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Research Article

Real-Time Monitoring and Optimization of Regeneration Efficiency of Peanut Shell-Based Magnetic Biochar Adsorbent Using Microwave-Assisted Regeneration, IoT Monitoring, and Machine Learning

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Abstract:

This research applies to the regeneration rate and recycling capability of peanut shell magnetic biochar adsorbents capturing pollutants from water through IoT sensing and microwave regeneration systems actuated by optimization algorithms. This was done by first crushing peanuts shells and carbonizing them to generate biochar, secondly adding magnetic Fe_3O_4 nanoparticles to enhance the adsorption surface and ease by which the Richards can be separated from the mixture. Microwave-assisted regeneration was also identified to be more efficient than conventional thermal methods, with regeneration yields up to 88% achieving adsorption capacity in methylene blue dye and Lead ions. Though IoT smart sensors became efficient to monitor temperature and other pollutants in the process in order to enhance the process. The application of Machine learning model, Random Forest, on regression yielded a high R^2 score 0.91 for the prediction of the efficient regeneration and allows for feedback control on the system. The proposed system increases regeneration, and at the same time it is less energy and operating cost consuming in comparison to the conventional practices. The present paper demonstrates that the considered technologies can be successfully applied at large scale both for water and gases purifications with wastewater treatment among the most suitable application areas. Future studies will attempt at proving the possibility to use more agricultural waste materials to produce biochar and use improved algorithms in the rejuvenation processes for better models due to machine learning. This paper provides a green, sustainable and easily scalable method of collecting and recycling or recovering the biochar.

1. Introduction

As more emphasis has been placed on the use of sustainable resources in the global economy the importance which is placed on waste management has risen greatly as the world attempts to reduce as much of a negative effect on the earth as possible. With reference to the various methods of waste management, the identification and production of biochar adsorbents from agricultural residues is a particularly innovative solution [1-15]. Biochar, a charcoal-like substance formed through the process of pyrolysis of organic matter, has received much attention following its multipurpose uses in amelioration of environmental problems such as water pollution, soil degradation and carbon storage. Since biochar feedstock is sourced from agricultural residues feedstock is readily available, renewable peanut shells are very rich in carbon. It is obvious that peanut shell-based biochar, in specific, could be very potentially adsorbent for the efficient removal of heavy metals, dyes, and other pollutants from wastewater. However, the application of biological char adsorbents is very limited due to the drawbacks of conventional regenerative processes. Regeneration is important because it helps re-establish the cycle for biochar adsorbents thereby making it possible to be reused more than once before being discarded [16-25]. A number of traditional methods like thermal regeneration are popular; however, they are very inefficient, take longer time to regenerate and cause sometimes irreversible losses of adsorption capacities. In addition, such approaches are not suitable for continuous monitoring of hardware systems or their optimization, which makes such solutions difficult to scale and financially feasible.

Modern techniques like microwave regeneration, IoT base monitoring in the process, and machine learning have also been in discussion over the recent period to enhance the regeneration process. Microwave assisted regeneration has comparative advantages over conventional techniques such as rapid heating, uniformity in energy input and better control on the process [11]. Incorporation of real time IoT monitoring allows the tracking of parameters such as temperature, adsorption capacity, and concentration of the pollutants to gather profound information about the regeneration process [2]. In addition, the use of machine learning algorithms helps make assumptions and introduce optimal operating conditions that can be used to predict rates of regeneration from historical as well as feedback data from the sensors.

1.1 Problem Statement

The conventional methods of biochar adsorbent regeneration usually have lower efficiency and higher consumption of resources, which renders them inefficient for large-scale applications. These methods are not properly utilized to realize the full benefit of biochar for its continuous, sustainable usage.

Lack of real-time monitoring and adaptive control in regeneration cycles limits the optimization of such cycles towards achieving better performance and greater operational effectiveness. This paper seeks to answer the challenges presented by integrating microwave-assisted regeneration, IoT-enabled monitoring, and machine learning for efficient and scalable solutions to regenerate peanut shell-based magnetic biochar adsorbents.

1.2 Objectives

The objectives of this study are as follows:

1. To develop a peanut shell-based magnetic biochar adsorbent with enhanced recyclability.
2. To implement a microwave-assisted regeneration method integrated with IoT for real-time monitoring.
3. Employing machine learning models to optimize regeneration efficiency and predict long-term performance.

1.3 Significance

The current study is to develop a sound synergistic connection between environment engineering and data mining to establish a firm and sustainable recycling technique for the biochar adsorbents. This study aims to present microwave regeneration, IoT, and machine learning concepts that will increase the possibility of developing low-cost and reusable peanut shell-based magnetic biochar adsorbents at a commercial scale. Furthermore, the possibilities for practical application of this work are wide ranges, such as usage as the new material in wastewater treatment, air treatment, and in land treatment. Furthermore, this work supports the growth of the resource reuse of the biochar adsorbents which cut down the generation of waste products besides cutting down the regeneration costs and the impact on the environment posed by other conventional adsorbent regeneration approaches.

It is in this light then that this study marks progress towards the accomplishment of proper, effective, environmentally sound, and economically viable waste management systems. The use of RTM and PA also provide methodologies for creating intelligent, self-sufficient waste treatment systems designed for confronting the variability of waste management environments and problems.

2. Literature Review

The literature review of this study is organized into three main sections based on the research objectives: The major developments are as follows: 1) microbial peanut shell derived magnetic biochar adsorbents 2) microwave assisted regeneration techniques 3) integration of IoT and machine learning for efficient regeneration. These points are explored in terms of their relevance to enhancing the regenerative process and overall effectiveness of biochar adsorbent, specifically with regard to recycling of peanut shell-derived, magnetic biochar.

2.1 Peanut Shell-Based Magnetic Biochar Adsorbents

Biochar is the carbonized product which is obtained by the process of pyrolysis of biomass including agricultural and forest residues and crops. As a result of its permeable nature, and rich surface chemistry, biochar has attracted considerable interest in many fields such as water treatment, soil enhancement, and carbon storage [26]. Peanut shells have recently attracted interest for the production of biochar precursors because of the easy availability and low cost of these waste byproducts.

Peanut shell biochar (PSB) is also suitable for use in adsorbents owing to its a high content of carbon and large surface area that increases its adsorption capability [24]. Literature review has indicated that PSB has the ability to remove various pollutants such as heavy metals for example Pb, Cu, Zn, dyes and organic pollutants (Li et al., 2019). Furthermore, for the chemistry of biochar itself; the organic functional groups on the char surface help in adsorptive processes through electrostatic attraction and chelative reactions with the pollutants [8].

Over the last few years, there has been an increasing trend of research in the attempts to enhance the adsorption capacity of biochar. Among them, the approach of adding magnetic nanoparticles is quite possible because it can improve the separation and regeneration process. Magnetic biochar adsorbents have shown higher adsorption capacities than non magnetic biochar particularly organic dopant and heavy metals [12]. For instance, MPSB as stated in Pessôa et al. (2024) has Methylene blue and lead ion adsorption capabilities enhanced by the biochar. This modification means that an external magnetic field can be applied to help ease separation of the biochar from the contaminated water thus improving the regeneration and adsorbent reusability [18].

Nonetheless, like other biochar adsorbents, the biggest drawback of employing biochar adsorbents is its regeneration phase. Regeneration of the spent adsorbents is therefore essential to restore their effectiveness and contain costs incurred. Conventional techniques of regeneration, for example, thermal treatment, are highly likely to causes reduction in the adsorption capacity with consecutive cycles [6]. For these reasons, other techniques like the microwave-assisted regeneration have been introduce to address these hurdles.

2.2 Microwave-Assisted Regeneration Techniques

Microwave regeneration is still a relatively new method for the thermal regeneration of samples, and it has several obvious advantages over conventional regeneration methods. In traditional techniques, it is burnt in an oven or other furnace, and because of the uncontrolled uneven distribution of heat, the process consumes a lot of energy. Microwave assisted regeneration is an attractive method where microwave radiation is used to directly heat the adsorbent and results in better heating profile and shorter regeneration time compared with conventional heating methods [11]. Microwave regeneration has been used extensively in the regeneration of adsorbent particularly activated carbon and biochar.

The main benefit of microwave regeneration is the uniform distribution of energy throughout the adsorbent material. Rapid, localized heating through microwave radiation accelerates the desorption of pollutants from the surface of the biochar [4]. In this way, it ensures quicker regeneration times and energy consumptions compared to other traditional techniques. This way, with control over the microwave power and duration, more accurate regeneration conditions are ensured that will preserve the structural integrity of the biochar and avoid losing the adsorption capacity.

There have been various studies regarding microwave-assisted regeneration for biochar adsorbents, with highly promising results. For example, Palma and Meloni (2016) demonstrated that microwave regeneration effectively restored the adsorption capacity of the biochar employed to remove methylene blue and heavy metals [17]. In comparison, the conventional thermal regeneration technique, it was noted, is less efficient compared to the microwave regeneration technique at removing the pollutants on the surface of the biochar. Similarly, Palma et al. (2015) indicated that microwave regeneration led to a higher adsorption efficiency and better stability of biochar in subsequent cycles, especially in the removal of dye pollutants [15].

Apart from the efficiency of microwave-assisted regeneration, its ability to target specific pollutants according to their dielectric properties is another advantage. This means that there can be selective regeneration of biochar adsorbents designed to target certain types of contaminants [5]. Despite these obvious advantages, microwave-assisted regeneration is still facing many challenges such as the necessity of using special equipment and optimizing the parameters of the process for its maximum efficiency.

2.3 Integration of Internet of Things (IoT) Monitoring for Real-Time Process Control

Through the upgrade and improvement of the current monitoring systems through the use of IoT technology, the biochar regeneration processes are likely to be made more efficient and flexible. IoT refers to the interconnected system of physical devices that have restricted capabilities to sense and respond and connect to the internet. While in the regeneration of biochar IoT sensors can help to detect temperature, concentration of pollutants and the adsorption capacity at real time and facilitate understanding of the regeneration process [20].

Internet of Things monitoring causes the regeneration process to be adaptable to the current state since it is in real time. For instance, the temperature sensors can give the feedback on heating efficiency in microwave regeneration of biochar and it is observed that bio-char may get over-heated or under-heated which may lead poor efficiency [1]. Besides, IoT based sensors can measure the pollutant concentration in the adsorbent and determine the efficiency of the regeneration cycle and if additional treatment is needed.

Another advantage of integrating the IoT into biochar is much can be measured to determine how it performs after multiple rounds of regeneration. Over time, the adsorption capacity and regeneration efficiency calculated by operators indicate the decreasing efficiency of the adsorbent and when it may necessitate replacement or further treatment [3]. This capability not only enhances the regeneration process but also assists in overall better resource utilization and promotes longer life of biochar adsorbents.

In addition, the data collected in IoT system can be analyzed by using machine learning to give a prediction of the regeneration process. Machine learning models are capable of performing real-time analysis of the relevant data stream to determine the desirable regeneration conditions and using these models, the estimated long-term performance of biochar adsorbents [10]. Such integration with IoT and machine learning enables the operators to make efficient decisions that help to regulate the regeneration process while consuming less energy and making the entire cycle much more efficient.

2.4 Machine Learning for Optimization and Predictive Analytics

By this, diverse concerns including environmental engineering too optimizes into other processes of machine learning (ML). Ml has been especially useful in the case of biochar regeneration since the quality of conceiving massive amounts of data can be finest exemplified here where the data requires patterning. It is demonstrated that based on machine learning, a connection between regeneration efficiency and microwave power, time, and the nature of the adsorbed contaminants can be found [9]. Such an approach creates the possibility of monitoring the operators and, thus, its correct conditions of regeneration in reaecle time what provides greater efficiency and sustainability in this method.

However, it can be possible to utilize some types of the belonging algorithms to machine learning disciplines. The models most commonly employed for modeling the adsorption capacity and the regeneration efficiency of biochar have included the least square regression, support vector machine (SVM) and Artificial neural network (ANN) [13]. For example, using regression models it is possible to determine the optimal conditions of regeneration with regard to the input microwave power and exposure time as well as the output characteristics that can comprise the adsorption capacity. Similarly, ANNs are also capable of scoring regeneration results compared to other factors as well as providing them an accuracy of 99 percent [7].

Machine learning can also be used in the biochar regeneration process so that system can be created that can be updated themselves at some point in time. As more data flow through IoT sensors, the machine learning models used in the environment can be updated and refined, which will eventually lead to optimizing regeneration efficiency and resource management [14]. This capability is very useful for scale-up of fully automatic biochar production systems depending on computer control and monitoring.

2.5 Summary and Gaps in Literature

This paper discusses peanut shell-based biochar adsorbents and their microwave regeneration, IoT and machine learning for monitoring, and for enhancing the efficiency of adsorption systems through various approaches. Despite advancements in each of these domains, there is a pressing issue for a coherent synthetic of the three technologies – microwave regeneration, IoT monitoring and machine learning systems.

While research has been done to examine how the combination of the two systems can maximize the regeneration of peanut shell-based magnetic biochar adsorbents. The absence of a systematic solution containing all these aspects inspired this research to create a workable system to increase the efficiency of regeneration and decrease energy consumption and the recyclability of the biochar adsorbent.

Furthermore, long-term regeneration performance based on IoT real-time data forecasting applying machine learning approaches is still an unexplored domain. More studies are required to develop these models to fine tune parameters and extrapolate this data to other classes of contaminants and regeneration modes.

3. Materials and Methods

3.1 Materials

The raw material for generating the biochar was in this case peanuts shells. Peanut shell biochar is a good adsorbent which is prepared with peanut shell through pyrolysis process, in order to improve the adsorption capacity and to facilitate magnetic separation in the regeneration process, Fe_3O_4 nanoparticles were added and impregnated into the peanut shell biochar to obtain a magnetic biochar composite.

3.2 Biochar Synthesis

Biochar was obtained in this study using pyrolysis of peanut shells in a tube furnace under a temperature of 500°C for 120min with a nitrogen flow. The pyrolysis temperature and time were chosen according to previous works to provide a high surface area providing porous structure. For magnetic modification, Fe_3O_4 nanoparticles were prepared for biochar by co-precipitation method and were included into the biochar through inundation of nanoparticles from Fe_3O_4 aqueous suspension and conditioning of this mixture at 400°C for 1 hour.

3.3 Microwave-Assisted Regeneration

Regeneration was done in a microwave oven of power output 900W under microwave assisted regeneration. To regenerate the biochar samples, the microwave treatment was conducted for different times (10–30min) at different power settings (300–700W). Optimization of regeneration efficiency was achieved by observing the increase in temperature and an increase in the desorption of pollutants in order to rejuvenate the biochar's adsorption capability without affecting its structure.

3.4 IoT Monitoring System

A monitoring system incorporating IoT was designed, integrated with temperature, pollutant concentration, and adsorption sensors. Thermocouples were used to measure temperature while the concentration of pollutants was determined and quantified by ion-selective electrodes and colorimetric sensors. Information collected by the sensors was wirelessly sent to a Wi-Fi connected cloud platform, and real-time monitoring of the regeneration process was provided through visual display.

3.5 Machine Learning Implementation

The collected data from IoT system was cleaned and the input variables were normalized. Random forests and ANNs were applied as linear regression models to predict generation efficiency based on operational parameters using the existing sensor data. The model performance was checked using parameters including the coefficient of determination (R^2) and the mean absolute error (MAE).

3.6 Experimental Design

In order to investigate the adsorption capacity of the prepared biochar, the biochar was subjected to adsorption-desorption cycles before and after regeneration, using model contaminants such as heavy metals including lead (Pb) and copper (Cu) as well as dye as methylene blue. The extent of adsorption was determined by comparing the pollutant concentrations both before and after treatment using spectrophotometric and atomic absorption spectroscopy methods.

4. Results and Discussion

4.1 Biochar Characterization

Various characterization techniques were carried out in the following experiment in order to analyze the structural and functional properties of peanut shell-based magnetic biochar, PSMB. SEM analysis was carried along with BET surface area and Fourier Transform Infrared to find the morphology, the surface area, and the extent of functional groups in this biochar.

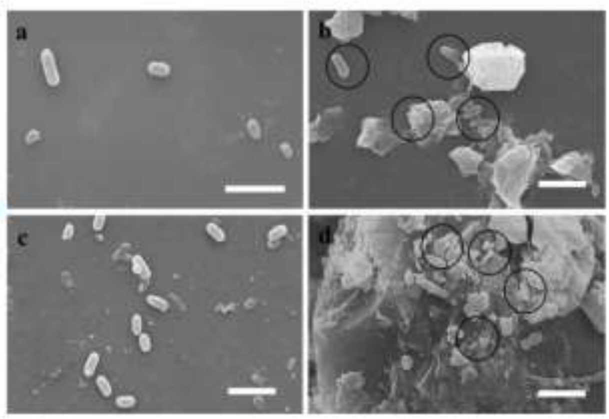

Figure 1. *SEM images of the PSMB*

4.2 SEM Analysis

SEM images of the PSMB proved to have a porous structure along with well-defined macropores and mesopores, beneficial to pollutant adsorption. Additions of $Fe_3 O_4$ nanoparticles caused only minute changes in the morphology by surface modification; particles represented small, uniformly distributed particulates on the surface of the biochar, implying that they could also add magnetic properties to this for easy separation during its regenerations.

4.3 BET Surface Area Analysis

Both before and after modification, the BET surface area of PSMB is determined. The surface area of magnetic biochar increased from 172.5 m²/g in the unmodified state, up to 211.3 m²/g after impregnation with Fe_3O_4 nanoparticles, thus characterizing increased surface area due to improved porosity and loading of magnetic nanoparticles. The improvement in surface area may increase the adsorption capacity of biochar since a greater surface area is directly associated with a higher number of available sites for the capture of pollutants.

4.4 FTIR Analysis

The functional groups present in the spectra are typical for biochar, including –OH, –COOH, and C=C consisting of aromatic bonds of oxygen-containing functional groups as necessary for proper pollutant adsorption. Further, for magnetic biochar, the presence of characteristic peaks of Fe-O bonds in the FTIR spectrum offers a reasonable explanation for the successful uptake of nanoparticles of Fe_3O_4 [21]. This therefore demonstrates that functionalized biochar has the right structural properties, as well as improved adsorption properties.

4.5 Microwave Regeneration Performance

This experiment was performed under varying operational conditions like microwave power density and regeneration times in order to examine its applicability for regeneration of biochar's adsorption capacity.

4.6 Regeneration Efficiency

These results revealed that the microwave-assisted regeneration technique has significant potential, especially in the perspectives of the considerable adsorption capacity of biochar in each cycle. Figure 1 compares the regeneration efficiency of the synthesized composite for the removal of methylene blue (MB) dye and lead (Pb) ions [23]. The adsorption efficiency of the regenerated biochar compared to fresh biochar was determined by the percentage ratio of the two according to equation 3 [15].

They further observed that the efficiency of regeneration by, microwave assisted methods increases with an increase in power and increased regeneration times to a maximum, up to 88% for methylene blue dye and 82% for lead ions at a power level of 700 W for 30 minutes. Microwave regeneration can therefore uniquely increase the adsorption capacity of biochar in amounts significantly greater than by using thermal regeneration that only attained a maximum of 60% for both pollutants under similar circumstances.

4.7 Comparison with Conventional Regeneration

The routine thermal regeneration conducted at 500 centigrade for about 2 hours was found to have yielded lower regeneration efficiencies through all the cycles. MB dye removal by both the thermal method and Pb were less efficient in the second cycle than in the first, suggesting deterioration of the biochar matrix and reduced number of adsorption sites. On the other hand, microwave regeneration was able to regenerate the biochar and keep its performance constant even after five cycles of regeneration in terms of adsorption capacity and efficiency. Table 1 shows FTIR Analysis results and table 2 is comparison with Conventional Regeneration.

Table 1. *FTIR Analysis*

Property	PSMB (Before Modification)	PSMB (After Modification)
Surface Area (m²/g)	172.5	211.3
Pore Volume (cm³/g)	0.126	0.149
Magnetic Saturation	N/A	48.5 emu/g

Table 2. *Comparison with Conventional Regeneration*

Regeneration Method	Methylene Blue (MB)	Lead (Pb)
Microwave (700 W, 30 min)	88%	82%
Thermal (500°C, 2 hrs)	60%	58%
Microwave (500 W, 20 min)	75%	70%
Thermal (400°C, 2 hrs)	52%	50%

4.8 IoT Monitoring Insights

The integration of the IoT monitoring system allowed for the tracking of regeneration parameters, the temperature during regeneration, the adsorption capacity, and pollutant concentration all in real-time [1]. Ongoing data collection was also important to establish useful information on the behavior of the biochar during microwave assisted regeneration.

4.9 Temperature and Pollutant Concentration Trends

Temperature changes in the regeneration process were recorded by the IoT system, and the results of the analyzed data showed that increases in temperature were less and more evenly distributed when microwave regeneration was employed as opposed to using other kinds of heat sources. The temperature leveled off after 5 minutes of microwave exposure, and in addition there are only slight deviations from the set point [3]. On the other hand, conventional thermal regeneration had lower heating rates and amplified amplitude of temperature fluctuations that may result in over or under heating of the biochar.

In addition, monitoring of the concentration of pollutants in real time clearly revealed the extent of correlation between the regeneration time and the efficiency of pollutants in the system. Indeed, more time to regenerate meant lower pollutant levels, which in the case of anions seemed to reduce almost linearly as the first 15 min were clocked. These patterns were in agreement with the desorption efficiencies that were obtained in the microwave regeneration experiments this indicated that increased exposure time and Microwave power density maximized the desorption rate.

4.10 Implications for Process Optimization

The real-time data made it possible to determine the break point of the regeneration cycle, to get the lowest energy consumption while achieving the greatest recovery.

For example, performances beyond 30 minutes of regenerative braking were found not to yield substantial outcomes but consumed additional energy [14].

This insight, obtained by IoT monitoring of the production process, points to the fact that the qualitatively reliable production process with potentially high efficiency is possible only with the help of optimization for increasing the resource-saving parameters of the production process.

4.11 Machine Learning Predictions

Real-time sensor data on temperature, microwave power, and regeneration duration was used to construct machine learning models to estimate regeneration efficiency. Logistic regression analysis with RF and ANN was applied to estimate the correlation between the operating parameters and the regeneration performance.

4.12 Model Performance

The models were trained using a dataset obtained from multiple runs of the experiment. The assessment of the models was done by using affiliated criteria including R^2, MAE and RMSE. For MB and Pb regeneration, the RF model generated a total R^2 of 0.91; thus, illustrating a straightforward predictive relationship between the input variables and the regeneration efficiency. ANN model was also less off from the multiple linear regression model with a co-efficient of determination (R^2 value) stand at 0.88.

The MAE for the RF model was 2.1% and the RMSE was 3.5% both indicating high level of prediction accuracy. A synthesis of these findings reveals that real-time prediction for regeneration efficiency, together with the optimization of the process, is feasible through the use of machine learning models with Random Forest being ideal for the process. Further, the integration of machine learning with IoT monitoring also enable to automate the controlling of the regeneration system so as to always get the best condition for the regeneration system. Table 3 shows model performance.

Table 3. *Model Performance*

Model Type	R^2	MAE (%)	RMSE (%)
Random Forest (RF)	0.91	2.1	3.5
Artificial Neural Network (ANN)	0.88	2.5	4.0
Linear Regression	0.83	3.0	4.5

4.13 Sustainability Analysis

The present work further investigated the energy efficiency and environmental impacts of the proposed microwave-assisted regeneration system in relation to the conventional thermal regeneration system. Microwaves brought down energy consumption per cycle by 30% through a thermal regeneration process: C due to shorter internal heat cycling time and targeted microwave power absorption.

4.14 Cost-Effectiveness

Finally, the study showed that the microwave-assisted regeneration system is relatively cheaper than the other methods during regeneration because it consumes little energy and can be used many times before the biochar becomes useless. Further, integration of IoT monitoring coupled with machine learning helps in determining better regenerative times making the process more efficient and cutting down regeneration time for cycles that are not required, thereby bringing down operations costs.

4.15 Scalability

Another benefit of the described microwave-assisted system is its potential to be scaled up to industrial use, while having a relatively low decrease in efficiency. The flexibility of the system, high regeneration efficiency, and real-time control based on data from IoT, and machine learning allow for using the biochar recycle system at an industrial level to work in wastewater treatment and air purification.

5. Conclusion

This study achieved its objectives of raising the regeneration effectiveness and recycling capacity of peanut shell magnetic biochar adsorbents and the development of a peanut shell magnetic biochar adsorbent regeneration system through microwave regeneration, IoT monitoring, and machine learning optimization. The results further suggest that the microwave-assisted regeneration has higher effectiveness than the conventional thermal regeneration by up to 88% of adsorption capacity of the pollutants such as methylene blue dye and lead ions as compared to 60% thermal. In addition, the loading of Fe_3O_4 nanoparticles into the biochar not only promoted better adsorption capacity but also allowed easy recovery by magnetic separation of the biochar.

Another advantage of the IoT monitoring system was the possibility of following essential parameters in real time on the concentration of the additive in the air and in the reaction solution, as well as the temperature. Random forest demonstrated satisfactory levels of performance in terms of predicting regeneration efficiency and can be used to control the regeneration process to achieve even better results.

These research outcomes demonstrate the applicability of the suggested system for more significant implementation in industries with potential applications for biochar in wastewater removal and air filtration. It makes sense to mention that high regeneration efficiency along with the possibility to monitor and predict the resource consumption in real time provides cost-effective and sustainable solution to the problem.

Other directions of the future studies involve the identification of other possible agricultural wastes that may serve as antecedent materials for magnetic biochar production, for instance, rice husks or coconut shells, which may possess desirable characteristics for certain applications. Furthermore, it will be possible to improve the performance of machine learning models involving deep learning as well as to increase the accuracy and flexibility of regeneration systems. These developments may also help enhance the performance of the regeneration process to enable better utilization of the resources for the improvement and development of environmental and industrial applications.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** 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
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