

ORIGINAL RESEARCH ARTICLE

Treatment of antibiotic fermentation effluents using charcoal adsorption

Salah Mohammed Aleid^{1*}, Siddig H. Hamad¹, and Sam Al-Dalali^{2,3*}

¹Department of Food and Nutrition Sciences, College of Agriculture and Food Sciences, King Faisal University, Al Ahsa, Eastern Province, Saudi Arabia

²School of Food and Health, Guilin Tourism University, Guilin, Guangxi, China

³Department of Food Science and Technology, Faculty of Agriculture and Food Science, Ibb University, Ibb, Yemen

*Corresponding authors: Salah Mohammed Aleid (seid@kfu.edu.sa);
Sam Al-Dalali (salihsam4@gmail.com)

Received: June 15, 2025; Revised: August 3, 2025; Accepted: August 11, 2025; Published online: August 28, 2025

Abstract: Activated carbon (AC) is widely used as an adsorbent in multiple sectors, including the pharmaceutical, chemical, beverage, and food industries. This study investigates the removal of organic materials from antibiotic fermentation effluents using powdered AC at various temperatures. Pristinamycin was synthesized by cultivating *Streptomyces pristinaespiralis* with date syrup as a glucose substitute. The fermentation effluent was treated with activated charcoal to reduce biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Optimal removal was achieved with 30 mg/L of activated charcoal at 25°C. Under these conditions, COD decreased by approximately 52%, and 5-day BOD decreased by approximately 9.1% compared to the untreated effluent. Increasing the AC dose enhanced the efficiency of COD removal. Based on these findings, AC adsorption of antibiotic pristinamycin from wastewater appears to be a viable treatment option.

Keywords: Antibiotic fermentation; Biochemical oxygen demand; Chemical oxygen demand; Adsorption; Charcoal; Pristinamycin

1. Introduction

Wastewater produced by biopharmaceutical facilities contains high concentrations of organic and microbial contaminants, substantially increasing the biochemical oxygen demand (BOD) and chemical oxygen demand (COD) of the effluent. Cations such as potassium (K⁺), sodium (Na⁺), magnesium (Mg²⁺), and calcium (Ca²⁺) ions significantly complicate the treatment process.^{1,2} Adsorption is among the most commonly employed techniques for treating antibiotic waste effluents in the industry. Adsorption of lactic or other organic acids from fermentation broth at room temperature has been

investigated using several anionic adsorbents, including IRA-92,³ IRA-67,⁴ IRA-425,⁵ and IRA-400,⁶ as well as non-polar adsorbents such as activated carbon (AC).^{4,7}

AC is widely used as an adsorbent in multiple sectors, including the pharmaceutical, chemical, beverage, and food industries.^{8,9} Its widespread use is attributed to its cost-effectiveness, simplicity, non-toxicity, and low energy requirements.⁸ Adsorption onto AC has demonstrated significant effectiveness in purifying industrial wastewaters and improving effluent quality from biologically treated facilities.⁹ The extensive use of AC in water and wastewater treatment is attributed to its vast surface area (approximately 1,100 m²/g) and

highly porous structure. Its non-polar nature under varied pH conditions also confers a unique affinity for organic acids such as lactic, acetic, and butyric acids.^{7,10}

Pradhan *et al.*¹¹ conducted an experimental study on the separation of lactic acid (<10 g/L) from a model fermentation solution using granular AC. Thermodynamic analysis demonstrated that optimal lactic acid adsorption occurs at a pH below the pKa of lactic acid (3.86) through a physical adsorption mechanism. The optimal conditions for using AC to remove amoxicillin and tetracycline (TC) have also been examined.^{12,13} Umrantezcanun *et al.*¹² reported a maximum COD removal of 91.2% at 20°C and pH 5, using 0.15 g of AC and an initial TC concentration of 100 mg/L after a 24-h adsorption period. Ranaweera *et al.*⁸ applied AC adsorption with 200 mL of TC solution and 200 mg of AC, achieving a high TC removal efficiency (>95%) from synthetic wastewater. Spit *et al.*¹⁴ investigated the effects of coagulation, ozonation, and granular AC filtration on the removal of small organic pollutants from treated wastewater, with particular focus on pharmaceutical residues. Abbas and Trari¹³ identified the optimal conditions for amoxicillin removal as a dose of 0.124 g, a temperature of 45°C, and pH 5.03, using the desirability function.

Mullai and Rajesh¹⁵ examined the post-treatment of antibiotic wastewater using AC as the adsorbent. The findings indicated that the color removal efficiency of the wastewater increased over time, reaching equilibrium after 120 min with 100 mg of AC under shaking conditions. The maximum COD removal efficiency achieved was 43.3% with 100 mg of AC after 120 min. Zhanga *et al.*¹⁶ employed an integrated approach combining powdered AC with ultrafiltration and reverse osmosis to treat waste liquor generated from TC production. The study demonstrated that the performance of ultrafiltration–reverse osmosis was enhanced by incorporating AC into the waste liquor, with an optimal concentration of 8.0 mg/L.

BOD represents the total dissolved oxygen (DO) required by microorganisms to decompose organic material in a water sample. Elevated BOD levels indicate reduced oxygen availability in the analyzed water body.¹⁷ DO in water samples contributes to the degradation of both organic and nitrogenous matter. The BOD curve comprises two distinct components: Carbonaceous BOD and nitrogenous BOD. The initial 5 days' demand primarily reflects carbonaceous BOD, which constitutes approximately 70% of the total BOD. The 5-day BOD (BOD_5) value generally indicates

the oxygen demand associated with organic matter decomposition.¹⁸

In our previous study, the antibiotic pristinamycin was synthesized by cultivating *Streptomyces pristinaespiralis* with date syrup as a glucose substitute. In this study, the effluent from this process was continuously treated with different charcoal concentrations at various temperatures to reduce its BOD and COD.

The present study aims to remove organic materials from the antibiotic fermentation effluent using powdered AC at varying concentrations (10, 20, and 30 mg/L) and temperatures (25, 50, and 75°C), and to determine the optimal concentration and temperature for effective removal.

2. Materials and methods

2.1. Samples

The antibiotic fermentation broth was collected from the fermentative bioreactors as described in our previous study.¹⁹ Samples were obtained from three different batches, with three replicates per batch for further analysis.

2.2. Determination of physicochemical properties

The pH of the sample was measured directly using a pH meter (MP512-03, Hangzhou Tuqi Instrument Co., Ltd, China). Color of the sample was analyzed using a colorimetric equipment (CR-400 Konica Minolta, Japan), and total solids were determined using a gravimetric approach, which involved drying and measuring the residue after a specified volume of material had been evaporated. Sugar content, expressed as glucose, was determined using high-performance liquid chromatography (Agilent 1260, infinity, Germany) based on the method established by Aleid,²⁰ where different concentrations of glucose were prepared to plot a calibration curve for quantification. Elemental composition was determined using atomic absorption spectroscopy (NOVA 300, USA).

2.3. Treatment of antibiotic fermentation effluents

After fermentation, the antibiotic fermentation broth was treated with three doses of AC (Sigma-Aldrich, United States [USA]) at 10, 20, and 30 mg/L, under three temperatures (25, 50, and 75°C). Nine treatments were analyzed, as presented in [Table 1](#).

2.4. Adsorption treatment

After 144 h of fermentation in a 100-L fermentor, 200 mL of pristinamycin fermentation broth was

Table 1. Three-level experimental design showing nine treatments of activated carbon dose and temperature

Treatments	Values
C ₁ T ₁	10 mg/L, 25°C
C ₁ T ₂	10 mg/L, 50°C
C ₁ T ₃	10 mg/L, 75°C
C ₂ T ₁	20 mg/L, 25°C
C ₂ T ₂	20 mg/L, 50°C
C ₂ T ₃	20 mg/L, 75°C
C ₃ T ₁	30 mg/L, 25°C
C ₃ T ₂	30 mg/L, 50°C
C ₃ T ₃	30 mg/L, 75°C

Abbreviations: C: Carbon; T: Temperature.

added to an Erlenmeyer flask containing the adsorbent material. The pH of the fermentation broth was 6.8. The mixture was heated for 120 min in a shaking water bath at 50 rpm (Gilson, USA). Samples were then collected for further analysis.

2.5. COD measurement

COD measures the amount of oxidizable organic matter in a wastewater sample. In an aqueous sample, organic and oxidizable inorganic substances are oxidized by potassium dichromate in a 50% (v/v) sulfuric acid solution. The excess dichromate is titrated with standard ferrous ammonium sulfate using orthophenanthroline ferrous complex (ferroin) as an indicator.²¹ The sample was reacted with acidic potassium dichromate in the presence of a silver catalyst and digested for 2 h at 150°C. Oxidizable organic compounds reduce dichromate ion to chromic ion. COD values are expressed as milligrams of oxygen consumed per liter of sample (mg/L).²² The COD was calculated according to the standard method (Equation I):²¹

$$COD(mg/L) = \frac{[(A-B) \times C \times 8000] - 50D}{Sample\ volume\ (mL)} \times 1.2 \quad (I)$$

where *A* is the volume of ferrous ammonium sulfate for the blank, *B* is the volume of ferrous ammonium sulfate for the sample, *C* is the normality of ferrous ammonium sulfate, *D* is the chloride correction from the calibration curve, and 1.2 is a compensation factor accounting for the extent of chloride oxidation, which differs in systems containing organic and non-organic material.

2.6. BOD measurement

The BOD₅ was measured following the standard method established by the American Public Health Association (5210 B) (<http://standardmethods.org>).²³ BOD measured in effluent samples over a 5-day incubation period at 25°C is referred to as BOD₅. The procedure involves filling an airtight bottle of the designated size with the sample until it overflows and incubating it at the specified temperature for 5 days. DO is measured at the beginning and end of incubation, with BOD calculated as the difference between initial and final DO levels.

BOD determination is an empirical test using standardized laboratory procedures to assess the relative oxygen demands of wastewater effluents and polluted waters. It is most commonly applied to assess waste loadings to treatment plants and evaluate BOD removal efficiency in these systems.²² The test quantifies the molecular oxygen consumed during a defined incubation period for the biochemical degradation of organic material (carbonaceous demand) and the oxygen utilized for the oxidation of inorganic substances, including sulfides and ferrous iron. The measurement may also quantify oxygen used to oxidize reduced nitrogen forms (nitrogenous demand), unless an inhibitor prevents their oxidation. Seeding and dilution procedures yield an estimate of BOD at a pH range of 6.5–7.5.²³

For each test bottle exhibiting a minimum DO depletion of 2.0 mg/L and a residual DO of at least 1.0 mg/L, BOD is calculated based on the following formula (Equation II):²²

$$BOD(mg/L) = \frac{(D_1 - D_2) - (S)V_s}{P} \quad (II)$$

where *D*₁ is the DO of the diluted sample immediately after preparation (mg/L), *D*₂ is the DO of the diluted sample after 5 days of incubation at 20°C (mg/L), *S* is the oxygen uptake of the seed (Δ DO/mL seed suspension added per bottle; *S* = 0 if samples are not seeded), *V*_{*s*} is the volume of seed in the respective test bottle (mL), and *P* is the decimal volumetric fraction of the sample used (1/*P* = dilution factor).

2.7. Statistical analysis

All results are presented as mean ± standard deviation. Figures were plotted using Origin 2022 (developer, country). Analysis of variance was performed using SAS version 9.1 (developer, country) to statistically compare the effects of different doses of AC combined with varying temperatures.

3. Results and discussion

3.1. Physicochemical properties

The physicochemical properties of the fermentation broth, containing organic materials and cells of *S. pristinaespiralis*, were evaluated (Table 2). The broth was semi-transparent with a creamy-yellow color. The total solids and sugars were 6.5 g/L and 3.84 g/L, respectively, while the concentrations of K⁺, Na⁺, Mg²⁺, and Ca²⁺ were 100, 150, 360, and 560 ppm, respectively.

3.2. Effects of AC dose and temperature on organic materials

Biopharmaceutical wastewater typically exhibits high BOD and COD levels due to the presence of microorganisms and organic compounds. This section discusses the application of different concentrations of AC at varying temperatures to reduce COD and BOD in pristinamycin fermentation broth. The pH of the fermentation broth was 6.8. However, no significant change was observed in the pH of treated effluents following AC treatment (data not shown). Neither increasing the AC dosage nor temperature significantly affected pH values. This may be attributed to the use of relatively low carbon concentrations, with the maximum being 30 mg/L.

3.2.1. Effects of AC dose and temperature on COD

The application of 30 mg/L AC at 25°C to antibiotic fermentation broth reduced COD from approximately 172,000 mg/L to 82,300 mg/L (Figure 1). COD reduction was significantly higher ($p < 0.05$) at 30 mg/L than at 10 mg/L. Treatments with 10 mg/L and 20 mg/L AC did not yield significant reductions in COD relative to the control group at 25°C ($p > 0.05$). However, increasing the treatment temperature to 50°C and 75°C for the 20 mg/L treatment led to significant COD reductions ($p < 0.05$), yielding residual COD values of 100,000 mg/L and 68,100 mg/L, respectively.

No statistically significant difference ($p > 0.05$) was observed between the 30 mg/L and 20 mg/L treatments at 75°C, which achieved maximum COD reductions of 66% and 62%, respectively. The reduced adsorption at elevated temperatures is primarily due to weak interactions between the active sites of the adsorbent and the adsorbate molecules.^{11,24} Farhadpour and Bono²⁵ reported that acid extraction by granular AC and amine groups is exothermic and decreases with increasing temperature due to: (i) decreased adsorption affinity for adsorbate molecules, (ii) a shift in equilibrium

Table 2. Physicochemical properties of the fermentation broth effluent

Parameter	Value
Color	Creamy yellow
pH	6.8±0.11
Total solids (g/L)	6.5±0.20
Sugars (g/L)	3.8±0.15
Calcium ion (ppm)	560±5.46
Sodium ion (ppm)	360±4.89
Potassium ion (ppm)	150±2.33
Magnesium ion (ppm)	100±3.12
Zinc (II) ion (ppm)	3.0±0.25
Copper (II) ion (ppm)	0.1±0.001
Chromium (II) ion (ppm)	0.1±0.001

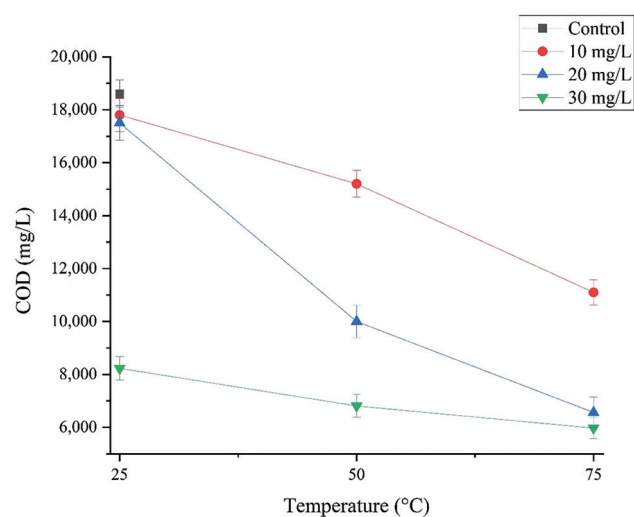


Figure 1. Effect of activated carbon dosage and temperature on COD reduction in the pristinamycin fermentation broth. Dosages of 10, 20, and 30 mg/L were evaluated, with the control receiving no activated carbon treatment.

Abbreviation: COD: Chemical oxygen demand.

toward the liquid phase, and (iii) enhanced desorption in exothermic reactions.

Increasing the AC dosage resulted in greater COD removal efficiency (Figure 1). Mullai and Rajesh¹⁵ observed a similar trend, attributing the enhanced efficiency to the abundant active sites present on the charcoal surface, which facilitate the removal of organic substances from fermentation broth.¹⁵ Umrantecanun *et al.*¹² investigated the effects of adsorbent dose, pH, temperature, initial antibiotic

concentration, and agitation duration on TC removal. TC removal efficiency was temperature-dependent; however, it improved with increasing adsorbent dose, pH, initial antibiotic concentration, and agitation duration. At 20°C, pH 5, with 0.15 g AC and an initial TC concentration of 100 mg/L, the COD concentration decreased from 1,000 mg/L to 88 mg/L after 24 h, indicating a removal efficiency of 91.2%. Based on these findings, AC adsorption of TC from wastewater appears to be a viable treatment option.

3.2.2. Effects of AC dose and temperature on BOD

BOD quantifies the oxygen consumed by bacteria and other microorganisms during the aerobic decomposition of organic matter at a designated temperature.²⁶ During the 5-day incubation period, the DO in the antibiotic fermentation broth is primarily utilized for the decomposition of organic matter. BOD₅ represents the amount of DO consumed by microorganisms while converting organic matter into carbon dioxide and water. To reduce the BOD₅ of the fermentation broth, samples were treated with AC at concentrations of 10, 20, and 30 mg/L, under temperature conditions of 25°C, 50°C, and 75°C for each treatment. The BOD₅ was subsequently measured for each treatment group and untreated samples. The results are illustrated in Figure 2.

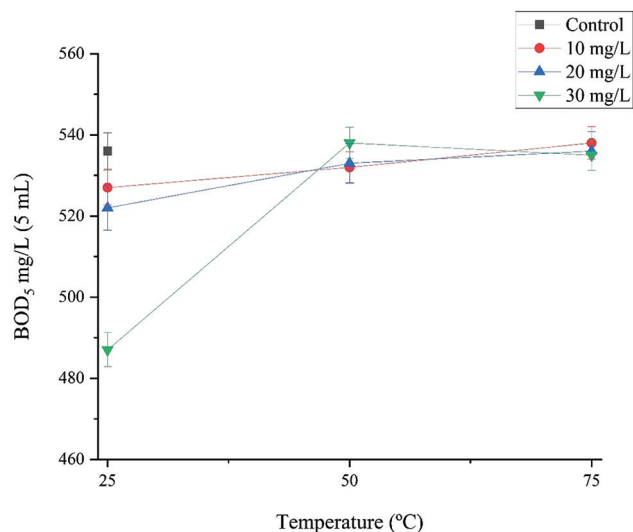


Figure 2. Effect of activated carbon dosage and temperature on BOD₅ reduction in the pristinamycin fermentation broth. Dosages of 10, 20, and 30 mg/L were evaluated, with the control receiving no activated carbon treatment.

Abbreviation: BOD₅: Biochemical oxygen demand over 5 days.

The most significant decrease in BOD₅ occurred when the broth was treated with 30 mg/L of AC at 25°C, where the BOD reduction was significantly higher ($p < 0.05$) at 30 mg/L than at 10 mg/L. The treatment reduced the BOD₅ from 536 mg/L in the untreated sample to 487 mg/L in the treated sample (Figure 2). Unlike COD, BOD reduction was temperature-dependent, as the introduction of charcoal at 50°C or 75°C did not significantly decrease ($p > 0.05$) the BOD₅ of the fermentation broth. This may be attributed to 25°C being a biologically optimal temperature for BOD testing, reflecting the natural decomposition of organic waste in aquatic ecosystems. Elevated temperatures (e.g., 75°C) facilitate procedures such as thermal hydrolysis or COD testing but compromise BOD analysis by killing the microorganisms essential to the test.

Elevated BOD values indicate increased oxygen depletion in the analyzed pristinamycin fermentation broth. The BOD results indicate the oxygen demand associated with pristinamycin organic waste discharge, supporting the assessment of its impact on the oxygen levels of the receiving water body. Data from BOD tests may be used to establish treatment criteria for the design of pristinamycin wastewater treatment facilities.²²

Antibiotic fermentation broths produce effluents containing residual antibiotics, organic byproducts, and nutrients, which pose environmental risks by potentially promoting antimicrobial resistance and disrupting aquatic ecosystems. Pristinamycin, a streptogramin antibiotic derived from the fermentation of *S. pristinaespiralis*, results in effluents that contain residual antibiotics, organic acids, and macromolecular byproducts such as proteins and sugars. Effluents containing pristinamycin pose environmental risks due to their persistence and potential to disseminate antimicrobial resistance genes.²⁷ Adsorption using an adsorbent material provides an effective treatment method by utilizing its extensive surface area and chemical affinity to capture pristinamycin and related organic compounds. The processes involved in binding antibiotics onto AC include hydrophobic interactions, hydrogen bonding, and π - π interactions.²⁸ The most effective adsorption was observed at a pH range of 6–7, which closely aligns with the isoelectric point of pristinamycin, thereby reducing electrostatic repulsion.²⁷ In this study, treatment with 30 mg/L of AC at 25°C resulted in a 52% reduction in COD in antibiotic fermentation effluent. Although lower than the findings reported by Umrantecanun *et al.*,¹² this likely reflects our ultra-low adsorbent dosage (30 mg/L) compared

to their dosage (150 mg/L), as well as the resistant characteristics of antibiotics.

Ranaweera *et al.*⁸ reported that AC adsorption was more successful in hospital wastewater, removing 50% of total organic carbon compared to 34% in ordinary wastewater. AC adsorption efficiently eliminated COD from effluent at a dose of 2 g/L, with a clearance rate of 66.2% in hospital wastewater and 65% in ordinary sewage. This is consistent with the findings from previous research, which reported a 55% COD elimination at 3–5 g/L and over 90% at 16 g/L.^{29,30} Uniform outcomes across different wastewater types illustrate AC's adaptability in adsorbing a range of organic molecules.

Consistent with earlier research, this study found that AC effectively removed COD and BOD. According to several studies, AC can effectively remove dissolved organic matter (DOM) and can be further optimized by doping or modifying commercial AC. For example, Choi *et al.*³¹ discovered that AC adsorbs TC more efficiently than sulfonamides in synthetic wastewater, but DOM interferes in high-DOM conditions. Zhou *et al.*³² proposed that ferroferric oxide nanoparticles could increase AC's adsorption capacity. In addition, Zhang *et al.*³³ demonstrated that modified AC made from petroleum coke had twice the adsorption capacity of commercial AC, lending credence to this finding. AC adsorption is extensively utilized in sewage treatment processes. The capital expenditure and operational expenditure associated with AC adsorption are significantly influenced by plant capacity, system configurations, and the removal or management of the adsorbent.^{34–37} Due to the frequent requirement for adsorbent replacement or regeneration, cost analyses show that AC adsorption incurs substantial operational expenditure but modest capital expenditure.^{38,39}

The 52% COD removal achieved at 30 mg/L demonstrates effective treatment performance; however, the economic feasibility of large-scale application is hindered by the costs associated with adsorbents. Hybrid systems integrating biological pretreatment with targeted charcoal application may achieve over 80% removal efficiency at approximately one-tenth the cost. However, charcoal regeneration is feasible only for facilities with a capacity exceeding 50,000 m³/day.

4. Conclusion

The traditional AC adsorption technique effectively removed pristinamycin, demonstrating high adsorption

capacity and rapid kinetics. AC adsorption reduced COD, BOD, and antimicrobial concentrations in fermentation wastewater. Treatment of antibiotic fermentation effluent with 20 mg/L of adsorbent material at 75°C resulted in a maximum COD reduction of 62%. Increasing the adsorbent material dose further enhanced the COD removal efficiency. The most significant decrease in BOD₅ occurred when the broth was treated with 30 mg/L of AC at 25°C, achieving a reduction of about 9.1%. AC effectively removes pristinamycin from fermentation effluents, but process efficiency depends on charcoal modification, pH, and effluent complexity. Further studies are warranted to explore the integration of adsorption with membrane filtration or biodegradation, which could enhance selectivity and cost-effectiveness while mitigating antimicrobial resistance risks in a sustainable manner.

Acknowledgments

None.

Funding

This study was funded by the Date Palm Research Center of Excellence, King Faisal University.

Conflict of interest

The authors declare that they have no known competing financial interests, and this manuscript has not been submitted to any other journal in parallel or published previously.

Author contributions

Conceptualization: Salah Mohammed Aleid

Formal analysis: Salah Mohammed Aleid, Sam Al-Dalali

Investigation: Salah Mohammed Aleid, Siddig H. Hamad

Methodology: Salah Mohammed Aleid, Siddig H. Hamad

Writing—original draft: Salah Mohammed Aleid, Sam Al-Dalali

Writing—review & editing: Sam Al-Dalali

Availability of data

Data are available from the corresponding author upon reasonable request.

References

1. Bódalo-Santoyo A, Gómez-Carrasco JL, Gómez-Gómez E, Máximo-Martín F, Hidalgo-Montesinos AM. Application of reverse osmosis to reduce pollutants present in industrial wastewater. *Desalination*. 2003;155:101-108. doi: 10.1016/S0011-9164(03)00287-x
2. Jarusutthirak C, Amy G, Croué JP. Fouling characteristics of wastewater effluent organic matter isolates on NF and UF membranes. *Desalination*. 2002;145:247-255. doi: 10.1016/S0011-9164(02)00419-8
3. Tong WY, Fu XY, Lee SM, et al. Purification of L-(+) lactic acid from fermentation broth with paper sludge as a cellulosic feedstock using weak anion exchanger Amberlite IRA-92. *Biochem Eng J*. 2004;18:89-96. doi: 10.1016/S1369-703X(03)00170-0
4. Yousuf A, Bonk F, Oyanedel JRB, Schmidt JE. Recovery of carboxylic acids produced during dark fermentation of food waste by adsorption on amberlite IRA-67 and activated carbon. *Bioresour Technol*. 2016;217:137-140. doi: 10.1016/j.biortech.2016.02.035
5. Antonio GR, Vaccari G, Dosi E, Trilli A, Rossi M, Matteuzzi D. Enhanced production of L-(+) lactic acid in chemostat by *Lactobacillus casei* DSM 20011 using ion-exchange resins and cross-flow filtration in a fully automated pilot plant controlled via NIR. *Biotechnol Bioeng*. 2000;67:147-156.
6. Cao X, Yun HS, Koo YM. Recovery of L-(+)-lactic acid by anion exchange resin amberlite IRA-400. *Biochem Eng J*. 2002;11:189-196. doi: 10.1016/S1369-703X(02)00024-4
7. Gao MT, Shimamura T, Ishida N, Takahashi H. pH-uncontrolled lactic acid fermentation with activated carbon as an adsorbent. *Enzyme Microb Technol*. 2011;48:526-530. doi: 10.1016/j.enzmictec.2010.07.015
8. Ranaweera R, Wu X, Ng D, et al. Comparative study of adsorption, thermally activated peroxymonosulfate and wet air oxidation for tetracycline removal and wastewater treatment. *J Water Process Eng*. 2025;72:107559. doi: 10.1016/j.jwpe.2025.107559
9. Cheremisinoff NP, Cheremisinoff PN. *Carbon Adsorption for Pollution Control [Process and Pollution Control Equipment Series]*; 1993
10. Park KM, Nam HG, Lee KB, Mun S. Adsorption behaviors of sugars and sulfuric acid on activated porous carbon. *J Ind Eng Chem*. 2016;34:21-26.
11. Pradhan N, Rene ER, Lens PNL, et al. Adsorption behaviour of lactic acid on granular activated carbon and anionic resins: Thermodynamics, isotherms and kinetic studies. *Energies*. 2017;10:665. doi: 10.3390/en10050665
12. Tezcanun U, Ocal SE, Gul A. Removal of antibiotic wastes by adsorption method. *Int J Adv Sci Eng Technol*. 2018;6(4):40-43.
13. Abbas M, Trari M. Removal of amoxicillin from wastewater onto activated carbon: Optimization of analytical parameters by response surface methodology. *Dose Response*. 2024;22:15593258241271655. doi: 10.1177/15593258241271655
14. Spit T, Van der Hoek JP, De Jong C, Van Halem D, De Kreuk M, Perez BB. Removal of antibiotic resistance from municipal secondary effluents by ozone-activated carbon filtration. *Front Environ Sci*. 2022;10:834577. doi: 10.3389/fenvs.2022.834577
15. Mullai P, Rajesh V. Post treatment of antibiotic wastewater by adsorption on activated carbon. *AIP Conf Proc*. 2018;1927:020002. doi: 10.1063/1.5021190
16. Zhanga J, Lidietta Giornob L, Driolib E. Study of a hybrid process combining PAC^s and membrane operations for antibiotic wastewater treatment. *Desalination*. 2006;194:101-107. doi: 10.1016/j.desal.2005.11.004
17. EPA. *Reduction in Mean Biochemical Oxygen Demand [BOD5] Due to Tree Cover*. EnviroAtlas: Led by the U.S. Environmental Protection Agency; 2014. p. 1-2.
18. Penn MR, Pauer JJ, Mihelcic JR. Biological oxygen demand. In: *Sabjic A, editor. Environment and Ecological Chemistry. Encyclopedia of Life Support System*. Vol. 2. Isle of Man, UK: UNESCO; 2009. p. 278.
19. Aleid SM, Hamad SH, Delaunay S, Fick M, Olmos E. Pristinamycin production using *Streptomyces pristinaespiralis* and date sirup as substrate-process modeling, optimization, and scale-up. *Prep Biochem Biotechnol*. 2022;52:1044-1050. doi: 10.1080/10826068.2021.2024849
20. Aleid SM. Chromatographic separation of fructose from date syrup. *Int J Food Sci Nut*. 2006;57:83-96. doi: 10.1080/09637480600658286
21. EPA. *Chemical Oxygen Demand (Titrimetric, High Level for Saline Waters). Method 410.3*. United States: EPS; 1978.
22. EPA. *Methods for Chemical Analysis of Water and Wastes. Biological Oxygen Demand (5201B) 5-day BOD Test*. EPA/600/4-79/020. Cincinnati, Ohio, USA: EPA Environmental Monitoring Laboratory; 1983.
23. APHA, American Public Health Association. Standard methods for the examination of water and wastewater. In: Greenberg AE, Eaton AD, Clesceri LS, Franson, MAH, editors. *Joint Editorial Board*. 20th ed. Publication Office: American Public Health Association, Washington, USA; 1998.
24. Ye C, Wang X, Wang H, Wang Z. Effects of counter anions on the adsorption properties of 4-methylimidazolium-modified silica materials. *J Taiwan Instit Chem Eng*. 2014;45:2868-2877.
25. Farhadpour FA, Bono A. Sorptive separation of ethanol-water mixtures with a bi-dispersed hydrophobic

- molecular sieve, silicalite: Determination of the controlling mass transfer mechanism. *Chem Eng Process*. 1996;35:141-155.
doi: 10.1016/0255-2701(95)04138-9
26. Delzer GC, McKenzie SW. *Five-Day Biochemical Oxygen Demand. USGS TWRI Book 9-A7*. 3rd ed. Reston: USGS; 2003. p. 1-21.
 27. Grenni P, Ancona V, Barra CA. Ecological effects of antibiotics on natural ecosystems: A review. *Microchem J*. 2018;136:25-39.
doi: 10.1016/j.microc.2017.02.006
 28. Ahmedna M, Marshall WE, Rao RM. Production of granular activated carbons from select agricultural by-products and evaluation of their physical, chemical, and adsorption properties. *Bioresour Technol*. 2000;71(2):113-123.
doi: 10.1016/S0960-8524(99)00070-X
 29. Margot J, Kienle C, Magnet A, *et al*. Treatment of micropollutants in municipal wastewater: Ozone or powdered activated carbon? *Sci Total Environ*. 2013;461-462:480-498.
doi: 10.1016/j.scitotenv.2013.05.034
 30. Bansode RR, Losso JN, Marshall WE, Rao RM, Portier RJ. Pecan shell-based granular activated carbon for treatment of chemical oxygen demand (COD) in municipal wastewater. *Bioresour Technol*. 2004;94(2):129-135.
doi: 10.1016/j.biortech.2003.12.009
 31. Choi KJ, Kim SG, Kim SH. Removal of tetracycline and sulfonamide classes of antibiotic compound by powdered activated carbon. *Environ Technol*. 2008;29(3):333-342.
doi: 10.1080/09593330802102223
 32. Zhou J, Ma F, Guo H. Adsorption behavior of tetracycline from aqueous solution on ferroferric oxide nanoparticles assisted powdered activated carbon. *Chem Eng J*. 2020;384:123290.
doi: 10.1016/j.cej.2019.123290
 33. Zhang D, Yin J, Zhao J, Zhu H, Wang C. Adsorption and removal of tetracycline from water by petroleum coke-derived highly porous activated carbon. *J Environ Chem Eng*. 2015;3(3):1504-1512.
doi: 10.1016/j.jece.2015.05.014
 34. Viegas RMC, Mesquita E, Campinas M, Rosa MJ. Pilot studies and cost analysis of hybrid powdered activated carbon/ceramic microfiltration for controlling pharmaceutical compounds and organic matter in water reclamation. *Water*. 2019;12(1):33.
doi: 10.3390/w12010033
 35. Ighalo JO, Omoarukhe FO, Ojukwu VE, Iwuzor KO, Igwegbe CA. Cost of adsorbent preparation and usage in wastewater treatment: A review. *Clean Chem Eng*. 2022;3:100042.
doi: 10.1016/j.clce.2022.100042
 36. Garcia L, Leyva-Diaz JC, Diaz E, Ordonez S. A review of the adsorption-biological hybrid processes for the abatement of emerging pollutants: Removal efficiencies, physicochemical analysis, and economic evaluation. *Sci Total Environ*. 2021;780:146554.
doi: 10.1016/j.scitotenv.2021.146554
 37. Yasir HA, Zein SH, Holliday MC, Jabbar KJ, Ahmed U, Jalil AA. Comparison of activated carbon and low-cost adsorbents for removal of 2,4-dichlorophenol from wastewater using Aspen adsorption and response surface methodology. *Environ Technol*. 2024;45(15):3029-3047.
doi: 10.1080/09593330.2023.2202829
 38. Jaria G, Calisto V, Esteves VI, Otero M. Overview of relevant economic and environmental aspects of waste-based activated carbons aimed at adsorptive water treatments. *J Clean Prod*. 2022;344:130984.
doi: 10.1016/j.jclepro.2022.130984
 39. Sulistiyo CD, Cheng KC, Su'andi HJ, *et al*. Removal of hexavalent chromium using durian in the form of rind, cellulose, and activated carbon: Comparison on adsorption performance and economic evaluation. *J Clean Prod*. 2022;380:135010.
doi: 10.1016/j.jclepro.2022.135010