and Q_3 represent the first and third quartiles, respectively, and $IQR = Q_3 - Q_1$ (Bahramian et al., 2023). In the missing data management step, detected outliers were removed and replaced using linear interpolation between neighboring values, assuming a linear trend between adjacent data points. This approach aligns with previous studies (Bu et al., 2024; Zaghloul and Achari, 2022). Notably, the dataset exhibited high quality, with only four data points identified as outliers. A summary of statistical parameters (mean values, standard deviations, and coefficient of variation) for the MBBR and aPBR data is presented in **Table 1**. The cleaned dataset was then split into training and testing sets to develop robust models capable of generalizing to unseen data (Xu and Goodacre, 2018). Aligning to previous studies in AI modeling, the dataset was divided, with 75% of the data utilized for training and the remaining 25% for testing. This strategy, widely adopted in AI studies (Kovacs et al., 2022; Nam et al., 2021; Nourani et al., 2021), ensures a sufficient amount of data is allocated for training while reserving an appropriate portion for testing. The training dataset underwent a feature engineering process, including feature selection, to exclude irrelevant features. This step aimed to retain features critical for modeling by removing those that do not substantially contribute (or may even negatively impact) model outcomes. Feature selection reduces noise, improves model learning efficiency, and minimizes computational overhead (Zhu et al., 2023). Multicollinearity and correlation analyses were conducted to identify highly correlated variables, either among features or between features and response variables, using the Pearson correlation coefficient (r). Removing highly correlated features is necessary to prevent redundancy in the model, while retaining features with higher r values relative to the response variables is generally beneficial, as they provide meaningful information for prediction. However, excluding features solely because they do not exhibit high r values relative to the response variables may not be appropriate, as this approach does not account for potential nonlinear relationships that the Pearson correlation analysis cannot capture. Based on the correlation matrix results (**Figure S2**), saturated oxygen and DO were found to be highly correlated for both MBBR and aPBR systems, which is reasonable. Consequently, saturated oxygen was excluded from the input variables, leaving six selected features: temperature,

pH, DO, TSS, CO_2 inlet, and H_2S inlet. Following feature selection, feature scaling was applied to standardize or normalize the ranges of predictor variables. This step improves model performance by minimizing overfitting risks and reducing errors caused by differences in parameter scales (Aghdam et al., 2023; Sadoune et al., 2023).

2.2.2 Model evaluation

Once the model is developed and optimized, its performance is assessed and compared with other models based on specific metrics for regression tasks. Specifically, model performance was evaluated using, as metrics, the Mean Squared Error (MSE), Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and Coefficient of Determination (R^2). These metrics provide a comprehensive assessment of the models' accuracy and goodness of fit by comparing predicted values against the actual test set data. To improve model interpretability, the best-performing model was analyzed using permutation feature importance (PFI), a method that ranks features based on their contribution to predicting the response variable. This approach evaluates the change in prediction error when a feature's values are randomly permuted, with larger increases in error indicating greater importance.

Comparisons with two well-established statistical methods, multiple linear regression (MLR) and partial least squares (PLS), were conducted to assess whether the proposed AI-based modeling approach offers superior predictive performance over traditional methods.

2.2.3 Artificial neural network (ANN)

ANNs are computational models inspired by the structure and function of the human brain. They consist of interconnected nodes (or neurons) organized into input, hidden, and output layers. The training process enables the ANN to learn from data by adjusting neuron weights. In this study, a feedforward neural network (FF-NN), specifically a multilayer perceptron (MLP), was employed. In an FF-NN, information flows unidirectionally from input to output neurons, never moving backward. The architecture of an ANN, including the number of hidden layers and the number of neurons per

layer, is crucial because it determines the network's capacity to learn and generalize from data. To optimize the ANN architecture, the number of hidden layers and neurons per layer were systematically varied between 1 and 25, yielding 625 potential configurations. The optimal configuration was selected based on minimizing MSE, RMSE, and MAE while maximizing the R^2 value. Grid search was conducted to optimize the learning rate hyperparameter, with tested values of 0.01, 0.1, 0.25, and 0.5. The sigmoidal transfer function ("tansig") and the Levenberg-Marquardt training algorithm ("trainlm") were chosen for their efficacy (Cifuentes-Cabezas et al., 2023; Hosseinzadeh et al., 2020). The optimized ANN was used to make predictions, which were compared to actual values for accuracy assessment.

2.2.4 Support vector machine (SVM)

SVMs are supervised learning models used for classification and regression tasks. They work by separating data into two classes using a hyperplane, or a set of hyperplanes, in a high-dimensional space, aiming to find the optimal hyperplane that maximizes the margin, i.e., the largest distance between the hyperplane and the nearest data points (called support vectors) from opposite classes. The data can be separated using hyperplanes described by linear or nonlinear functions. Both linear and nonlinear kernel functions were tested in this study, including linear, Gaussian radial basis function (RBF), and polynomial kernels (degree of 2, 3 and 4). Hyperparameter optimization was performed through grid search and cross-validation, varying values for Gamma (0.001, 0.01, 0.1, and 1) and the box constraint (or regularization, C = 0.1, 1, 10, 100, 250, 500, 600, 750, 800, and 1000). A k-fold cross-validation (with k = 2, 5, and 10) was conducted to identify the most robust configuration.

2.2.5 Random forest (RF)

RF is an ensemble learning method suitable for classification and regression tasks. RF models generate multiple decision trees, each trained on a random subset of the training dataset. The final prediction is made by aggregating the outputs of all individual trees. The number of decision trees is

a key hyperparameter affecting model accuracy. Although increasing the number of trees in an RF model generally improves its accuracy, improvement often reaches a plateau beyond a certain number of trees, yielding diminishing returns while increasing computational costs. Therefore, it is crucial to balance model accuracy with computational efficiency. In this study, RF models were optimized by varying the number of decision trees (50, 100, 250, 500, 600, 700, 800, and 1000). A k-fold cross-validation (with k = 2, 5, and 10) was conducted to evaluate each configuration and determine the optimal model.

2.2.6 Least-squares boosting (LSBoost)

LSBoost is a gradient boosting algorithm designed for regression tasks. It builds an ensemble of weak learners, typically decision trees, sequentially. Each subsequent tree in the ensemble is trained to correct the residual errors of the previous trees, optimizing the model by minimizing the least squares error. Key hyperparameters, including the learning rate (0.01, 0.1, 0.25, 0.5, and 1), the number of boosting trees (50, 100, 250, 500, 600, 700, 800, and 1000), and the subsample (0.4, 0.6, 0.8, 1), were optimized through grid search. A 5-fold cross-validation was used to identify the best-performing LSBoost model configuration.

3. Results and discussion

3.1 MBBR modeling

This section presents the results of the AI models used to predict the performance of the MBBR.

The ANN model exhibited high accuracy in predicting CO_2 outlet concentrations (**Figure 3a**) but showed reduced performance for H_2S outlet concentrations (**Figure 2a**). Specifically, while the ANN model provided relatively accurate predictions for early H_2S samples, its performance diminished for later samples. This reduction may reflect the difficulty in capturing the temporal variability or nonlinear nature of the H_2S inlet and outlet concentrations, indicating that improvements in model

architecture or additional input features may be necessary to account for these dynamics. The optimization process identified the optimal ANN architecture for H_2S predictions, comprising 14 hidden layers with 14 neurons each, whereas CO_2 predictions were best modeled with 19 hidden layers containing 15 neurons each. Additionally, an ANN capable of simultaneously predicting both CO_2 (**Figure 3b**) and H_2S (**Figure 2b**) outlet concentrations (multi-task ANN) was tested and optimized. The best configuration for this combined prediction task consisted of 16 hidden layers with 7 neurons per layer. The ability to predict both CO_2 and H_2S outlet concentrations with a single ANN model suggests that a multi-task approach could effectively balance predictive performance across distinct target outputs, potentially reducing the need for separate models.

The SVM model exhibited high accuracy in predicting both H_2S (**Figure 2c**) and CO_2 (**Figure 3c**) outlet concentrations. The SVM's capacity to capture the patterns in both emissions highlights its potential in specialized tasks but also underscores the challenges of applying the same model architecture to both emissions without additional refinement. In fact, optimal hyperparameters for the SVM were determined as Gamma = 1 and C = 500 for H_2S predictions, while Gamma = 1 and C = 800 were preferable for CO_2. This difference in hyperparameter values reflects the necessity of fine-tuning SVM models to meet the specific objectives of the modeling task.

The RF model showed relatively poor accuracy in predicting H_2S outlet concentrations (**Figure 2d**) but performed better for CO_2 emissions (**Figure 3d**). The optimal RF configuration involved 500 decision trees for H_2S predictions and 600 decision trees for CO_2 predictions. The observed discrepancy in performance between H_2S and CO_2 suggests that further optimization of the RF model is needed, possibly by experimenting with different tree depths or incorporating additional feature engineering. This may help the model better capture the complexity of H_2S emissions patterns, which appear more challenging for RF to predict accurately. These conditions can be attributed to the substantial variability in H_2S inlet concentrations (Cv = 0.28), resulting from its real-time artificial generation through an extemporaneous chemical reaction that is sensitive to environmental conditions

(Morse et al., 1987; Reddy et al., 2019). This variability provides an opportunity to verify the system's robustness in handling large fluctuations in inlet load. On the other hand, outlet concentrations exhibited great variability, which is challenging to predict using "conventional" AI modeling approaches.

LSBoost demonstrated strong performance in predicting both H_2S (**Figure 2e**) and CO_2 (**Figure 3e**) outlet concentrations. LSBoost's sequential learning approach, which focuses on minimizing residual errors, contributed to its superior performance by effectively capturing complex emission patterns. The optimal configuration consisted of 800 decision trees and a learning rate 0.5, which was applied to both H_2S and CO_2 predictions. The robustness of the LSBoost model highlights its potential as a reliable and versatile tool for environmental system modeling, particularly in scenarios involving complex and nonlinear data.

Table S1 summarizes the evaluation metrics for the AI models in predicting H_2S and CO_2 outlet concentrations from the MBBR. According to the results, LSBoost achieved the best performance in predicting CO_2 emissions (MSE = 0.006; R^2 = 0.967), followed by SVM (MSE = 0.011; R^2 = 0.938), ANN (MSE = 0.012; R^2 = 0.933), and RF (MSE = 0.022; R^2 = 0.872). For H_2S emissions, LSBoost again outperformed the other models (MSE = 0.011; R^2 = 0. 945), followed by SVM (MSE = 0.013; R^2 = 0.934), ANN (MSE = 0.049; R^2 = 0.758), and RF (MSE = 0.096; R^2 = 0.528). These findings underscore LSBoost's versatility, as it demonstrated high accuracy in predicting both CO_2 and H_2S outlet concentrations. Similarly, SVM showed accurate predictions for both CO_2 and H_2S outlet concentrations, while ANN exhibited specialized performance for CO_2 but reduced accuracy for H_2S. In contrast, RF exhibited relatively low accuracy in predicting both CO_2 and H_2S outlet concentrations. This emphasizes the importance of selecting the appropriate model based on specific emission characteristics. The tested AI models consistently outperformed the statistical methods for predicting both H_2S and CO_2 outlet concentrations from the MBBR (**Table S1**). Specifically, while the MLR (**Figure S3b**) and PLS (**Figure S4b**) methods performed reasonably well for CO_2

predictions (MSE = 0.03; R^2 = 0.8), their accuracy dropped dramatically for H_2S emissions (**Figure S3a** and **Figure S4a**), with both methods yielding an R^2 of only 0.06 (MSE = 0.2). This disparity may be attributed to the relatively strong correlation between CO_2 outlet concentrations and most features, compared to the absence of high correlations between H_2S outlet concentrations and the features (**Figure S2a**). These results highlight the limitations of conventional statistical methods in capturing complex, nonlinear relationships among variables, which are common in environmental technologies.

Analyzing the PFI results of the best-performing LSBoost model predicting MBBR performance, it is evident that all features had approximately equal importance for H_2S outlet predictions, with H_2S inlet and TSS showing slightly greater importance compared to other features (**Figure S7a**). In contrast, for CO_2 outlet predictions, the LSBoost model for MBBR primarily relied on DO and H_2S inlet, which exhibited higher importance relative to the other features (**Figure S7b**). It is essential to emphasize that a feature's importance reflects its contribution to the model's predictive mechanism and does not necessarily correspond to its relevance in the underlying biophysicochemical processes. Therefore, feature importance analysis serves as a tool for model interpretability rather than a direct representation of real-world processes. This point will be further discussed in Section 4.

3.2 aPBR modeling

This section discusses the results of the AI models used to predict the performance of the aPBR.

The ANN model showed high accuracy in predicting H_2S outlet concentrations (**Figure 4a**) but lower accuracy for CO_2 outlet concentrations (**Figure 5a**). The optimal architecture for H_2S predictions consisted of 4 hidden layers with 8 neurons per layer, while the best architecture for CO_2 predictions involved 3 hidden layers with 11 neurons per layer. Additionally, a multi-task ANN capable of simultaneously predicting both CO_2 (**Figure 5b**) and H_2S (**Figure 4b**) outlet concentrations was optimized. The optimal configuration, with 15 hidden layers and 23 neurons each, suggests that multi-task approaches can efficiently balance predictive performance across output targets, which may be valuable in modeling complex environmental technologies.

The SVM model achieved high accuracy for H_2S outlet concentrations (**Figure 4c**) but performed poorly for CO_2 outlet concentrations (**Figure 5c**). The optimal hyperparameters for both emissions were Gamma = 1 and C = 800. While the SVM showed strong performance for H_2S, further adjustments are needed to improve CO_2 predictions, possibly by refining the model's feature selection or architecture.

The RF model exhibited low accuracy for both H_2S (**Figure 4d**) and CO_2 (**Figure 5d**) outlet concentrations. The optimal RF configuration included 700 decision trees for H_2S predictions and 800 decision trees for CO_2. However, the consistently low performance indicates that RF may not be well-suited for this task without further optimization, such as modifying tree depths or incorporating more relevant features. Specifically, in real-scale applications, it would be feasible to integrate predicted H_2S inlet concentrations into the model, accounting for process conditions (Zwain et al., 2020). By incorporating H_2S inlet concentrations to the aPBR as an additional parameter to be predicted, the model can provide a more comprehensive representation of the H_2S dynamics within the MBBR+aPBR system. This integration enables a complete prediction of the complex processes involving H_2S dynamics across the system, enhancing the reliability of outlet concentration predictions. Consequently, including H_2S inlet concentrations strengthens the model's overall predictive accuracy and supports optimizing the system's performance.

LSBoost demonstrated very high accuracy in predicting both H_2S (**Figure 4e**) and CO_2 (**Figure 5e**) outlet concentrations. The optimal configuration involved 800 decision trees and a learning rate of 0.5 for both outlet concentrations.

Table S2 summarizes the evaluation metrics for AI models in predicting H_2S and CO_2 outlet concentrations from the aPBR. LSBoost achieved the best performance in predicting both H_2S (MSE = 0.002; R^2 = 0.965) and CO_2 (MSE = 0.001; R^2 = 0.851) outlet concentrations, underscoring its efficacy in modeling complex emissions patterns. The multi-task ANN capable of simultaneously predicting CO_2 and H_2S outlet concentrations also performed relatively well. This may be attributed

to its capacity to identify shared underlying patterns and interdependencies between CO_2 and H_2S outlet concentrations, highlighting the benefit of multi-task learning in complex systems. In contrast, ANN and SVM demonstrated specialized performance for CO_2, with R^2 values of 0.897 and 0.934, respectively, but performed poorly for H_2S, with R^2 values of 0.660 and 0.679, respectively. Consistent with observations for MBBR modeling (Section 3.2), RF exhibited relatively low accuracy in predicting both CO_2 (MSE = 0.013; R^2 = 0.750) and H_2S (MSE = 0.003; R^2 = 0.467) outlet concentrations. These findings further confirm the importance of carefully selecting the algorithm most suitable for specific modeling goals. The tested AI models consistently outperformed the statistical methods in aPBR modeling (**Table S2**). Specifically, both the MLR (**Figure S5**) and PLS (**Figure S6**) methods performed poorly for both H_2S (R^2 = 0.510 and 0.575, respectively) and CO_2 emissions (R^2 = 0.146 and 0.106, respectively). As highlighted in the MBBR modeling (Section 3.1), these results emphasize the ability of AI/ML models to handle complex, nonlinear relationships that traditional statistical methods may not effectively capture.

Consistent with the observations for MBBR modeling (Section 3.1), the PFI results revealed that all features had approximately equal importance in the best-performing LSBoost model for predicting H_2S outlet concentrations from the aPBR (**Figure S8a**). As observed for MBBR modeling (Section 3.1), the LSBoost model for predicting CO_2 outlet concentrations from the aPBR attributed varying importance to each feature, with temperature and DO showing the highest importance in this case (**Figure S8b**). As discussed in Section 3.1, it is important to reiterate that these results do not necessarily reflect the role of these parameters in the actual treatment process. Instead, they represent the parameters' contribution to the model's predictive mechanisms (Section 4).

3.3 MBBR+aPBR integrated system modeling

Based on the results discussed in section 3.1, the LSBoost algorithm was selected for modeling the MBBR due to its superior prediction performance for both CO_2 and H_2S outlet concentrations. The outputs from the optimal LSBoost model were used to predict the performance of the aPBR, enabling

374 the estimation of emissions from the MBBR+aPBR integrated system. As shown in section 3.2, the
375 LSBoost model also achieved the highest accuracy for H_2S and CO_2 outlet concentrations from the
376 aPBR. Therefore, the LSBoost+LSBoost integrated ML approach was employed to model the entire
377 process, predicting H_2S and CO_2 outlet concentrations at the end of the treatment (**Figure 6**). The
378 results, summarized in **Table S3**, highlight the high prediction accuracy for both H_2S (MSE = 0.01;
379 $R^2 = 0.90$) and CO_2 (MSE = 0.00; $R^2 = 0.83$) outlet concentrations.

380 The main strength of this integrated modeling approach is its capability to predict the entire treatment
381 process's behaviour without the need for direct measurement of gaseous emissions from the MBBR,
382 thereby reducing costs and time associated with gas analysis. However, inaccuracies in predicting
383 emissions from the MBBR could propagate to the aPBR predictions, reducing overall accuracy.
384 Specifically, a comparison between using measured concentrations of gaseous compounds at the
385 MBBR outlet and those estimated through modeling shows a slight reduction in predictive
386 performance when relying on modeled data. This reduction might be attributed to the high fluctuation
387 of H_2S inlet concentrations and the influence of various mechanisms on the CO_2 mass balance within
388 the sequenced system, making computed estimations complex (Pasquarelli et al., 2024b). Among
389 these mechanisms, sulfate oxidation driven by sulfur-oxidizing bacteria (SOB) plays a key role, as it
390 competes with CO_2 fixation in algal biomass, ultimately contributing to carbon dioxide reduction
391 (Syed et al., 2006). Additionally, the oxidation of sulfate in the liquid medium may create mixotrophic
392 conditions by accelerating the breakdown of biodegradable organic matter present in the DWW
393 influent (José Carlos De et al., 2024). The release of CO_2 from the oxidation of organic matter in
394 DWW could therefore be considered significantly affected by SOB metabolism (Klatt and Polerecky,
395 2015; Pudi et al., 2022). This effect becomes more pronounced as H_2S inlet concentrations increase,
396 resulting in a simultaneous rise in CO_2 release from the breakdown of carbonyl compounds, along
397 with enhanced nutrient uptake (Pasquarelli et al., 2024a). Furthermore, pH is a parameter that can
398 significantly influence CO_2 assimilation and dissolution. In the investigated conditions, pH remained

within a narrow range, without significantly impacting the CO_2 mass balance (Meier et al., 2018; Omri et al., 2011).

Despite this complexity, the promising results from the LSBoost+LSBoost approach demonstrate its potential as an effective tool for enhancing the monitoring and control of gaseous emissions in CCU biotechnologies. Since this 'integrated modeling' approach relies on MBBR model outputs as input variables for predicting aPBR performance, some inherent inaccuracies are unavoidable, leading to a decrease in overall accuracy compared to a model based solely on measured data. However, this approach could be further optimized by incorporating more advanced techniques or algorithms to reduce these inaccuracies in predicting the MBBR outlet concentrations used as inputs for the aPBR. This would, in turn, improve the overall accuracy of the 'integrated modeling' approach in predicting the performance of the MBBR+aPBR integrated system.

4. AI-controlled MBBR+aPBR integrated system: potential benefits and current challenges

AI models have demonstrated promising potential in predicting the performance of the MBBR+aPBR integrated system for controlling CO_2 and H_2S. More broadly, these models could support the development of AI-controlled MBBR+aPBR systems, potentially enabling improvements in real-time monitoring and process optimization. In such smart systems, AI modeling could offer valuable insights to dynamically adjust critical operational parameters, such as aeration rates in the MBBR, nutrient supply, and light intensity in the aPBR, based on predictive models' outputs. This adaptive approach can potentially enhance treatment efficiency while simultaneously reducing energy consumption and operating costs. Additionally, AI-driven predictive control may help stabilize system performance under fluctuating environmental conditions and varying loads, supporting more consistent treatment efficiency.

The monitored operating parameters (pH, temperature, DO, saturated oxygen, and TSS) play distinct yet interconnected roles in the treatment processes of the MBBR+aPBR system. The operating pH influences not only microbial activity and chemical reactions in the bioreactors but also nutrient assimilation, making pH control crucial to ensure an optimal environment for both bacteria and microalgae. For example, an acidic pH can inhibit the growth of microbes responsible for H_2S biodegradation in the MBBR (Lebrero et al., 2014), while in the aPBR, pH significantly affects microalgal growth by affecting the solubility and availability of CO_2 and carbonates (Yan et al., 2016). Maintaining optimal temperature is equally important, as it affects the metabolic rates of the microbial community in the MBBR and microalgal growth in the aPBR. Additionally, temperature influences the solubility of gases like O_2 and CO_2, which impacts mass transfer and overall system efficiency (Barten et al., 2021). DO and saturated O_2 are critical for aerobic degradation in the MBBR, where O_2 supports microbial respiration and the degradation of organic matter. In the aPBR, O_2 is a by-product of photosynthesis, but excessively high DO concentrations can limit microalgal growth (Fu et al., 2019). TSS concentrations serve as an indicator of biomass concentration and treatment efficiency. Low TSS values may suggest insufficient biological activity, while excessively high concentrations can compromise system performance by reducing aPBR effectiveness due to limited light penetration (Foladori et al., 2020; Soaudy et al., 2023). Overall, each of these operating parameters plays a crucial role in treatment performance, and implementing efficient monitoring and adjustment strategies for process parameters can significantly enhance treatment efficiency. Similarly, monitoring CO_2 and H_2S concentrations at both the inlet and outlet is essential for assessing the performance of the MBBR+aPBR system, as these gases have been selected to reflect the system's effectiveness in controlling GHGs and odour emissions, respectively. While this discussion highlights the relevant role of each monitored parameter in the processes occurring within the MBBR+aPBR integrated system, the results of the feature importance analysis (**Figure S7** and **Figure S8**) reveal that the 'reasoning' behind AI models' predictive mechanisms may sometimes be inconsistent with domain knowledge. For instance, the model may attribute lower importance to variables that are

448 widely recognized as key parameters for a given process. To enhance model interpretability and
449 explainability, there has been growing interest in adopting more sophisticated interpretability methods
450 and explainable AI techniques (XAI), such as Shapley Additive exPlanations, (SHAP) and Local
451 Interpretable Model-agnostic Explanations (LIME) (Majnooni et al., 2024; Onay and Onay, 2024).
452 However, it is important to emphasize that aligning model interpretability and explainability with the
453 actual mechanisms driving a biophysicochemical phenomenon remains a challenging task that
454 requires critical evaluation by experts (Zhu et al., 2023).

455 The integration of AI into the MBBR+aPBR system introduces advanced monitoring and early
456 warning capabilities, which are key strengths of this approach. Developing digital twins by integrating
457 AI models with real-time monitoring systems could enable continuous emissions tracking (e.g., CO_2
458 and H_2S), support predictive tasks, and detect anomalies that may help identify process inefficiencies
459 or potential system failures. This proactive strategy would support rapid intervention, potentially
460 minimizing downtime and improving system resilience. Consequently, an AI-controlled
461 MBBR+aPBR system could operate more efficiently, with the possibility of reduced energy demands,
462 improved contaminant removal efficiency, and a lower carbon footprint, contributing to a more
463 sustainable wastewater treatment process.

464 Despite these potential advantages, several challenges remain in integrating AI into treatment
465 technologies, such as MBBR+aPBR system. One critical issue is the need for high-quality and
466 comprehensive datasets to ensure accurate model training and validation. In many WWTPs, data are
467 either limited or insufficiently processed or analyzed (Bahramian et al., 2023). To address this, robust
468 sensor networks and advanced data management systems are essential to provide reliable inputs for
469 AI models, enabling accurate predictions and dynamic control adjustments. Creating global,
470 comprehensive, and standardized databases that integrate data from multiple WWTPs offers a
471 potential solution, promoting the applicability of AI-driven strategies. Several valuable features can
472 be incorporated into the modeling to enhance the prediction performance. Among these, H_2S inlet

concentrations can be estimated using process monitoring data, which allows for improved predictions of H_2S outlet concentrations, as extensively discussed in the existing literature (Baawain et al., 2019; Hamad et al., 2024; Santos et al., 2006; Tian et al., 2021; Zwain et al., 2020). Significant challenges are also related to the "black-box" nature of AI models, which hinders operators' understanding of the decision-making process behind AI-driven outcomes (Holzinger et al., 2022; Tsang and Benoit, 2023). CO_2 assimilation and release are instead influenced by a combination of different interdependent mechanisms, including the degradation of carbonyl compounds, which increase CO_2 emissions while simultaneously enhancing nutrient utilization and potentially improving CO_2 fixation (Oliva et al., 2023; Pasquarelli et al., 2024b). Although a black-box approach may not explicitly capture such mechanisms during modeling, the collection of a sufficient amount of high-quality data and the implementation of appropriate preprocessing and feature engineering strategies in this study enabled accurate predictions of CO_2 emissions from the sequenced system. This paves the way for AI to model processes difficult to describe with conventional mathematical approaches. Future research should focus on developing and optimizing explainable and interpretable AI models, along with user-friendly interfaces that allow operators to visualize and comprehend the logic behind AI predictions. Infrastructure compatibility is also a crucial hurdle. Many existing WWTPs are not designed to integrate sophisticated AI-driven control strategies, and upgrading these facilities may require substantial investment in implementing advanced control systems, smart sensors, and automation infrastructure (Cairone et al., 2024a). While the initial cost may be high, the long-term environmental and economic benefits, including reduced operational costs and improved treatment performance, make such investment feasible. Additionally, training WWTP operators in AI technologies and introducing new roles, such as data analysts and AI/ML specialists, will be crucial for the effective implementation of AI-driven control strategies (Cairone et al., 2024b).

While the findings of this study demonstrate the potential of AI modeling in enhancing process monitoring and control of the MBBR+aPBR integrated system, several limitations and uncertainties

must be considered. First, the models were evaluated using a relatively limited dataset from a laboratory-scale setup, which may not fully capture the variability of real-world operating conditions in full-scale WWTPs. Additionally, although LSBoost exhibited the highest accuracy in predicting CO_2 and H_2S emissions from the MBBR+aPBR system, the generalizability of this model to other CCU systems or varying plant conditions remains uncertain. The study also did not explore the impact of external factors, such as fluctuations in environmental conditions or raw wastewater composition, on model performance. Furthermore, the study focused on a single biotechnology system, and further research is needed to assess the applicability of these AI approaches across diverse CCU technologies. In future studies, the proposed approach can be extended to other wastewater treatment and CCU technologies, helping to demonstrate the broader potential of AI in optimizing operational parameters across different treatment systems and driving advancements toward carbon-neutral wastewater treatment. Cooperation among researchers and plant managers will be essential in addressing current challenges and fully realizing the benefits of AI-driven control systems for optimizing wastewater treatment processes.

5. Conclusion

This study demonstrates the effectiveness of AI models in accurately predicting the performance of CCU biotechnologies, focusing on the novel MBBR+aPBR integrated system. The optimized AI models outperformed conventional statistical methods. Among the tested models, LSBoost emerged as the most accurate, achieving high prediction accuracy for CO_2 and H_2S outlet concentrations from the MBBR+aPBR system. The varying predictive performances across the models deployed underscore the importance of selecting the appropriate AI model tailored to the specific characteristics of the treatment technology and the target outputs.

The proposed AI-driven approach provides valuable insights into developing accurate predictive tools, contributing significantly to enhanced process monitoring and control systems. The advanced

predictive capabilities of these AI models offer the potential for real-time monitoring, enabling operators to receive early warnings about critical operational conditions. This approach allows timely interventions, reducing potential issues that could otherwise impact treatment performance. Integrating an advanced AI-driven monitoring and control system within the MBBR+aPBR setup can lead to substantial benefits, including improved degradation of undesirable compounds such as H_2S and reductions in CO_2 emissions. These advancements may significantly mitigate the negative environmental impacts associated with WWTPs.

To fully exploit the potential of the proposed approach, future research should address limitations, such as enhancing prediction accuracy and validating the models across a broader range of datasets. Comparative studies with other ML techniques will be essential in further improving the practical utility of these models. This research direction is crucial for advancing scientific and technical progress toward achieving carbon neutrality and sustainability in wastewater treatment.

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832

Glossary of AI modeling terms

Activation (or transfer) functions: Functions that determine the activation level of each node and connect neurons within the network by propagating the output of nodes from one layer to the next.

Artificial neural network (ANN): A computational model inspired by the structure and function of the human brain, consisting of interconnected nodes (or neurons) organized into layers.

ANN architecture (or ANN configuration): The structure of an ANN, including the number of layers, the number of neurons per layer, and the types of connections between neurons.

Box constraint (or regularization): Hyperparameter that controls the maximum penalty on margin-violating observations, balancing model accuracy and complexity to prevent overfitting.

Classification task: A machine learning task that involves assigning labels (or categories) to input data based on learned patterns.

Coefficient of Determination (R^2): A statistical measure indicating the goodness of fit for a model's predictions compared to actual data, with values closer to 1 representing a better fit.

Cross-validation: A technique for evaluating the performance of a model by training and testing it on new (unseen) data.

Decision tree: An algorithm that uses tree-like structure to make sequential decisions to reach a specific outcome.

Deep learning: A subfield of machine learning that uses deep neural networks (multi-layered ANNs) to capture complex patterns from large datasets.

Feature engineering: The process of selecting, transforming, and creating the most relevant variables from raw data to be used as inputs (features) in a machine learning model.

Gamma: Hyperparameter that determines the influence of each training example on the decision boundary.

Gradient boosting algorithm: An algorithm that builds a sequence of weak learners (typically decision trees), with each learner correcting errors from the previous ones.

Grid search: A hyperparameter tuning technique that tests multiple combinations of parameters to identify the best configuration for a model.

Hyperparameters: Parameters defined before training that govern model learning process.

Hidden layers (ANN): Intermediate layers in an ANN that process data from the input layer before passing it to the output layer.

Input layer (ANN): The first layer in an ANN, composed of input neurons, that brings the initial data to the model.

Input variables: Features or variables in a dataset used by a model to make predictions.

Kernel functions: Mathematical functions used to transform data into higher-dimensional spaces.

Learning rate: A hyperparameter controlling the rate at which an algorithm updates the parameters during training.

Least-squares boosting (LSBoost): A gradient boosting algorithm that builds an ensemble of decision trees to minimize the residual errors from previous trees.

Levenberg-Marquardt algorithm ("trainlm"): A training algorithm used to optimize weights and biases of a model.

Linear kernel: The simplest and most straightforward kernel function that assumes the data are linearly separable.

Machine learning: A branch of AI focused on algorithms that learn patterns from data, enabling them to make predictions or decision based on learned representations.

Mean absolute error (MAE): A metric that calculates the average absolute difference between predicted and actual values.

Mean squared error (MSE): A metric that computes the average of squared differences between predicted and actual values.

Model training: The process of feeding data to a model to learn underlying patterns and relationships.

Output layer (ANN): The final layer in an ANN that produces predictions or outputs based on the learned model.

Output variables: Target variables that a model aims to predict using input data.

Polynomial kernel: A kernel function that transforms data into a higher-dimensional space using polynomial functions. It is particularly useful with non-linear decision boundaries.

Radial basis function (RBF) kernel (or Gaussian kernel): A kernel function used for non-linear separation of data by measuring the similarity between data points based on their distance in the input space.

Root mean squared error (RMSE): The square root of MSE, a metric that measures the average difference between predicted and actual values.

Random forest (RF): An ensemble learning method that combines many decision trees for classification or regression tasks.

Regression task: A machine learning task for predicting values of continuous dependent variables based on independent variables.

Subsample: Hyperparameters that control the fraction of observations used for training each tree.

Supervised learning: machine learning technique that relies on labeled data, meaning that input variables (predictors) are used to predict output variables (responses), whose 'true' values are readily

available in the training data, allowing the model's performance to be evaluated using appropriate metrics.

Support vector machine (SVM): A supervised learning algorithm for classification and regression that separates data into classes by finding the optimal hyperplane or set of hyperplanes.

Support vectors: Data points closest to the hyperplane in an SVM model, influencing its position and orientation.

Sigmoidal transfer function ("tansig"): An "S"-shaped function that introduces nonlinearity into the model.

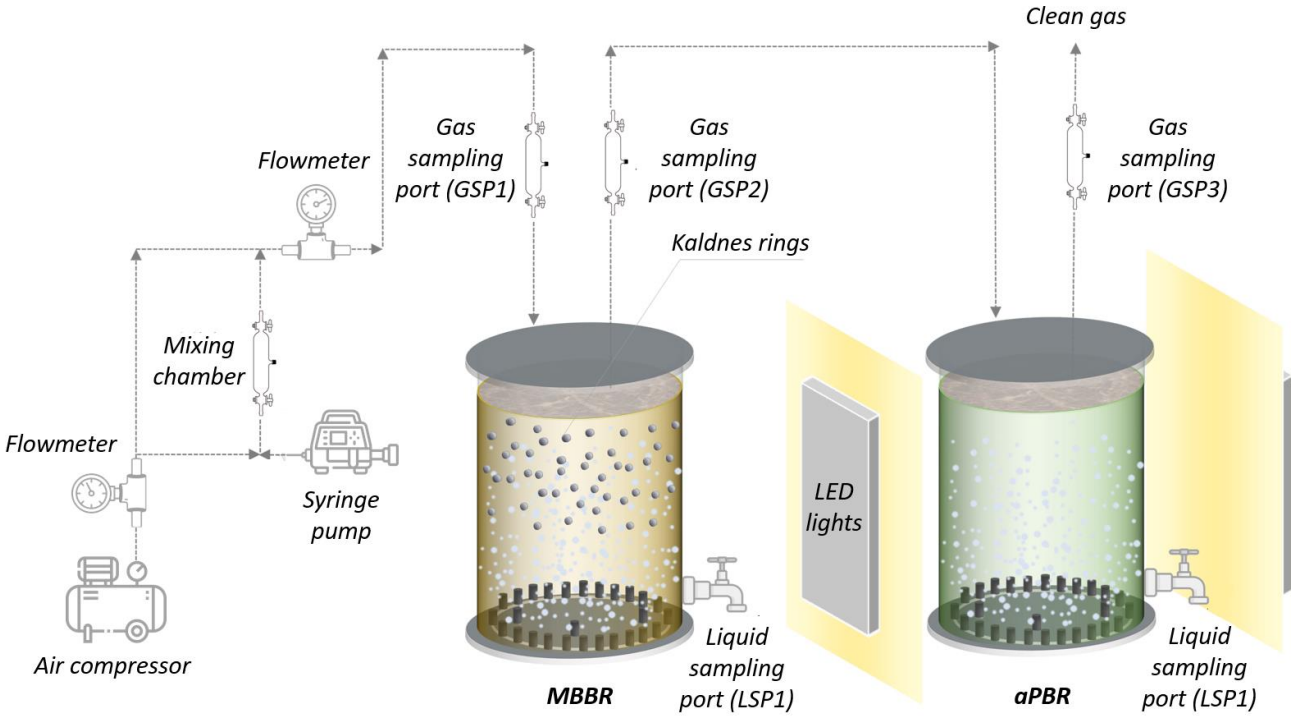
Training algorithm: An algorithm that adjusts model parameters during training.

Training dataset: The subset of data used to train a model, allowing it to learn the patterns/relationships required for a given task.

Testing dataset: The subset of data used to evaluate the performance of a trained model, assessing its ability to generalize to unseen data.

912 **Figures**

913



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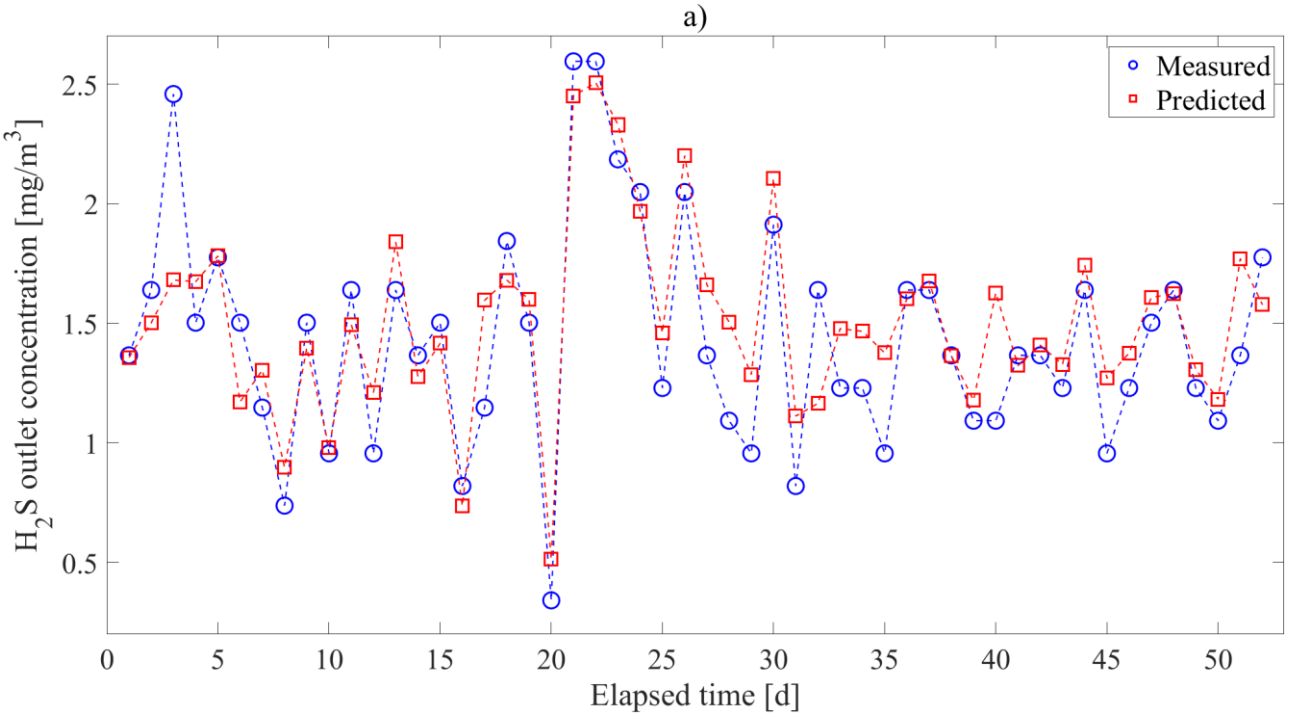
915 **Figure 1.** Schematic representation of the MBBR+aPBR integrated system.


a)
Measured
Predicted
H_2S outlet concentration [mg/m^3]
Elapsed time [d]
0
5
10
15
20
25
30
35
40
45
50
0.5
1
1.5
2
2.5

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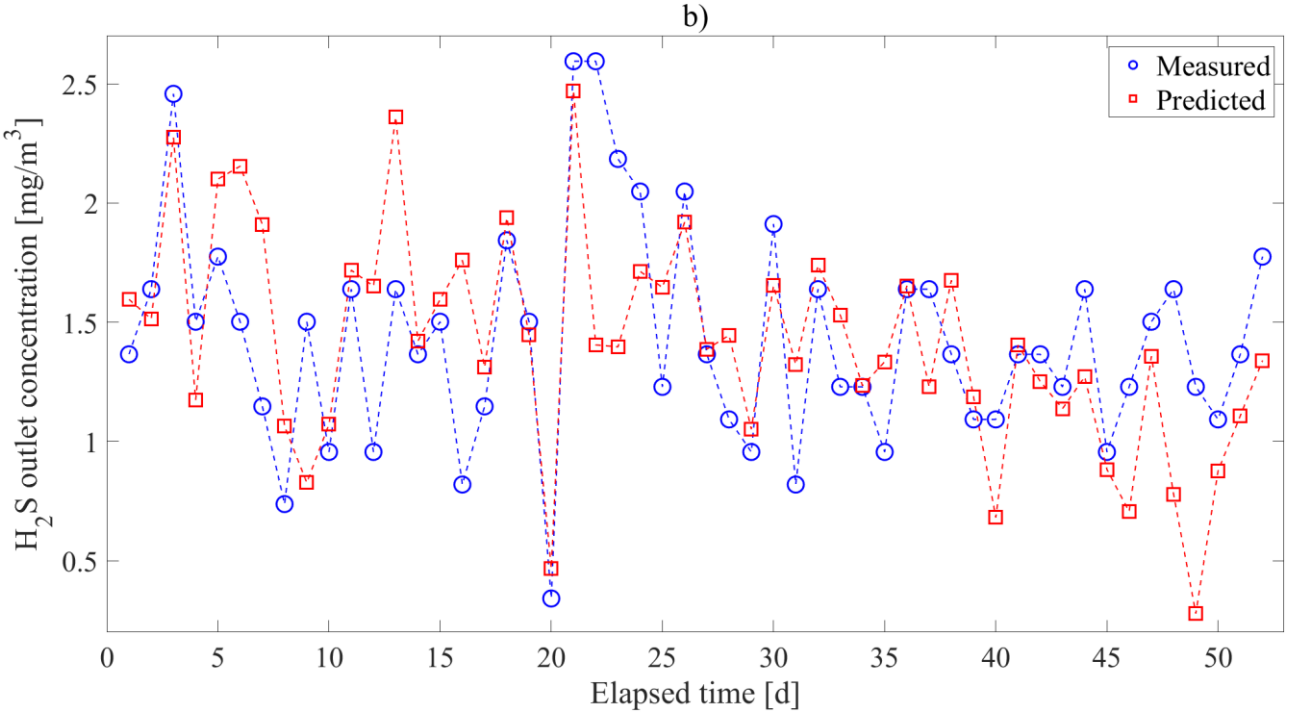
b)
Measured
Predicted
H_2S outlet concentration [mg/m^3]
Elapsed time [d]
0
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10
15
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40
45
50
0.5
1
1.5
2
2.5

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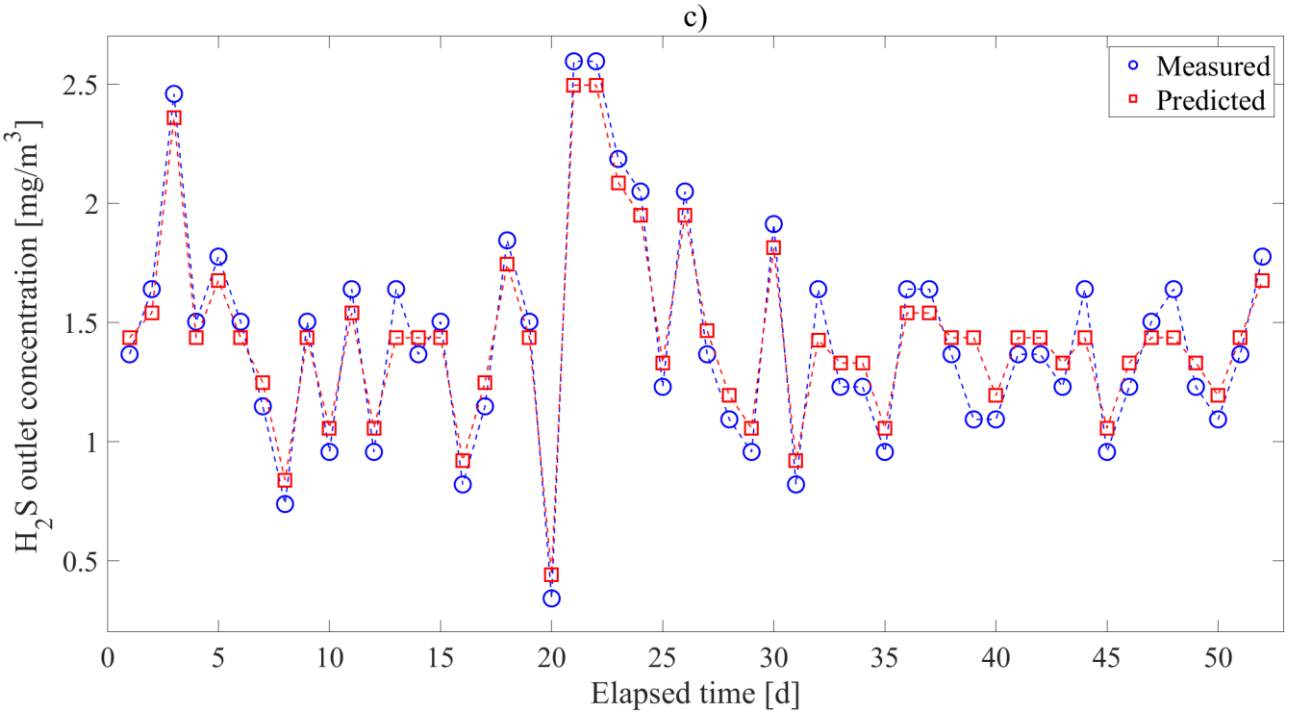
c)
Measured
Predicted
H_2S outlet concentration [mg/m^3]
Elapsed time [d]

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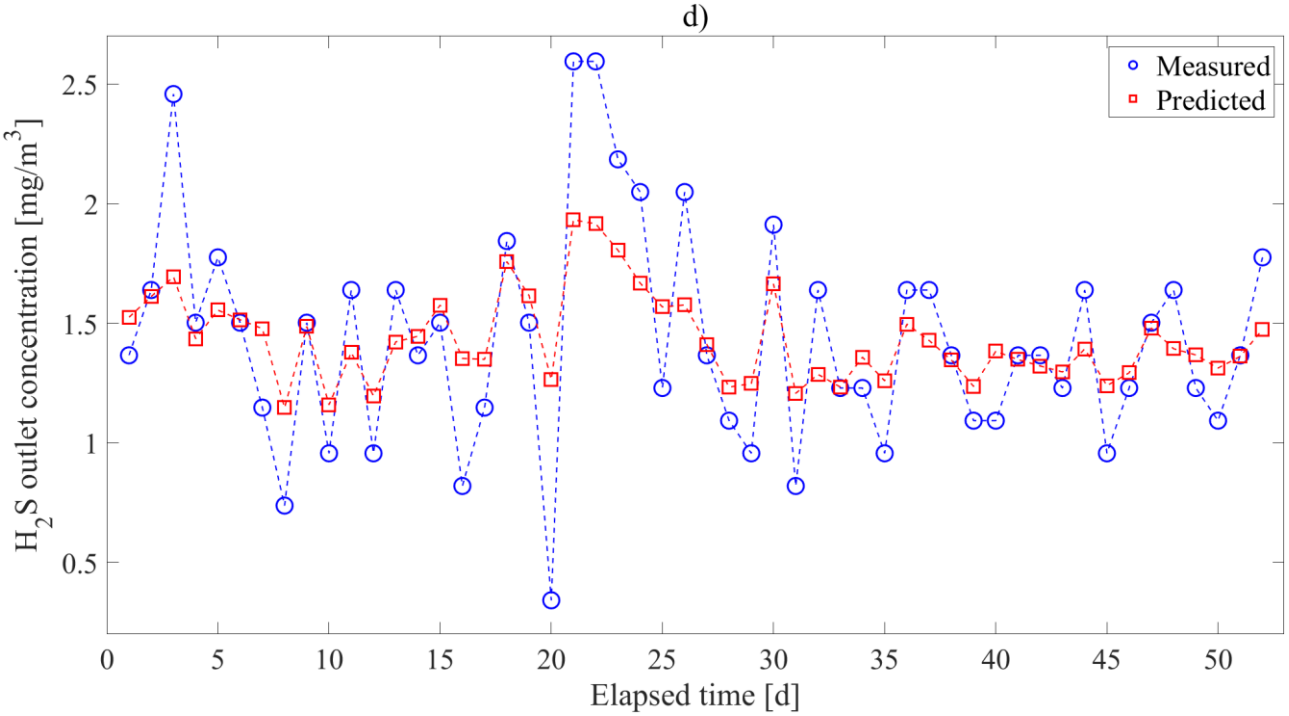
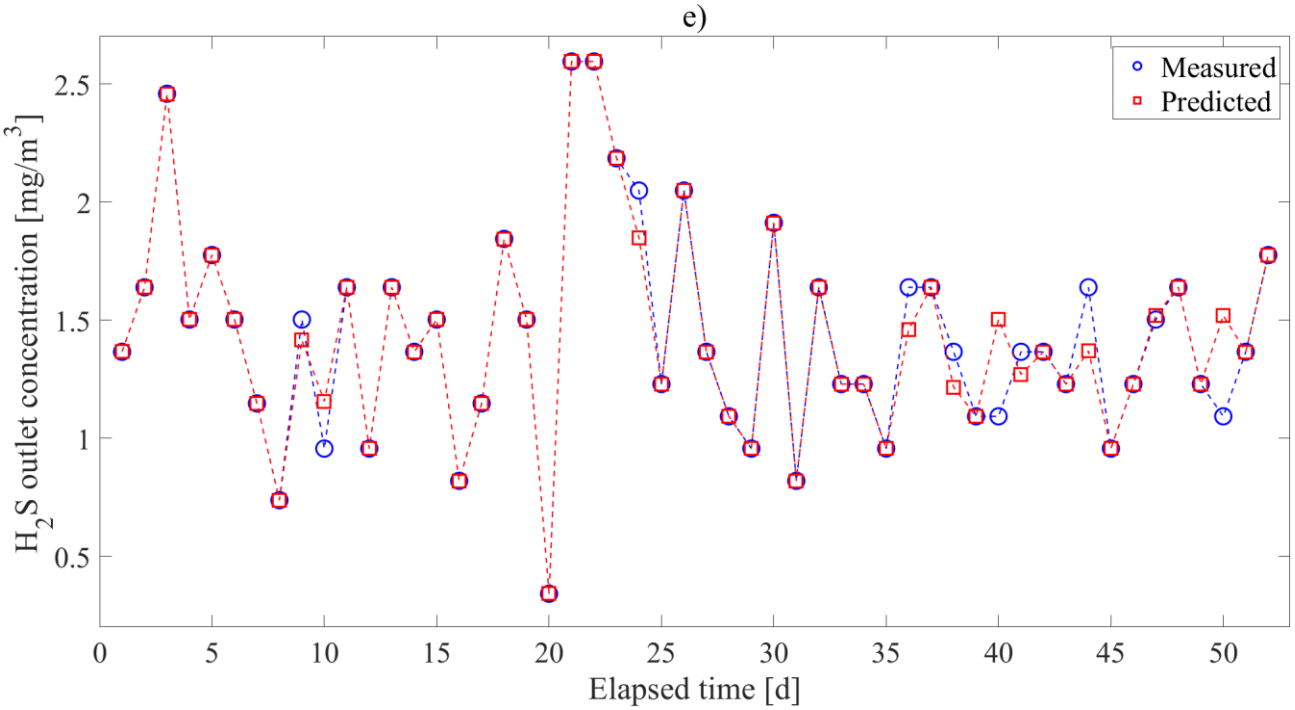

d)
Measured
Predicted
H_2S outlet concentration [mg/m^3]
Elapsed time [d]

921



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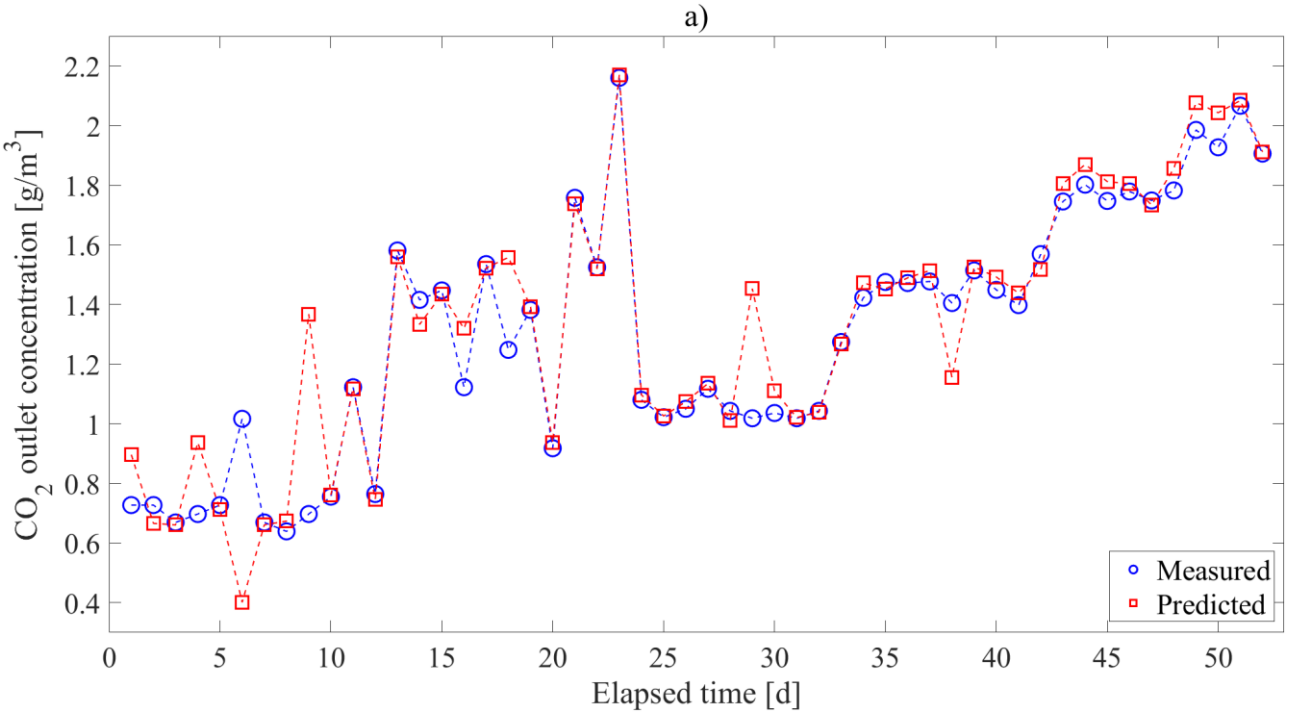
924 **Figure 2.** Predictions of H_2S outlet concentrations from the MBBR using (a) ANN, (b) multi-task

925 ANN, (c) SVM, (d) RF, and (e) LSBoost models.


a)
CO_2 outlet concentration [g/m^3]
Elapsed time [d]
Measured
Predicted

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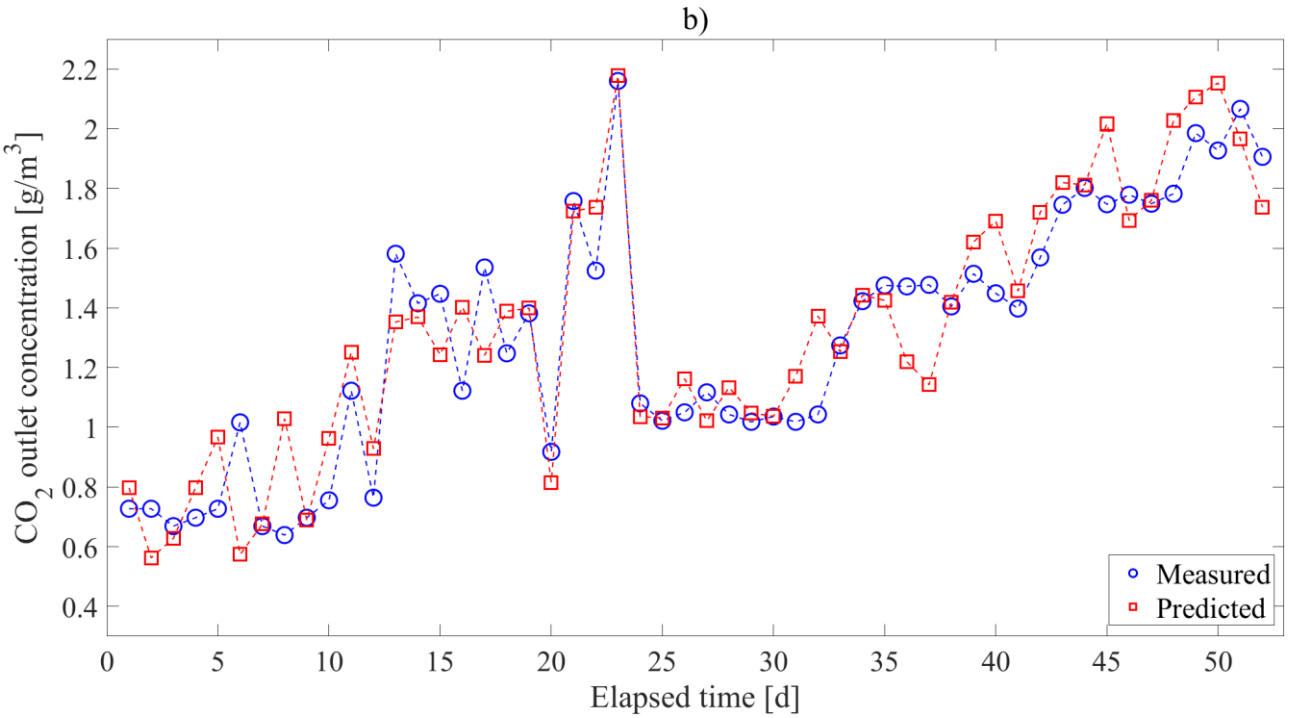
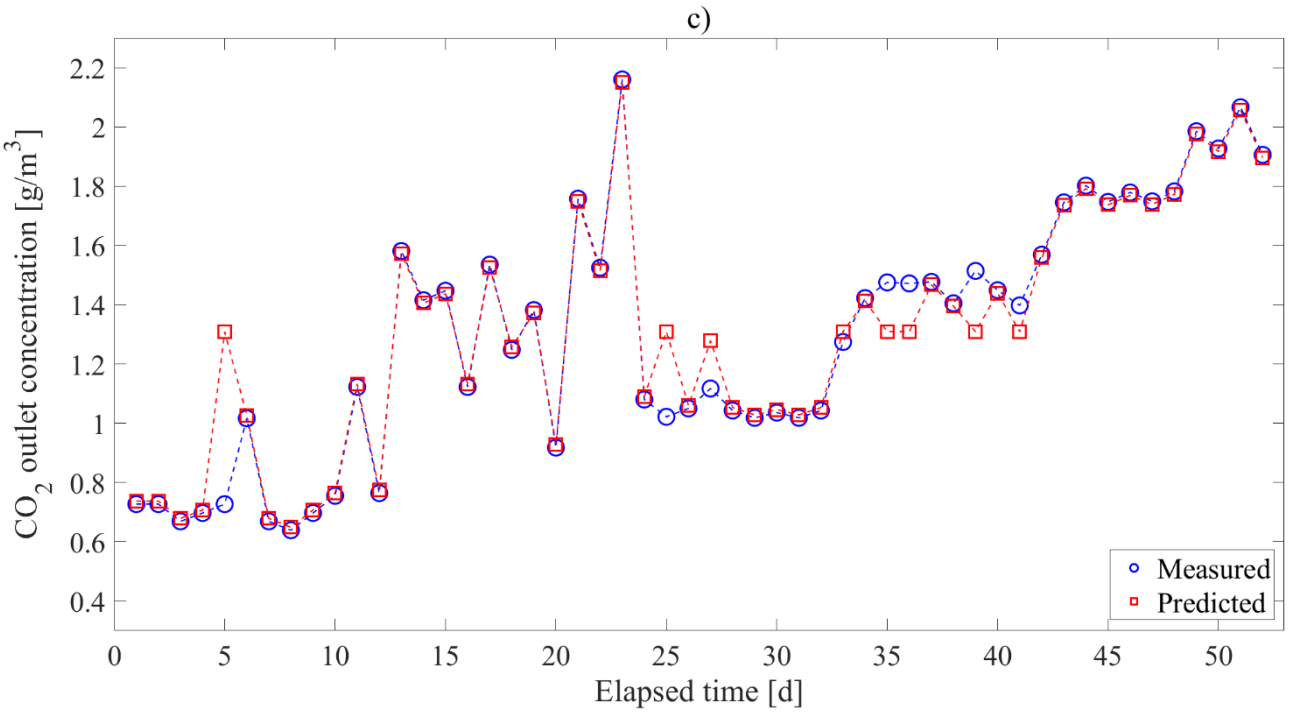

b)
CO_2 outlet concentration [g/m^3]
Elapsed time [d]
Measured
Predicted

928


c)
CO_2 outlet concentration [g/m^3]
Elapsed time [d]
Measured
Predicted

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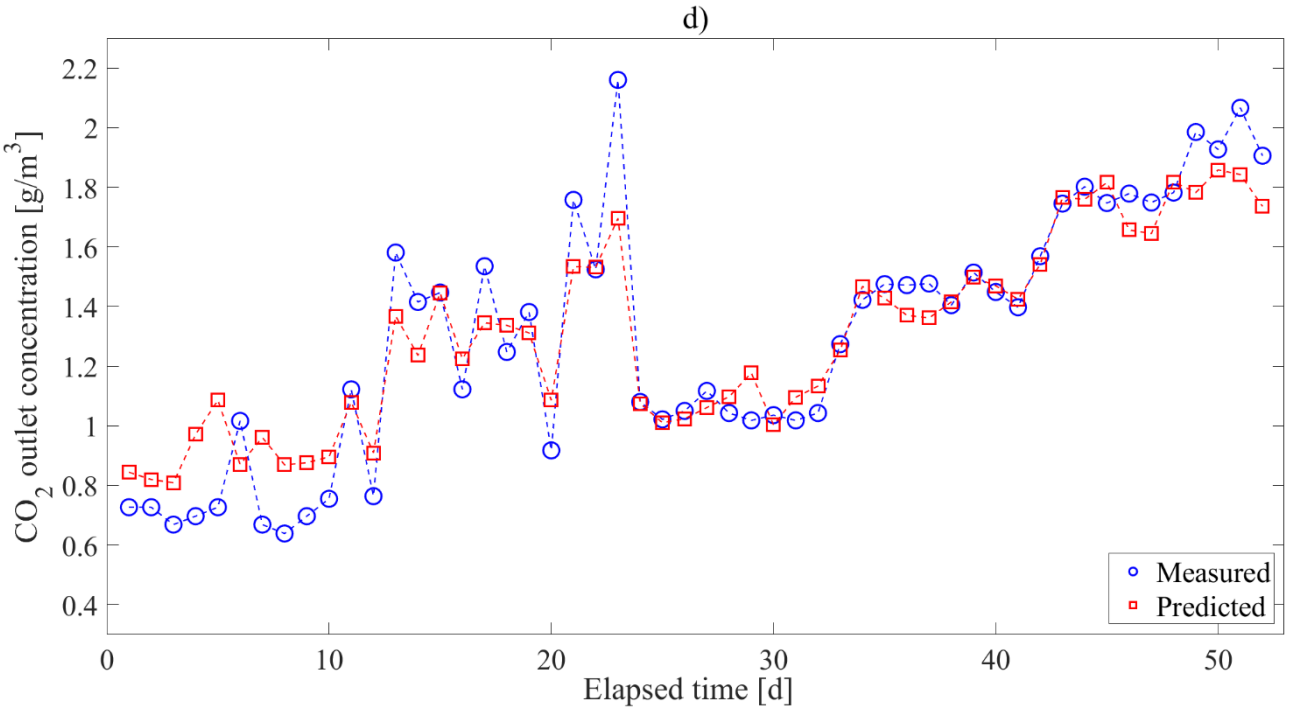
d)
CO_2 outlet concentration [g/m^3]
Elapsed time [d]
Measured
Predicted

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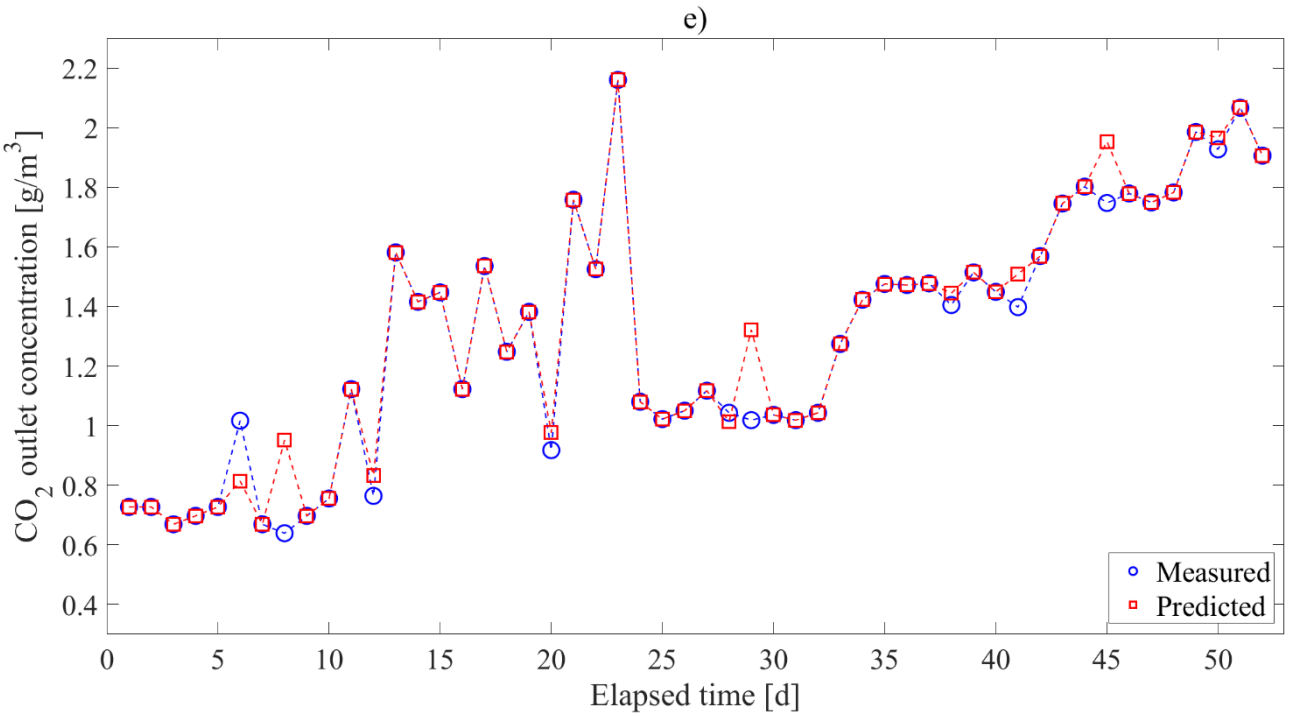

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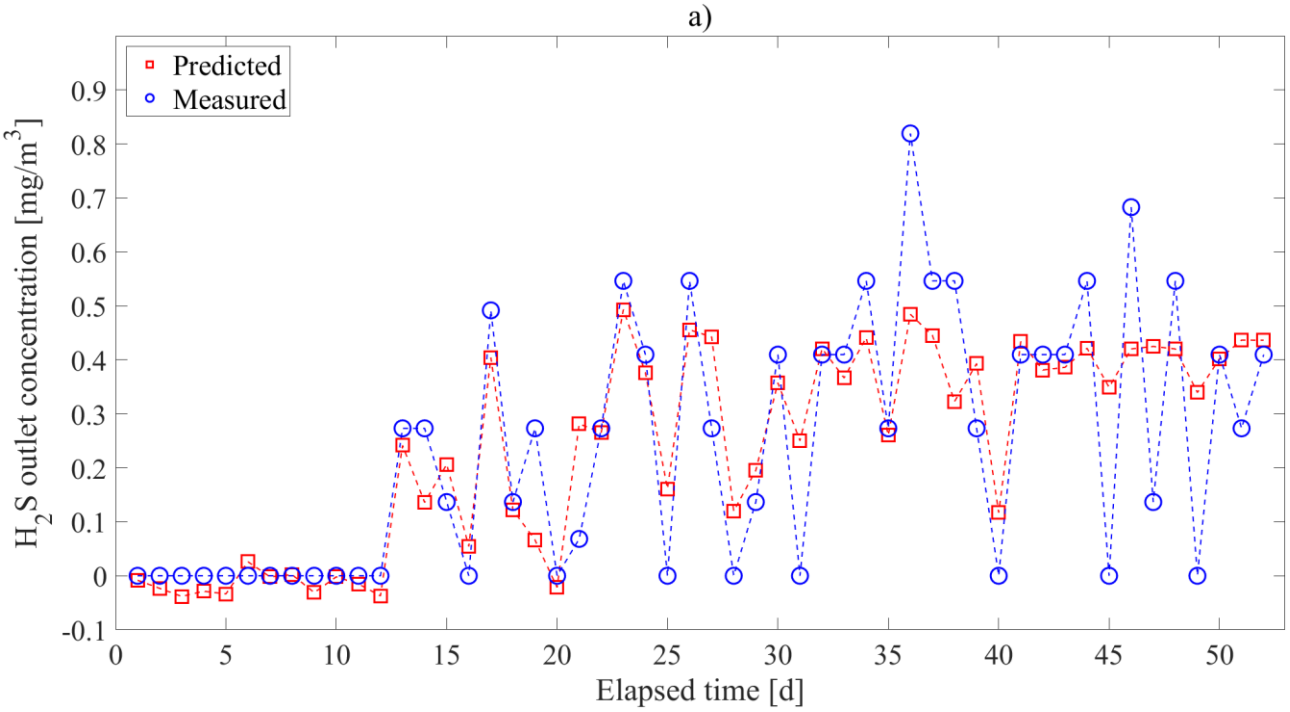
933 **Figure 3.** Predictions of CO_2 outlet concentrations from the MBBR using (a) ANN, (b) multi-task

934 ANN, (c) SVM, (d) RF, and (e) LSBoost models.


a)
Predicted
Measured
H2S outlet concentration [mg/m3]
Elapsed time [d]

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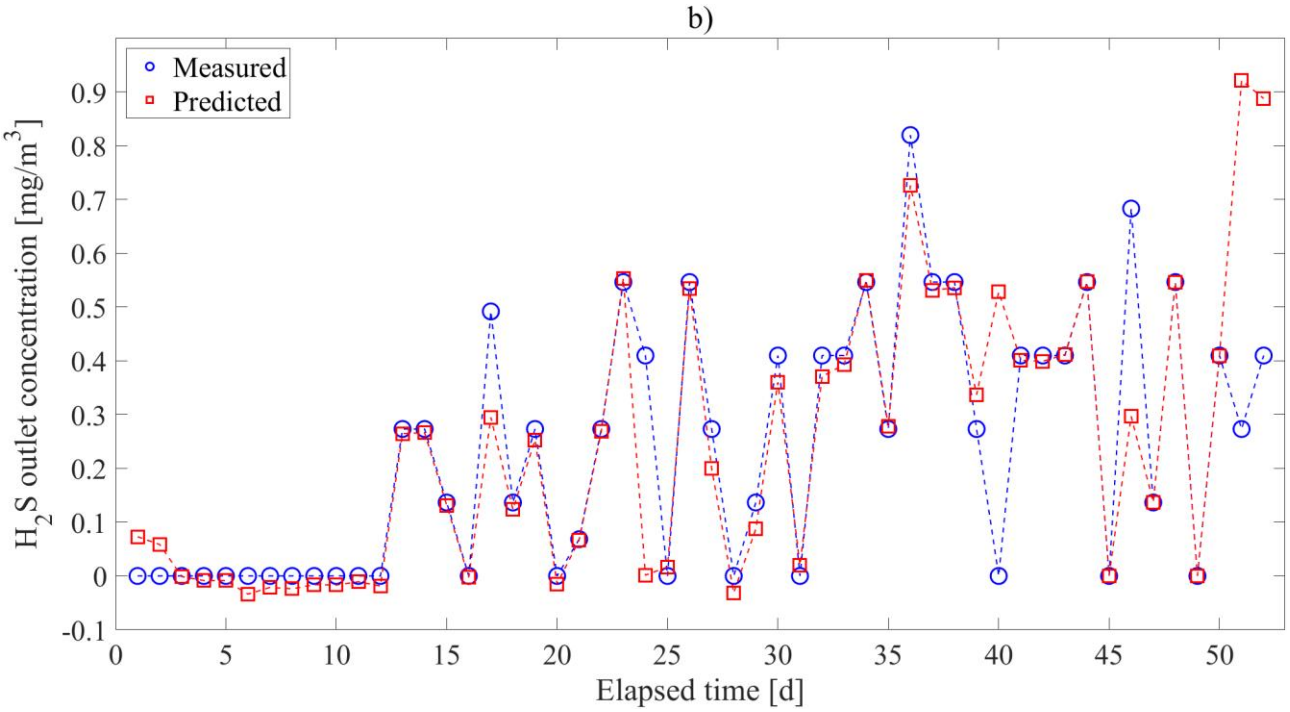
b)
Measured
Predicted
H2S outlet concentration [mg/m3]
Elapsed time [d]

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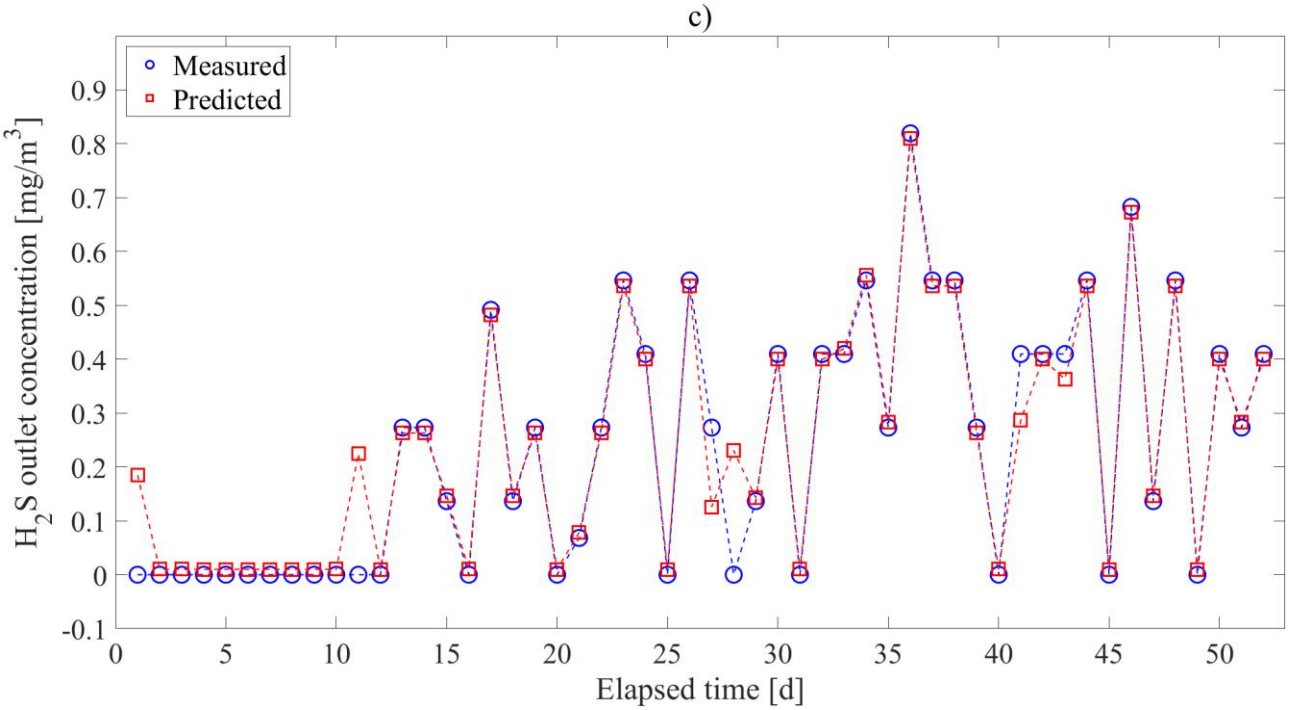
c)
Measured
Predicted
H2S outlet concentration [mg/m3]
Elapsed time [d]

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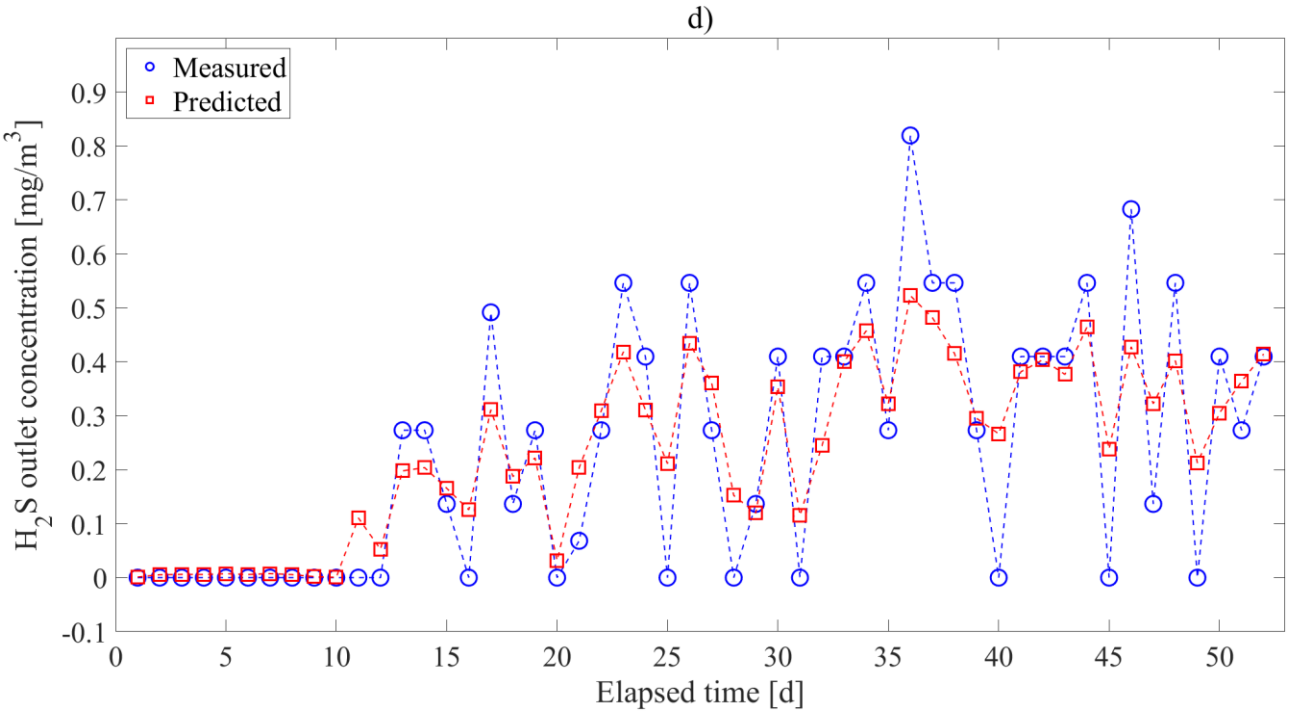
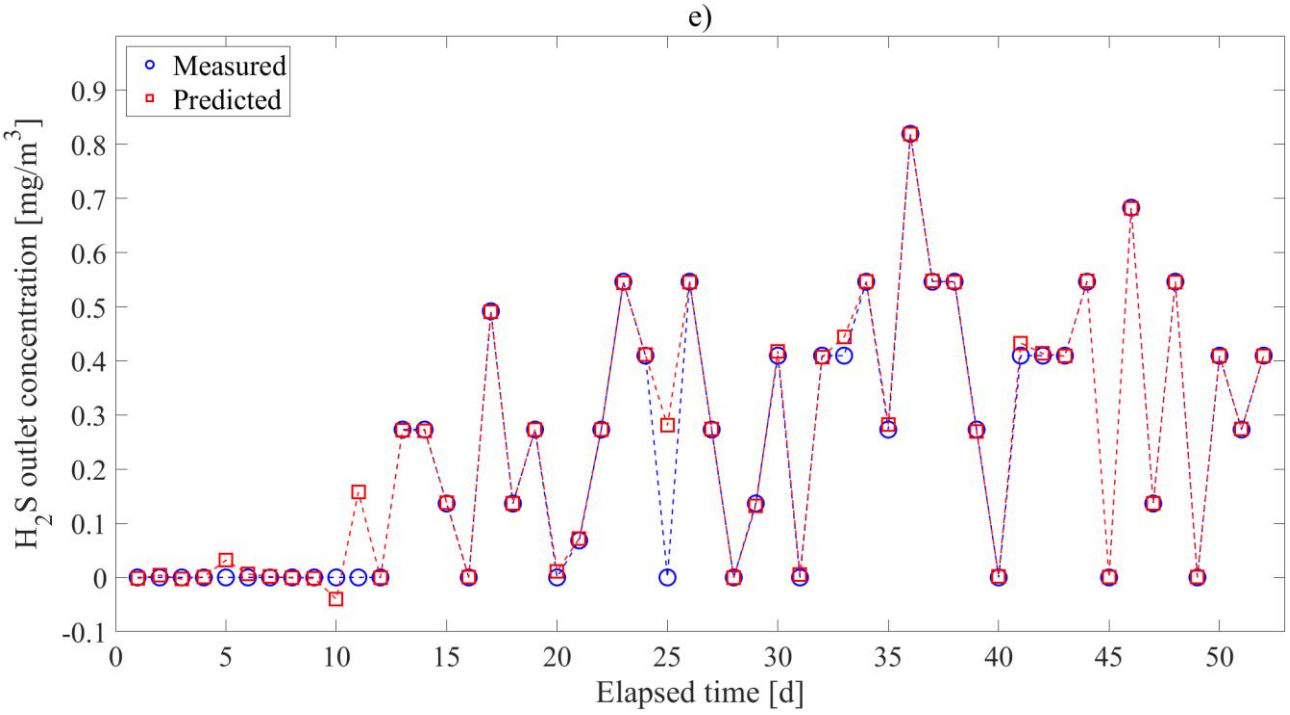

d)
Measured
Predicted
H2S outlet concentration [mg/m3]
Elapsed time [d]

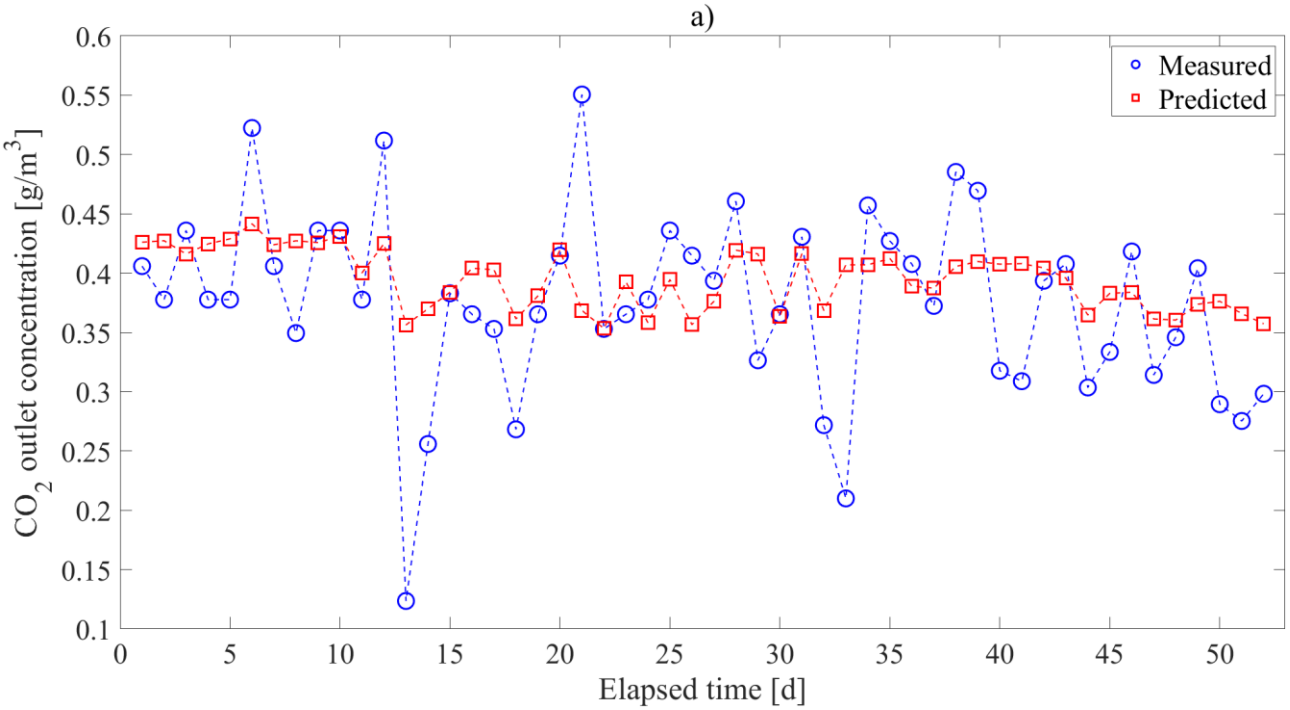
940



941

942 **Figure 4.** Predictions of H_2S outlet concentrations from the aPBR using (a) ANN, (b) multi-task

943 ANN, (c) SVM, (d) RF, and (e) LSBoost models.


a)
Measured
Predicted
CO_2 outlet concentration [g/m^3]
Elapsed time [d]
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0
5
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40
45
50

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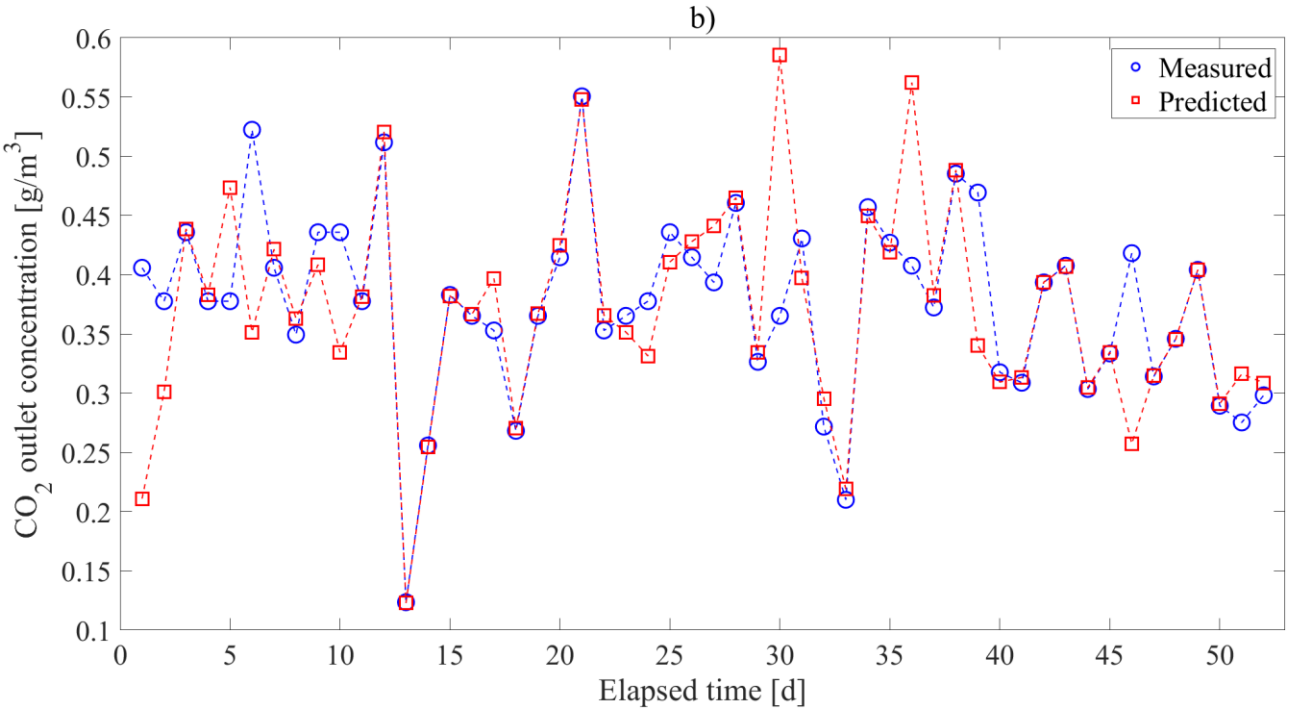
b)
Measured
Predicted
CO_2 outlet concentration [g/m^3]
Elapsed time [d]
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0
5
10
15
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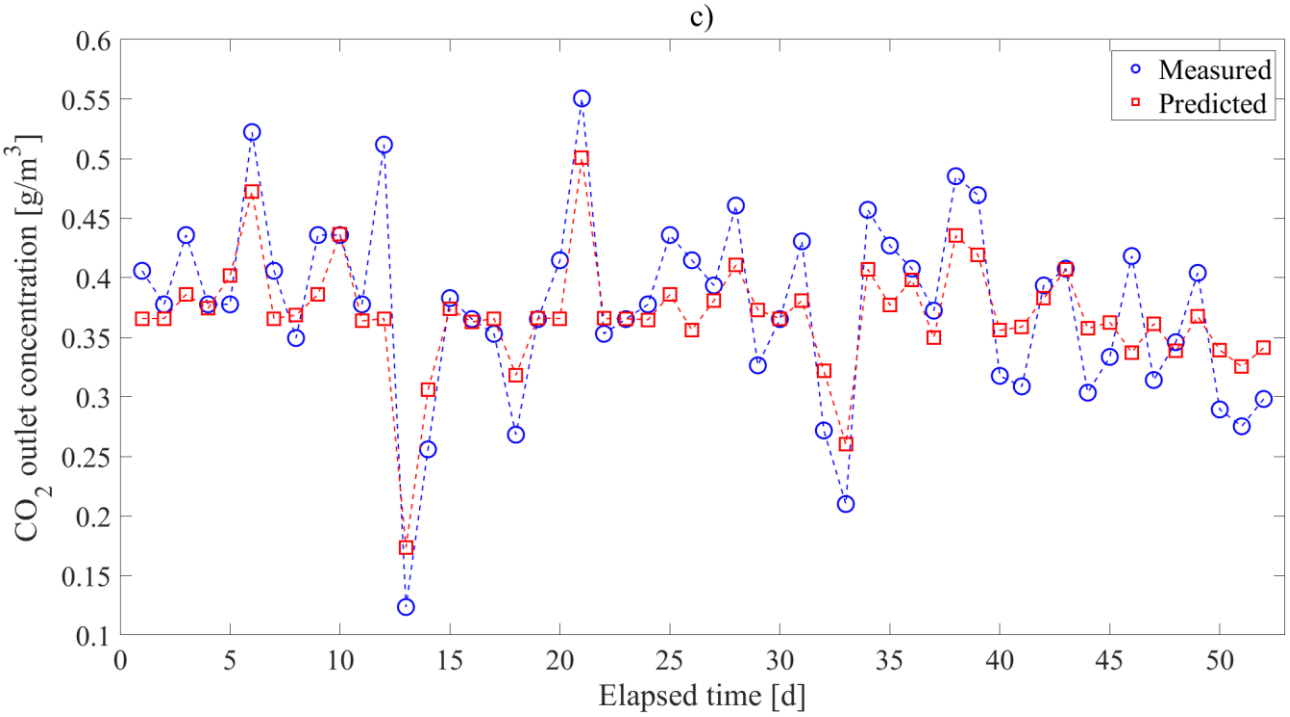
c)
Measured
Predicted
CO_2 outlet concentration [g/m^3]
Elapsed time [d]
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
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20
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30
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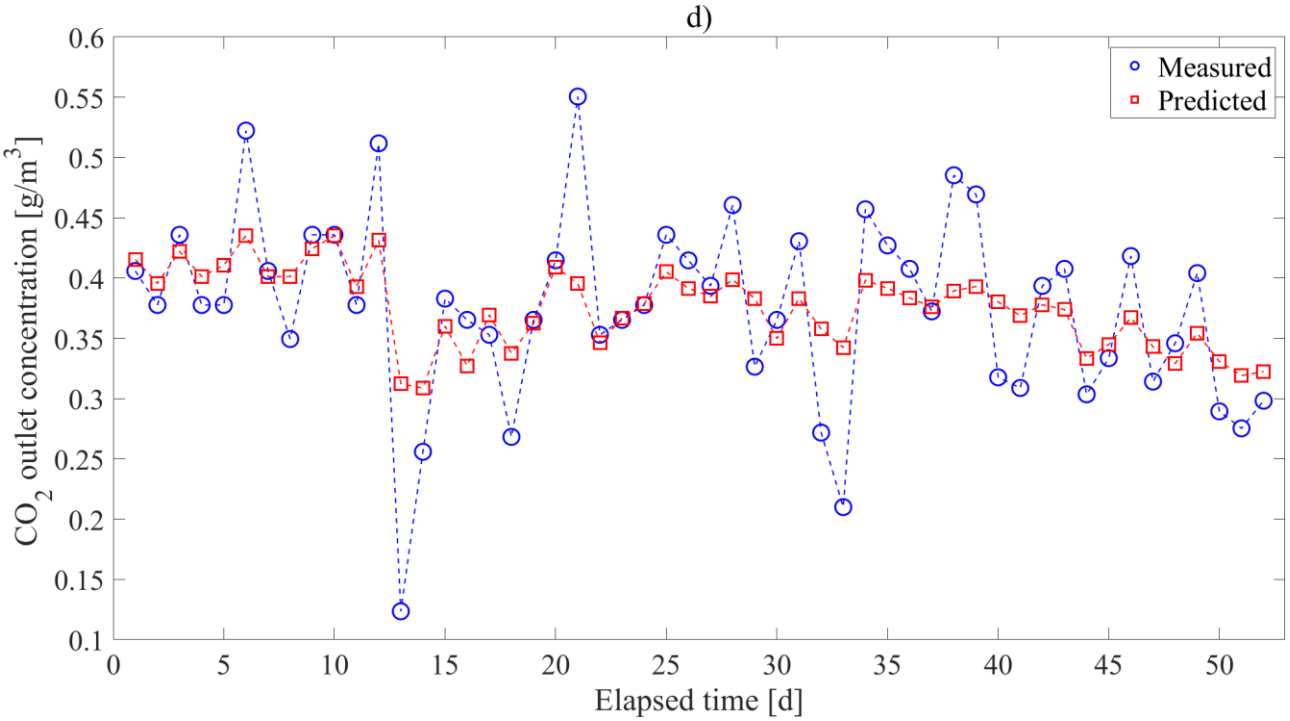
d)
Measured
Predicted
CO_2 outlet concentration [g/m^3]
Elapsed time [d]
0.6
0.55
0.5
0.45
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0.3
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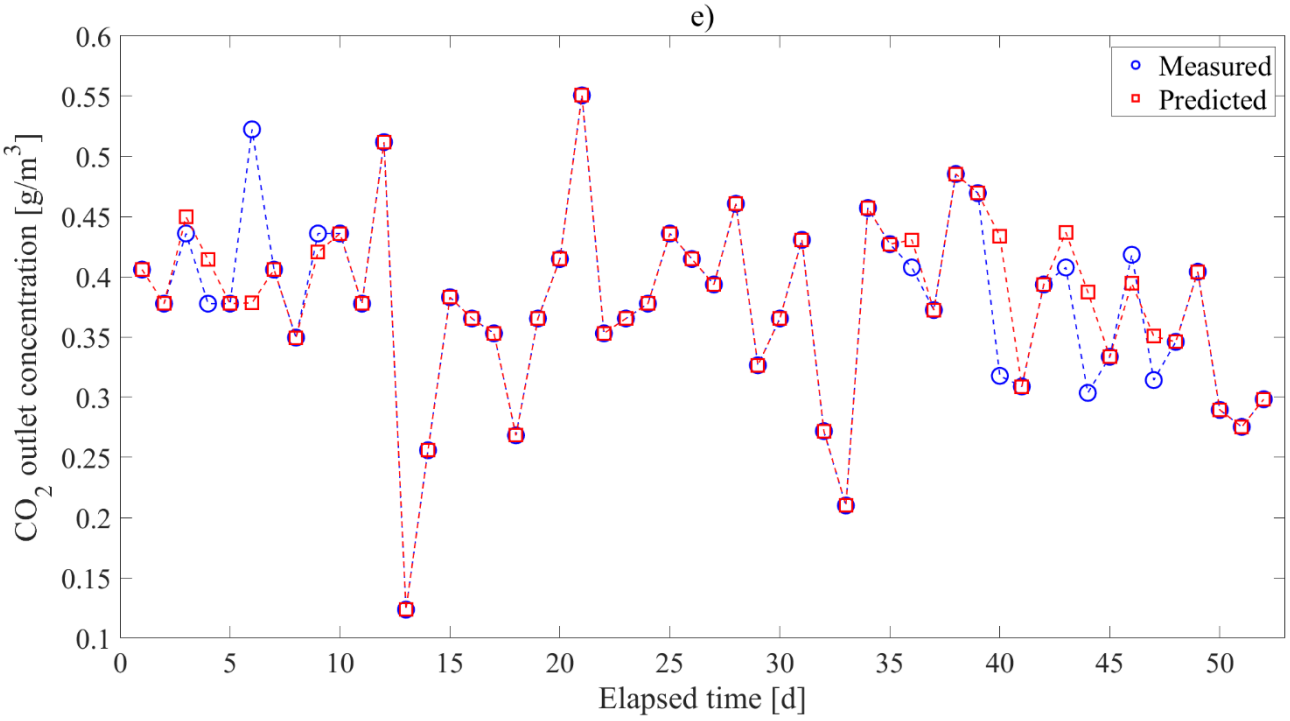

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951 **Figure 5.** Predictions of CO_2 outlet concentrations from the aPBR using (a) ANN, (b) multi-task

952 ANN, (c) SVM, (d) RF, and (e) LSBoost models.

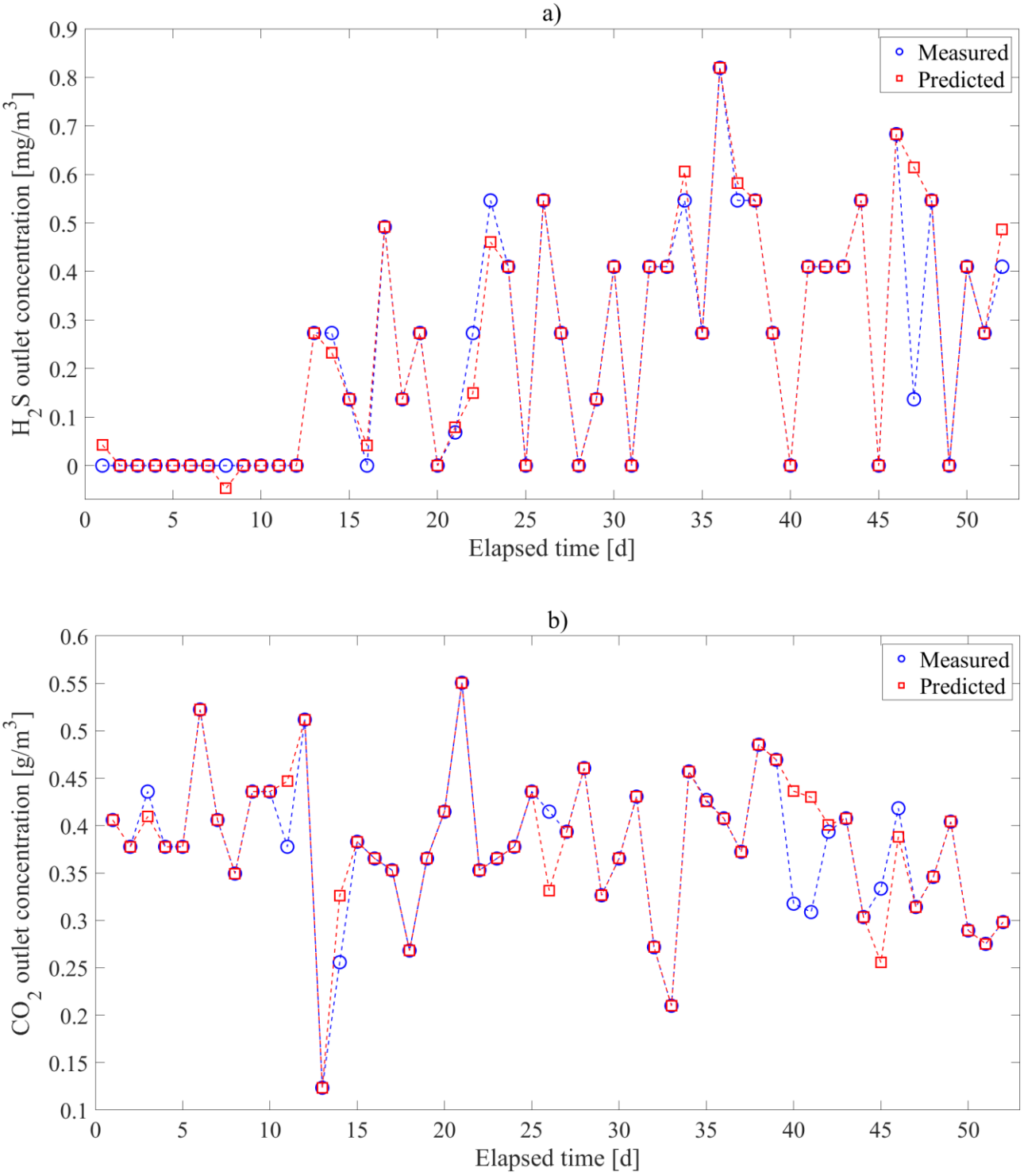

Figure 6. LSBoost+LSBoost approach for predicting (a) H_2S and (b) CO_2 outlet concentrations from the MBBR+aPBR integrated system.

957 **Table**

958 **Table 1.** Statistical parameters for the MBBR and aPBR.

Parameter	Measurement units	MBBR			aPBR		
		Mean	**St. Dev.**	**Cv**	**Mean**	**St. Dev.**	**Cv**
Temperature	°C	21.96	2.19	0.10	24.08	1.86	0.08
pH	-	6.37	0.27	0.04	7.00	0.88	0.13
Saturated O_2	%	80.85	7.09	0.09	89.73	10.18	0.11
Dissolved O_2	mg/L	6.97	0.69	0.10	7.72	1.07	0.14
TSS	g/L	1.25	0.17	0.14	1.41	0.33	0.24
H_2S inlet	mg/m^3	216.48	60.58	0.28	1.43	0.45	0.32
CO_2 inlet	g/m^3	0.59	0.07	0.11	1.30	0.42	0.32
H_2S outlet	mg/m^3	1.43	0.45	0.32	0.24	0.23	0.98
CO_2 outlet	g/m^3	1.30	0.42	0.32	0.38	0.08	0.21

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Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Enhancing process monitoring and control in novel carbon capture and utilization biotechnology through artificial intelligence modeling: an advanced approach toward sustainable and carbon-neutral wastewater treatment

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