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Innovative utilization of dairy processing sludge for biochar production and wastewater treatment

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Abstract
This study investigates the potential of transforming dairy processing sludge (DPS) into biochar, a promising product for tackling wastewater contamination. DPS contains a variety of harmful pollutants such as antimicrobial agents, hormones, pesticides, disinfectants, and microplastics, all of which pose considerable environmental threats. Through pyrolysis, DPS can be converted into biochar, offering a sustainable solution for cleaning up polluted water. The study presents an innovative biochar production technique known as BioCharan, which utilizes a modified oil tin container for small-scale, on-site processing, operating at pyrolysis temperatures between 250°C and 350°C.The resulting biochar from DPS displayed favorable chemical properties, including 40.067% carbon, 5.354% hydrogen, and 2.743% nitrogen content. Fourier transform infrared (FTIR) spectroscopy identified the functional groups, while x-ray diffraction (XRD) analysis revealed the crystalline structures. Its high porosity and surface area enhance its ability to adsorb contaminants, making it highly effective for wastewater treatment.A filtration system combining biochar and river sand showed exceptional performance in removing pollutants, with reductions of 83.71% in total suspended solids (TSS), 66.82% in oil and grease, 42.86% in chemical oxygen demand (COD), and 31.55% in biochemical oxygen demand (BOD). Other contaminants like sulphate, phosphate, nitrate, total Kjeldahl nitrogen (TKN), total dissolved solids (TDS), and fluoride were also significantly diminished. Additionally, the pH of the treated water increased from 6.30 to 6.74, reflecting the biochar's ability to neutralize acidic conditions. This method not only provides an effective way to treat wastewater but also offers an eco-friendly solution for the disposal of DPS.

Keywords: *Biochar, BioCharan, Dairy processing sludge, Pyrolysis, Wastewater treatment*

Introduction

The global dairy industry has shown consistent growth, with a projected market value of $649.9 billion in 2025, expected to reach $813.6 billion by 2030, growing at a compound annual growth rate (CAGR) of 4.60% (Mordor Intelligence, 2025). However, this expansion has brought environmental challenges, particularly the discharge of organic and inorganic pollutants into aquatic systems, leading to wastewater generation and reduced freshwater availability (Khurshid et al., 2021). India, the world's leading milk producer, contributes over 24% of global output, with per capita milk availability rising from 130 grams per day in 1950-51 to 459 grams per day in 2022-23 (BAHS, 2023). Dairy processing sludge (DPS), a byproduct of milk production, poses significant environmental issues due to its high organic matter and nutrient content. Traditional disposal methods such as land-filling and land application risk nutrient runoff and soil contamination, highlighting the need for more sustainable disposal strategies (Ashekuzzaman et al., 2019). Moreover, DPS can contain contaminants such as pesticides, antibiotics, and hormones, which accumulate during wastewater treatment and enter the waste stream (Montgomery et al., 2020; Fischer et al., 2011). Disinfectants used in

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dairy processing, along with micro-plastics and persistent organic pollutants (POPs), further contribute to wastewater contamination and environmental degradation (Phuong et al., 2016; Jones and Voogt, 1999). Biochar, a carbonaceous material produced through pyrolysis, has gained significant attention for its environmental applications, particularly in remediation, soil enhancement, and wastewater treatment. Its high surface area, porosity, and functional groups make it an effecttive adsorbent for pollutants. A study highlighted biochar's potential in mitigating greenhouse gases as the production of biochar, in combination with its storage in soils, has been suggested as one possible means of reducing the atmospheric CO_2 concentration (Woolf et al., 2010), while another research demonstrated its efficacy in reducing contaminants in swine wastewater, particularly when combined with ozonation (Thao et al., 2023). Other studies explored biochar's integration with vermicomposting, showing reduced heavy metal content and improved plant growth (Dutta et al., 2023). Biochar derived from shellfish waste possesses remarkably high adsorption efficiency, particularly for the removal of antibiotics and heavy metals from contaminated water sources. The porous structure and surface characteristics of this type of biochar enable it to effectively capture and retain these pollutants, reducing their presence in wastewater and mitigating their harmful environmental impact (Mahari et al., 2022). Biochar has shown remarkable potential in the removal of nitrogen and phosphorus from wastewater. Studies indicate that its performance can be significantly enhanced through various modifications, such as surface functionalization and activation techniques, which improve its adsorption capacity and overall effectiveness (Zhang et al., 2020). Furthermore, extensive research has demonstrated that biochar produced from elephant grass exhibits exceptional efficiency in eliminating nitrate contaminants from wastewater, making it a promising solution for mitigating nutrient pollution in aquatic environments (Adesemuyi et al., 2020). The environmental risks associated with DPS disposal were discussed advocating for sustainable alternatives (Ashekuzzaman et al., 2019). The energy retention potential of DPS-derived biochar was validated (Kwapinska et al., 2020) and its fluoride adsorption capabilities were demonstrated (Abeysinghe and Baek, 2022). An innovative method BioCharan based on cost-effective small-scale pyrolysis for biochar production, enabled its straight forward application in wastewater treatment (Choudhary et al., 2021a, 2021b, 2022, 2023a, 2023b) and performance of biochar filter was found better or equal as compared to sand (Kaetzl et al., 2020). Studies have also emphasized biochar's effectiveness in removing contaminants such as sulfates and antibiotics from dairy wastewater (Rumjit et al., 2021; Giraldo et al., 2017). In conclusion, biochar's versatility in wastewater treatment and waste management positions it as a promising solution for environmental challenges, particularly in the dairy industry. The knowledge gap of utilizing biochar derived from dairy processing sludge itself for subsequent treatment of dairy wastewater has been noticed in the literature and hence the objectives of this study include assessing the feasibility of dairy processing sludge for production of biochar and evaluating the effectiveness of biochar in removing contaminants from dairy wastewater.

Methodology

An innovative pyrolysis technique, termed the Bio-Charan method, was employed for biochar production. The methodology encompasses biochar production, filter media design, and wastewater treatment evaluation, ensuring an integrated approach to waste valorization and pollution mitigation. The samples of dairy processing sludge were collected from the Saras Dairy Plant situated in Kota city, as shown in Figure 1(a).

Figure 1. (a) *Dairy processing sludge tank at Saras Dairy Plant, Kota;* (b) *Biochar produced from DPS*

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Biochar production

DPS was collected and processed to remove impurities before undergoing pyrolysis. The collection process involved using sterile sampling containers to ensure no external contamination. Samples were obtained from different stages of sludge processing to capture representative characteristics. Before further processing, the sludge was subjected to a series of purification steps. First, large debris and non-organic materials were removed through sedimentation and filtration. Next, the sludge was washed with deionized water to eliminate soluble contaminants. Finally, drying and sieving processes were employed to obtain a uniform sample free from unwanted coarse particles. The BioCharan method, a small-scale and cost-effective technique, was utilized for biochar production. A modified oil tin container served as the pyrolysis reactor, enabling localized production. The sludge was subjected to pyrolysis at temperatures ranging from 250°C to 350°C in a low-oxygen environment. This controlled thermal decomposition converted the organic-rich sludge into biochar with high carbon content. The biochar produced is shown in Figure 1(b). Post-pyrolysis, the material was cooled, crushed, and sieved with 200 μm mesh size to obtain uniform biochar particles suitable for experimental use.

Filter media design

A layered filtration system was developed to evaluate the adsorptive capacity of DPS-derived biochar. The filter media consisted of two primary layers: a 50 cm thick base of river sand with particle sizes ranging from 300 to 600 micrometers, and a 10 cm layer of DPS-derived biochar, as shown in Figure 2. The design aimed to optimize contact time between the wastewater and the adsorbent, enhancing the removal of contaminants. Initially, three different columns were used with different contact time and subsequently based on trial and error, 5 min was chosen as the optimized contact time. Finally, all three columns with same contact time were used to replicate 3 samples simultaneously. The layered configuration also ensured effective filtration while preventing clogging.

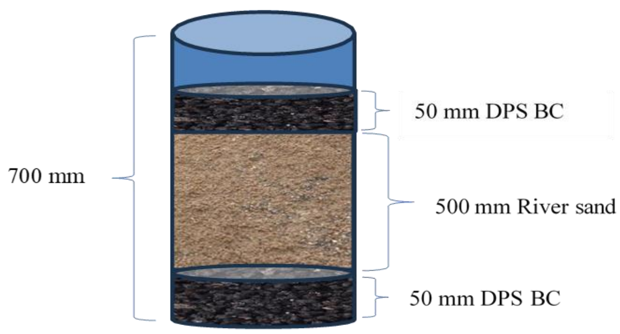

Figure 2. *Schematic diagram of filter media*

Wastewater treatment evaluation

Laboratory experiments were conducted to test the filter media's performance in treating dairy wastewater. Samples of untreated dairy wastewater were passed through the filtration system, and key water quality parameters were analyzed before and after treatment using the standard methods of measurement (APHA, 1998). The study focused on measuring reductions in total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), oil and grease, nitrate, phosphate, and fluoride concentrations. Additionally, changes in pH were monitored to assess the biochar's buffering capacity. The efficiency of the filtration system was determined by comparing pollutant concentrations in treated and untreated wastewater samples. A brief description of the standard methods is presented below:

pH measurement

Principle: pH is a measure of hydrogen ion concentration in water/wastewater and indicates whether a solution is acidic or basic.

Method: A pH meter with a glass electrode is used to determine the pH value.

Procedure:

- Calibrate the pH meter using standard buffer solutions (pH 4.0, 7.0, and 10.0).
- Rinse the electrode with deionized water and immerse it in the wastewater sample.
- Stir gently and allow the reading to stabilize.
- Record the pH value.

Total Suspended Solids (TSS)

Principle: TSS represents the solid particles suspended in wastewater, which affect water clarity and quality.

Method: Filtration through a pre-weighed glass fiber filter, followed by drying and weighing.

Procedure:

- Filter a known volume of wastewater through a pre-weighed glass fiber filter.
- Dry the filter at 103–105°C in an oven.
- Cool in a desiccator and weigh again.
- The difference in weight represents the TSS concentration in mg/L.

Total Dissolved Solids (TDS)

Principle: TDS includes all dissolved substances in

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water/wastewater, such as salts, minerals, and organic matter.
Method: Evaporation and weighing of the residual solids.
Procedure:
- Filter the wastewater sample to remove suspended solids.
- Evaporate a known volume of filtrate in a pre-weighed dish.
- Dry at 180°C until a constant weight is achieved.
- The difference in weight represents TDS concentration in mg/L.

Oil and Grease
Principle: Oil and grease are extracted from wastewater using an organic solvent and measured by weight after solvent evaporation.
Method: Solvent extraction and gravimetric analysis.
Procedure:
- Add n-hexane or another suitable organic solvent to the wastewater sample.
- Shake the sample vigorously to extract the oil and grease.
- Separate the solvent layer and evaporate it to dryness.
- Weigh the remaining residue, which represents the oil and grease content in mg/L.

Nitrate (NO_3^-) Measurement
Principle: Nitrate is determined using spectrophotometric or ion chromatography methods.
Method: Cadmium reduction method (for spectrophotometry).
Procedure:
- Convert nitrate (NO_3^-) to nitrite (NO_2^-) using a cadmium reduction column.
- React nitrite with sulfanilamide and N-(1-naphthyl)-ethylenediamine to form a pink-colored compound.
- Measure absorbance at 540 nm using a spectrophotometer.
- Compare with a calibration curve to determine nitrate concentration.

Phosphate (PO_4^{3-}) Measurement
Principle: Phosphate reacts with ammonium molybdate and ascorbic acid to form a blue-colored complex, measured using spectrophotometric method.
Method: Ascorbic acid colorimetric method.
Procedure:
- Add ammonium molybdate and ascorbic acid to the wastewater sample.
- The solution develops a blue color due to the formation of a molybdenum-phosphate complex.
- Measure absorbance at 880 nm using aspectrophotometer.
- Compare with a calibration curve to determine phosphate concentration.

Sulphate (SO_4^{2-}) measurement
Principle: Sulphate ions react with barium chloride ($BaCl_2$) to form an insoluble barium sulfate ($BaSO_4$) precipitate, which is measured turbidimetrically.
Method: Turbidimetric method.
Procedure:
- Add barium chloride solution to the wastewater sample.
- The formation of barium sulfate causes turbidity.
- Measure absorbance at 420 nm using a spectrophotometer.
- Compare with a calibration curve to determine sulphate concentration.

Fluoride (F^-) measurement
Principle: Fluoride concentration is determined using an ion-selective electrode (ISE) or a colorimetric SPADNS method.
Method: Ion-Selective Electrode Method / SPADNS Colorimetric Method.
Procedure (SPADNS Method):
- Mix the wastewater sample with SPADNS reagent.
- Fluoride reacts with zirconium dye, causing a color change.
- Measure absorbance at **570 nm** using a spectrophotometer.
- Compare with a calibration curve to determine fluoride concentration.

Biochemical Oxygen Demand (BOD)
Principle: BOD measures the amount of oxygen consumed by microorganisms during the decomposition of organic matter over a 5-day incubation period.
Method: 5-day incubation at 20°C method.
Procedure:
- Fill two BOD bottles with wastewater samples.
- Measure initial dissolved oxygen (DO) concentration using a DO meter.
- Incubate one sample for 5 days at 20°C in the dark.
- Measure final DO after incubation.
- BOD (mg/L) = Initial DO - Final DO.

Chemical Oxygen Demand (COD)
Principle: COD measures the oxygen required to oxidize organic and inorganic matter using a strong oxidizing agent (potassium dichromate, $K_2Cr_2O_7$).
Method: Closed reflux, colorimetric method.
Procedure:
- Digest the wastewater sample with acidified potas-

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sium dichromate ($K_2Cr_2O_7$) and silver sulfate in a reflux system at 150°C for 2 hours.
- Cool and add ferroin indicator.
- Measure absorbance at 600 nm using a spectrophotometer.
- Compare with a calibration curve to determine COD concentration.

Total Kjeldahl Nitrogen (TKN)

Principle: TKN measures the total organic nitrogen and ammonia in wastewater by acid digestion, distillation, and titration.
Method: Kjeldahl digestion, distillation, and titration.
Procedure:
- Digest the wastewater sample with concentrated sulfuric acid (H_2SO_4) and a catalyst (copper or selenium).
- Convert organic nitrogen to ammonium sulfate.
- Neutralize with sodium hydroxide (NaOH).
- Distill the sample and trap ammonia in boric acid solution.
- Titrate with standard sulfuric acid (H_2SO_4) to determine nitrogen concentration.

Physical and chemical analysis of the dairy processing sludge

Physicochemical properties of the DPS-derived biochar, such as porosity, surface area, and elemental composition, were characterized using techniques like Fourier Transform Infrared (FTIR) spectroscopy and X-ray Diffraction (XRD). These analyses provided insights into the biochar's adsorption mechanisms and its potential to remove contaminants. These analyses were performed by SAIF (Sophisticated Analytical Instruments Facility) at Indian Institute of Technology, Mumbai. A brief description of these methodologies is given below:

Elemental analysis (CHNS analysis)

1. Sample Preparation

Drying: Biochar samples are dried at 105°C for at least 24 hours to remove moisture.
Grinding: The dried biochar is ground into a fine powder using a ball mill or mortar and pestle to ensure uniform particle size.
Weighing: A small amount (~2-5 mg) of the powdered biochar is precisely weighed in a tin capsule (for CHNS analysis) or a ceramic crucible (for oxygen analysis).

2. CHNS analysis (Carbon, Hydrogen, Nitrogen, Sulfur)

Instrument Used: Elemental Analyzer
Process:
- The weighed sample is introduced into a high-temperature combustion chamber (~900–1000°C).
- The sample is oxidized in the presence of pure oxygen, converting elements into their gaseous forms:
$C \rightarrow CO_2$ (carbon dioxide)
$H \rightarrow H_2O$ (water vapor)
$N \rightarrow NO_x$ (converted to N_2 gas)
$S \rightarrow SO_2$ (sulfur dioxide)
- The gases are separated using a gas chromatography (GC) column and detected using a thermal conductivity detector (TCD).
- The instrument provides the percentage composition of C, H, N, and S in the sample.

3. Oxygen analysis (O)

Instrument Used: Oxygen Analyzer
Process:
- The sample is combusted in a pyrolysis furnace at 1200–1400°C in an inert atmosphere (helium or nitrogen gas).
- Oxygen is converted into carbon monoxide (CO).
- The CO gas is detected using infrared (IR) absorption or TCD.
-The percentage of oxygen is calculated based on CO detection.

4. Data interpretation

The results provide the elemental composition of biochar in weight percentages (%).
The elemental C/N ratio is useful in understanding biochar stability and nutrient content.
High carbon content indicates good porosity and adsorption potential.
The presence of oxygen and hydrogen gives insight into the functional groups present on the biochar surface.

Fourier Transform Infrared (FTIR) spectroscopy

FTIR spectroscopy is a widely used analytical technique to identify functional groups present on the surface of biochar. The method involves passing infrared radiation through the sample and measuring the absorption at different wavelengths. The procedure includes the following steps:
Sample Preparation: The biochar sample is ground into a fine powder and mixed with potassium bromide (KBr) to form a pellet or analyzed directly using an attenuated total reflectance (ATR) accessory.
Spectral Measurement: Infrared radiation is passed through the sample, and the absorbance at different wavelengths is recorded.
Data Analysis: The resulting spectrum is analyzed to

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identify peaks corresponding to functional groups such as hydroxyl (-OH), carboxyl (-COOH), carbonyl (C=O), and aromatic structures. These functional groups play a crucial role in the adsorption capacity of biochar, influencing its interaction with pollutants in wastewater treatment.

X-ray Diffraction (XRD) analysis

XRD analysis is employed to determine the crystalline and amorphous phases in biochar. This technique uses X-rays to investigate the structural composition of biochar by analyzing the diffraction pattern produced when the sample is exposed to X-ray beams. The procedure consists of the following steps:
Sample Preparation: The biochar sample is finely ground and placed on an XRD sample holder.
X-ray Exposure: The sample is subjected to X-ray radiation at different angles, and the diffracted rays are recorded.
Pattern Analysis: The diffraction pattern is analyzed to determine the presence of crystalline phases such as quartz, calcite, and other inorganic compounds. The analysis also helps assess the degree of graphitization in biochar, which impacts its stability, conductivity, and adsorption behavior in wastewater treatment applications.

Results and discussion

Elemental analysis reveals that carbon is the primary component, constituting 40.067% of the biochar, which is essential for its adsorption capacity. Nitrogen (2.743%) and hydrogen (5.354%) are also present, reflecting the retention of nitrogenous compounds and volatile organic matter from the original sludge. The high carbon content indicates the biochar's potential for binding contaminants during filtration, making it effective for wastewater treatment. Similar findings have been reported in a study in which biochar having high carbon content exhibited superior adsorption properties, enhancing its application in wastewater treatment (Ahmad et al., 2014). Fourier-transform infrared (FTIR) spectroscopy is used to identify functional groups in the biochar. The FTIR spectrum reveals a mix of hydroxyl groups (O-H), aliphatic hydrocarbons (C-H), and aromatic structures (C=C), which are crucial for the biochar's adsorption capabilities. The presence of oxygenated groups such as alcohols and esters further enhances its pollutant-removal properties. These findings are supported by a previous study with similar functional group compositions in biochar, contributing to its affinity for heavy metals and organic contaminants and improving its pollutant-removal efficiency (Li et al., 2017). X-ray diffraction (XRD) analysis shows a mixture of graphitic and amorphous carbon in the biochar. The prominent peak at 26.5° suggests graphitic carbon, indicating a significant degree of carbonization. The broad peaks between 20° and 30° indicate amorphous carbon, typical of biochar produced at lower pyrolysis temperatures. This combination of graphitic and amorphous carbon enhances the biochar's stability and porosity, which is beneficial for absorbing a wide range of contaminants. These findings align with an earlier study, confirming that biochar's structural composition plays a vital role in determining its adsorption efficiency and overall performance in wastewater treatment systems (Zhao et al., 2018). Hence, the study demonstrates that biochar derived from DPS is an effective, sustainable, and cost-efficient material for wastewater treatment. The biochar's unique composition and functional properties make it an ideal candidate for removing pollutants from dairy wastewater. Various physico-chemical properties of both the biochar and the wastewater are analyzed before and after filtration, and the results are presented in Table 1 to evaluate the contaminant removal performance.
The results show a general reduction in most contaminants, with the highest removal efficiency observed for total suspended solids (TSS) at 83.71%, and the lowest for fluoride at 1.72%. Other parameters, such as oil & grease, nitrate, phosphate, sulphate, BOD, COD, and TKN, also show significant reductions, though the extent varies. The pH increased by 6.98% indicating potential alkalization. The study explores the effectiveness of a biochar-based filter media in treating dairy processing wastewater and the results are also compared with similar studies available in the literature.

pH Increase: The increase in pH from 6.30 to 6.74 in the present study reflects biochar's buffering capacity. Similar increases in pH have been observed in dairy wastewater treatment, where biochar-based filters released alkaline substances that neutralize acidity (Mohan et al., 2012).

Total Suspended Solids (TSS) Reduction: The reduction of TSS from 614 mg/L to 100 mg/L aligns with other studies where biochar filters have been effective in reducing particulate matter, showing a removal efficiency of up to 86% for suspended solids (Visiy et al., 2022; Thao et al., 2023).

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Table 1. *Physicochemical parameters of dairy wastewater sample before and after treatment*

S. No.	Parameter	Pre-treatment observation (in mg/L except pH)	Post-treatment observation (in mg/L except pH)	% Removal
1	pH	6.30 ± 0.15	6.74 ± 0.12	-6.98
2	Total Suspended Solids (TSS)	614 ± 25	100 ± 10	83.71
3	Total Dissolved Solids (TDS)	5624 ± 180	4965 ± 160	11.72
4	Oil and Grease	434 ± 22	144 ± 15	66.82
5	Nitrate	64 ± 3.5	48 ± 2.8	25
6	Phosphate	3.0 ± 0.2	2.2 ± 0.1	26.67
7	Sulphate	52 ± 2.8	36 ± 2.4	30.77
8	Fluoride	1.74 ± 0.05	1.71 ± 0.04	1.72
9	Biochemical Oxygen Demand (BOD)	374 ± 15	256 ± 12	31.55
10	Chemical Oxygen Demand (COD)	1344 ± 50	768 ± 35	42.86
11	Total Kjeldahl Nitrogen (TKN)	6.8 ± 0.4	5.2 ± 0.3	23.53

Total Dissolved Solids (TDS) Reduction: The 11.72% reduction in TDS is consistent with findings from similar research, where biochar has been used to remove dissolved contaminants, improving overall water quality (Mohan et al., 2012; Visiy et al., 2022).

Oil and Grease Removal: A 66.82% reduction in oil and grease concentrations observed in this study is similar to the findings of other studies whichreported a significant reduction of oil and grease in wastewater due to biochar's high surface area and adsorptive properties (Sudhir and Prasanna, 2023).

Nutrient Removal (Nitrate and Phosphate): The reductions in nitrate (25%) and phosphate (26.67%) align with other studies, where biochar effectively adsorbed nitrogenous and phosphate compounds, contributing to nutrient removal and improving water quality (Janyasupeb and Jampeetong, 2022).

Sulphate Reduction: The 30.77% decrease in sulphates is consistent with biochar's known ability to remove sulphate ions, as demonstrated in other studies where biochar facilitated effective sulphate removal (Panghal et al., 2024).

Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) Reduction: The reductions of 31.55% in BOD and 42.86% in COD are comparable to results found by other studies where biochar was shown to reduce organic pollutants in wastewater, thereby lowering BOD and COD levels (Yi et al., 2020; Chaoukiet al., 2021; Sudhir and Prasanna, 2023).

Total Kjeldahl Nitrogen (TKN) Reduction: The reduction of 23.53% in TKN corresponds with findings from other studies where biochar was effective in removing nitrogen compounds from wastewater, contributing to lower nutrient loads (Janyasupeb and Jampeetong, 2022; Panghal et al., 2024). Overall, the results from the DPS biochar-based filter media treatment of dairy processing wastewater are consistent with various studies in the literature; highlighting biochar's potential for improving water quality by removing multiple contaminants.

Conclusions

This study highlights the successful production of biochar from dairy processing sludge using the BioCharan pyrolysis method at temperatures between 250-350°C. The biochar produced exhibited favorable physicochemical properties, with an elemental composition of 40.067% carbon, 5.354% hydrogen, and 2.743% nitrogen. The study also utilized FTIR (Fourier Transform Infrared) and XRD (X-ray Diffraction) analyses, confirming the structural and functional suitability of the biochar as an effective adsorbent for wastewater treatment. The biochar's performance as an adsorbent in wastewater treatment was evaluated, showing significant reductions in various pollutants. Notably, the filter system demon-

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strated removal efficiencies of 83.71% for Total Suspended Solids (TSS), 66.82% for oil & grease, 42.86% for Chemical Oxygen Demand (COD), 31.55% for Biological Oxygen Demand (BOD), 30.77% for sulphate, 26.67% for phosphate, 25% for nitrate, 23.53% for Total Kjeldahl Nitrogen (TKN), 11.72% for Total Dissolved Solids (TDS), and 1.72% for fluoride. Additionally, the pH of the treated wastewater increased from 6.30 to 6.74, a 6.98% rise, suggesting the biochar's ability to buffer acidic conditions in wastewater. The findings suggest that biochar derived from dairy processing sludge could serve as a sustainable, dual-purpose material for both waste valorization and environmental remediation. The biochar production process is influenced by various factors, including the type of livestock waste, pyrolysis temperature, duration, and potential modifications such as activation techniques. Future research is recommended to refine these pyrolysis conditions, optimize biochar modifications to improve its adsorption capacity, and develop scalable production methods for industrial applications. Long-term studies, life cycle assessments, and comprehensive cost-benefit analyses are also essential to assess the sustainability and economic feasibility of large-scale biochar utilization in wastewater treatment. Several potential future research directions are outlined, including optimization of biochar production and modifications to improve pollutant removal, especially for TDS and specific contaminants; scaling up biochar production for industrial wastewater treatment and assess its long-term durability and cost-effectiveness, and exploring biochar's potential as a soil amendment and evaluate its environmental and economic impacts through life cycle assessments. These areas of research could significantly advance biochar as an effective, sustainable, and economically viable solution for wastewater treatment and environmental management.

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