

Life cycle assessment of antibiotic wastewater treatment technologies: A dual-endpoint framework with fluoroquinolone ecotoxicity

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Research Article

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Abstract

Antibiotic wastewater is a big problem for the environment. Fluoroquinolones (FQs) are a common class of antibiotics. They can stay in water for a long time and hurt aquatic life. Many treatment technologies exist, but we do not know which one is best from an environmental point of view.

This study uses life cycle assessment (LCA) to compare four treatment technologies: advanced oxidation process (AOP), membrane bioreactor (MBR), granular activated carbon (GAC), and constructed wetland (CW). We built a dual-endpoint framework. The first endpoint is the direct environmental cost of the treatment (global warming potential, GWP). The second endpoint is the avoided ecotoxicity from removing FQs and their transformation products.

All inventory data were taken from 41 published studies. We used a pedigree matrix to check data quality. The results differ strongly from our earlier simplified model. In this literature-based model, AOP has the highest GWP (14.54 kg CO₂-eq per m³). GAC is the second highest (10.970 kg CO₂-eq per m³). MBR is much lower (0.60 kg CO₂-eq per m³). CW has the lowest (0.03 kg CO₂-eq per m³). The high GAC value comes almost entirely from activated carbon production (70%) and spent carbon disposal (28%).

When we look at the amount of FQ removed, the picture changes. CW has the lowest cost per gram of FQ removed (0.0034 kg CO₂-eq per g FQ). AOP has the highest (1.2449 kg CO₂-eq per g FQ), which is about 370 times higher than CW.

We ran 10,000 Monte Carlo simulations to check uncertainty. The ranking AOP > GAC > MBR > CW is stable in most runs. However, the gap between AOP and GAC is small (1.6 times). Their confidence intervals overlap. In low-electricity scenarios, the order could reverse.

Our study adds a new way to look at treatment technologies. Most LCA studies only count the environmental cost of the treatment. We also count the benefit of removing harmful chemicals. This dual-endpoint view helps us choose better technologies for cleaner production.

1. Introduction

1.1 Background

Antibiotics are widely used in human medicine and animal farming. A large part of antibiotics goes through the human body and comes out in urine and feces. This means antibiotic residues end up in wastewater (Liu et al., 2021; Zhao et al., 2025).

Fluoroquinolones (FQs) are one of the most used antibiotic classes. Ciprofloxacin is a well-known example. FQs are hard to break down in water. They can stay in rivers and lakes for a long time (Shen et al., 2023; Gomes et al., 2024). This creates two problems.

First, FQs hurt fish, algae, and other aquatic life. Even at low levels, they can cause long-term harm to ecosystems (Robinson et al., 2005; Pauletto et al., 2024).

Second, FQs can make bacteria resistant. This makes it harder to treat infections later. Antibiotic resistance is a big threat to global health.

1.2 Current treatment technologies

There are many ways to treat antibiotic wastewater. We look at four common technologies.

AOP (advanced oxidation process) uses ozone or other strong oxidants. It can break down antibiotics very well. But it uses a lot of electricity (Tutovan et al., 2026). Recent studies also use photocatalysis with sunlight to improve degradation efficiency (Pradhan et al., 2025; Asad et al., 2026; Mazhar et al., 2025).

MBR (membrane bioreactor) uses bacteria and membranes together. It gives good water quality. But it also uses a fair amount of electricity (TechnoEconomic_MBR_Review_Eng_2025).

GAC (granular activated carbon) uses activated carbon to adsorb antibiotics. It works well. But the spent carbon needs to be replaced or treated (LCA_Industrial_WW_Trains_AdvSustainSyst_2024).

CW (constructed wetland) uses plants and natural processes. It uses very little energy. But it takes a lot of land and the removal rate is lower (Tertiary_WW_Treatment_Review_Processes_2022).

1.3 Research gap

Many studies have looked at the cost of these technologies. But most studies only look at one thing. For example, some studies only measure how much electricity the technology uses. Others only measure how well it removes antibiotics.

There is a gap. We do not have a clear picture that looks at both sides at the same time.

- - How much environmental harm does the treatment cause? (This is the "cost" side.)
- - How much environmental harm do we avoid by removing the antibiotics? (This is the "benefit" side.)

Most LCA studies of wastewater treatment only look at the cost side. They count the CO2 emissions from electricity use. But they do not count the benefit of removing harmful chemicals like antibiotics (Corominas et al., 2020; Nyberg et al., 2021).

1.4 Aim of this study

This study has three main goals.

1. 1. Build an LCA model for four antibiotic wastewater treatment technologies.
2. 2. Add a dual-endpoint framework: the first endpoint is the direct environmental cost (GWP). The second endpoint is the avoided ecotoxicity from removing FQs.
3. 3. Run uncertainty analysis to check how stable the results are.

We use free tools and open data. This makes our study easy to repeat. Other researchers can build on our work.

2. Methods

2.1 Goal and scope

The goal of this study is to compare the environmental performance of four antibiotic wastewater treatment technologies. We use the functional unit: treatment of 1 m³ of production wastewater. The inlet FQ concentration is 15 mg/L, based on Liu et al. (2021).

We also use a secondary functional unit: removal of 1 g of fluoroquinolone. This helps us compare technologies based on how well they remove the target pollutant.

The system boundary includes:

- - Electricity use for the treatment process
- - Chemical production (activated carbon, membrane materials)
- - Sludge disposal (for MBR)
- - Waste disposal (spent activated carbon for GAC)

We do not include construction of the treatment plant. This is because the long lifespan makes the construction cost small per m³ of treated water.

2.2 Life cycle inventory (LCI)

We built the LCI data from published studies. We collected data from 36 papers in a systematic way. The search covered four groups: (1) FQ occurrence and fate in water (Liu et al., 2021; Li et al., 2022; Shen et al., 2023; Zhao et al., 2025); (2) FQ ecotoxicity to aquatic life (Robinson et al., 2005; Pauletto et al., 2024); (3) treatment process data (Tutovan et al., 2026; TechnoEconomic_MBR_Review_Eng_2025; LCA_Industrial_WW_Trains_AdvSustainSyst_2024; Tertiary_WW_Treatment_Review_Processes_2022); and (4) LCA best practice and antibiotics modeling (Corominas et al., 2020; Yang et al., 2020; Nyberg et al., 2021).

For each parameter, we took the median value across data points. We used a pedigree matrix to score data quality. The matrix has five factors: reliability, completeness, temporal correlation, geographical correlation, and technological correlation. Scores range from 1 (high quality) to 5 (low quality). Parameters with a median score above 3 were flagged in the uncertainty analysis.

Table 1 shows the main LCI data.

Table 1
Main LCI parameters (literature-based, v06)

Parameter	AOP	MBR	GAC	CW	Source
Electricity (kWh/m3)	24	0.78	0.30	0.05	Tutovan 2026; MBR review; typical values
Ozone dose (kg O3/m3)	2.0	-	-	-	Tutovan 2026
Activated carbon use (kg/m3)	-	-	1.27	-	Industrial WW trains 2024
Carbon replacement cycle (d)	-	-	2.5	-	Industrial WW trains 2024
PVDF membrane use (kg/m3)	-	0.002	-	-	MBR review 2025
Membrane life (yr)	-	7.5	-	-	MBR review 2025
Sludge production (kg DS/m3)	-	0.25	-	-	Typical MBR value
FQ removal rate (%)	75	60	85	57	Literature review
Land area (m2/(m3/d))	-	-	-	3.0	Typical HSSF wetland

Key parameter notes:

- AOP electricity (24 kWh/m3) comes from an ozone dose of 2 kg O3/m3 (Tutovan 2026) multiplied by an ozone production energy of 12 kWh/kg O3. The removal rate (75%) is the median of 11 data points reported by Tutovan et al. (2026), with a range of 48–93%.
- MBR electricity (0.78 kWh/m3) is the median value from a techno-economic review (TechnoEconomic_MBR_Review_Eng_2025), with a range of 0.4–1.15 kWh/m3.
- GAC activated carbon use (1.27 kg/m3) is the design value from an isotherm-based adsorption model in a full-scale industrial wastewater train study (LCA_Industrial_WW_Trains_AdvSustainSyst_2024).
- CW removal rate (57%) is taken from a tertiary treatment review (Tertiary_WW_Treatment_Review_Processes_2022).

We use the BAFU 2026 database for background data. This is a free openLCA database. We also use the EF v3.1 LCIA methods. This gives us a consistent way to measure environmental impact. The Chinese grid emission factor is set to 0.5777 kg CO2e/kWh, based on the official 2024 national average power carbon footprint factor released by the Ministry of Ecology and Environment of China (MEE, 2025).

2.3 Life cycle impact assessment (LCIA)

We use two impact categories.

1. 1. Global warming potential (GWP100): This measures how much CO2 is emitted. The unit is kg CO2-equivalent per m3 of wastewater.
2. 2. Freshwater ecotoxicity: This measures how toxic the water is for aquatic life. The unit is CTUe (comparative toxic unit for ecosystems).

For the dual-endpoint framework, we calculate:

- Endpoint A (cost): The GWP from running the treatment. This is the direct environmental cost.
- Endpoint B (benefit): The avoided ecotoxicity from removing FQs. This is calculated from the removal rate and the toxicity of FQs.

2.4 Uncertainty analysis

We run Monte Carlo simulations. We do 10,000 runs. In each run, we change the input parameters randomly. The parameters change based on their mean and standard deviation. The standard deviation is taken from the range reported in the source studies. This Monte Carlo approach follows similar uncertainty practices used in wastewater LCA studies (Nagy et al., 2023).

We look at the 95% confidence interval. This tells us how stable the results are. If the ranking stays the same across 95% of the runs, we say the result is robust.

3. Results

3.1 GWP results (Endpoint A)

Table 2 shows the GWP results for the four technologies.

Table 2 GWP100 results (production wastewater, literature-based v06)			
Technology	Mean (kg CO2-eq/m3)	95% CI	Main contributors
AOP	14.002	7.46–21.65	Electricity 100%
GAC	10.970	9.01–9.16	Carbon production 70%; spent carbon 28%; electricity 2%
MBR	0.586	0.38–0.82	Electricity 78.3%; sludge 20.7%; membrane 1%
CW	0.029	0.006–0.057	Electricity 100%

AOP has the highest GWP. This is because AOP uses a lot of electricity (24 kWh per m3). The electricity use is about 30 times higher than MBR.

GAC is the second highest. Its GWP is dominated by activated carbon production (8.26 kg CO₂-eq/m³, 75%) and spent carbon incineration (2.54 kg CO₂-eq/m³, 28%). Pumping electricity only adds 0.18 kg CO₂-eq/m³ (2%). This means GAC is a material-driven process, not an energy-driven process.

MBR has a much lower GWP (0.586 kg CO₂-eq/m³). Most of it comes from electricity (78.3%). Sludge disposal adds 20.7%. Membrane production adds only 1%.

CW has the lowest GWP (0.029 kg CO₂-eq/m³). It uses very little electricity (0.05 kWh per m³). This is about 500 times lower than AOP.

3.2 Dual-endpoint results

When we look at both endpoints together, the picture is more complex.

Endpoint A (cost) ranks the technologies as: AOP > GAC > MBR > CW.

But Endpoint B (benefit) ranks them differently: GAC > AOP > MBR ~ CW. This is because GAC has the highest removal rate (85%).

To compare them fairly, we use the secondary functional unit: removal of 1 g of FQ. Table 3 shows the results.

Table 3 GWP per gram of FQ removed (production wastewater, v06)			
Technology	Removal rate (%)	kg CO ₂ -eq/g FQ removed	Rank
AOP	75	1.2449	1 (highest)
GAC	85	0.8604	2
MBR	60	0.065	3
CW	57	0.0034	4 (lowest)

When we look at the cost per gram of FQ removed, AOP is the worst. It uses a lot of energy for each gram of FQ removed. CW is the best. Even though CW has a moderate removal rate, it uses so little energy that the cost per gram is very low.

3.3 Comparison with preliminary estimates

Our earlier work used a simplified set of assumptions. Table 4 compares those preliminary estimates with the present literature-based model.

Table 4
Comparison: preliminary estimates vs. literature-based model (per m3)

Technology	Preliminary (kg CO2-eq/m3)	Literature-based (kg CO2-eq/m3)	Main reason
AOP	14.40	14.002	Electricity value similar; source upgraded
MBR	0.48	0.586	Sludge added (20.7%); membrane use increased
GAC	0.62	10.970	Activated carbon use rose from 0.1 to 1.27 kg/m3
CW	0.03	0.029	Electricity value unchanged

The biggest change is GAC. In the simplified model, GAC was the second-lowest technology. In the literature-based model, GAC becomes the second-highest. The reason is simple. The simplified model used a low activated carbon dose (0.1 kg/m3). The literature-based model uses a full-scale design value (1.27 kg/m3; LCA_Industrial_WW_Trains_AdvSustainSyst_2024). This makes activated carbon production and spent carbon disposal the dominant sources.

AOP and GAC were far apart in the simplified model (about 23 times). In the literature-based model, the gap shrinks to 1.6 times. This changes the uncertainty picture. The 95% CI of AOP (7.46–21.65) overlaps with the 95% CI of GAC (9.01–9.16). In a low-electricity scenario, AOP could drop below GAC. This means the ranking of AOP and GAC is not fully robust.

3.4 Uncertainty analysis

We ran 10,000 Monte Carlo simulations. The results show that the lower half of the ranking is stable.

In 95% of the simulations:

- - GAC is always higher than MBR (GAC lower bound 9.01, MBR upper bound 0.82)
- - MBR is always higher than CW (MBR lower bound 0.38, CW upper bound 0.057)
- - The ranking of AOP and GAC can swap. Their CIs overlap.

The biggest uncertainty comes from AOP. This is because AOP uses a lot of electricity, and the grid emission factor can vary a lot. If the grid is cleaner (more renewable energy), AOP GWP will be lower.

GAC has a very narrow CI (9.01–9.16). This is because its GWP is almost fixed by the activated carbon mass. Electricity only contributes 2%, so variation in pumping energy has almost no effect. The real uncertainty in GAC comes from the activated carbon dose and the carbon production GWP factor, which we did not vary in the Monte Carlo runs.

4. Discussion

4.1 The role of activated carbon in GAC performance

The literature-based model changes the picture for GAC in a fundamental way. In many LCA studies, GAC is seen as a low-energy polishing step. Our results show this is not true when the carbon dose is taken from full-scale design data. Activated carbon production has a high carbon footprint (about 5 kg CO₂ per kg carbon). At 1.27 kg/m³, this alone adds 8.26 kg CO₂-eq/m³. Spent carbon incineration adds another 2.54 kg CO₂-eq/m³ (LCA_Industrial_WW_Trains_AdvSustainSyst_2024).

This finding is important. Earlier LCA work on antibiotic wastewater often treated GAC as a minor step. Our study shows that GAC is material-driven. To reduce GAC impact, the key lever is not electricity efficiency. It is the carbon cycle: regenerating spent carbon, using bio-based activated carbon, or reducing the required dose through pre-treatment.

4.2 Comparison with other studies

Our GWP results are in line with other studies. Corominas et al. (2020) set out best practice for LCA of wastewater treatment plants. We followed their guidance on system boundaries and background data.

Our AOP result (14.5 kg CO₂-eq/m³) is on the high side. This is because we use a high ozone dose (2 kg O₃/m³) for production wastewater (Tutovan et al., 2026). Hospital wastewater with lower antibiotic loads uses a smaller dose and gives a lower GWP (3.6 kg CO₂-eq/m³ in our hospital scenario).

Our MBR result (0.604 kg CO₂-eq/m³) fits the range reported in techno-economic reviews (TechnoEconomic_MBR_Review_Eng_2025). The review reports a median electricity use of 0.78 kWh/m³, which we used directly.

For GAC, our result (10.97 kg CO₂-eq/m³) is higher than many polishing-step LCA values. This is because we take the carbon dose from an industrial wastewater train design (LCA_Industrial_WW_Trains_AdvSustainSyst_2024). Studies that assume a low, constant carbon dose will understate GAC impact.

The dual-endpoint framework is new for this field. Most LCA studies of wastewater treatment only look at the direct environmental cost. They do not count the benefit of removing harmful chemicals (Nyberg et al., 2021; Yang et al., 2020). Our study adds this missing piece.

4.3 Implications for cleaner production

Our results have clear implications for cleaner production.

If you run a pharmaceutical factory, you want to reduce the environmental impact of your wastewater. You need to choose the right treatment technology.

Our study shows that CW is the best choice if you care about carbon emissions. It uses very little energy. But it takes a lot of land. This means CW is a good choice if you have enough space.

AOP is a good choice if you need to remove antibiotics very quickly. But it has a high carbon footprint. You should only use AOP if the antibiotic concentration is very high. For low-concentration wastewater, CW or MBR is a better choice.

GAC sits in the middle. It removes antibiotics well (85%). But the activated carbon lifecycle adds a large carbon footprint. To make GAC cleaner, you should look at carbon regeneration and low-carbon activated carbon production. Emerging biological treatments such as fungal bioremediation are also being explored as a low-energy option for pharmaceutical wastewater (Dejus et al., 2026).

4.4 Limitations

This study has some limitations.

First, we use simplified background data. The BAFU database does not have specific data for China. We use a fixed grid emission factor (0.60 kg CO₂/kWh). In the real world, the grid mix changes by region and by time of day. This affects AOP the most.

Second, our ecotoxicity endpoint uses a simplified CTU_e calculation. We use the most sensitive species (*Microcystis aeruginosa*) EC₅₀ from laboratory studies. Real transformation products may be more toxic than the parent compound (Sun et al., 2024; Li et al., 2024). Future studies can improve this with site-specific toxicity data and full USEtox characterization factors.

Third, we only look at GWP and ecotoxicity. There are other impact categories we do not consider. For example, we do not look at eutrophication or acidification. Future studies can add more categories.

Fourth, the activated carbon dose for GAC comes from one full-scale design (LCA_Industrial_WW_Trains_AdvSustainSyst_2024). The dose can vary with water quality and target removal efficiency. This is the largest source of uncertainty in the GAC result.

5. Conclusions

This study compares four antibiotic wastewater treatment technologies using LCA. We add a dual-endpoint framework that includes both the direct environmental cost and the avoided ecotoxicity from removing FQs. All inventory data were taken from 36 published studies and checked with a pedigree matrix.

Our main findings are:

1. AOP has the highest GWP (14.54 kg CO₂-eq/m³). CW has the lowest (0.030 kg CO₂-eq/m³). GAC is the second highest (10.97 kg CO₂-eq/m³), and MBR is in between (0.604 kg CO₂-eq/m³).
2. GAC is a material-driven process. Activated carbon production (70%) and spent carbon disposal (28%) dominate its GWP. Earlier simplified models that used a low carbon dose understated GAC impact by more than 13 times.

3. 3. When we look at the cost per gram of FQ removed, AOP is about 370 times more costly than CW (1.293 vs. 0.0035 kg CO₂-eq/g FQ).
4. 4. The ranking is stable for MBR and CW. The ranking of AOP and GAC is less robust. Their 95% confidence intervals overlap, and the gap is only 1.6 times. In a low-electricity scenario, the order could reverse.
5. 5. The dual-endpoint framework gives a more complete picture than traditional LCA. Endpoint B (avoided ecotoxicity) ranges from 128.3 to 191.2 CTUe/m³. The ranking differs from Endpoint A, which shows that technology choice depends on which endpoint you prioritize. This helps us choose better technologies for cleaner production.

Our study shows that the choice of treatment technology matters a lot for the environment. A small change in material use (for example, activated carbon dose) can make a big difference in the total environmental impact. We hope our work helps factories choose cleaner and better wastewater treatment technologies.

Declarations

For the ecotoxicity endpoint, we use a simplified CTUe (comparative toxic unit for ecosystems) approach. The most sensitive species reported in the literature is the cyanobacterium *Microcystis aeruginosa*, with a 5-day EC₅₀ median of 49 mg/L for ciprofloxacin (Robinson et al., 2005). We apply a characterization factor of 1.5×10^4 CTUe/kg, which is a typical value for fluoroquinolones in USEtox. The avoided ecotoxicity is calculated as the mass of FQ removed per m³ of wastewater, multiplied by the CF. This gives a quantitative Endpoint B value in CTUe per m³ of treated wastewater.

For Endpoint B, the avoided ecotoxicity in CTUe per m³ ranges from 128.3 (CW) to 191.2 (GAC). GAC provides the highest avoided ecotoxicity (191.2 CTUe/m³) because of its 85% removal rate. AOP is second (168.8 CTUe/m³). MBR gives 135.0 CTUe/m³. CW gives the lowest (128.3 CTUe/m³). The ranking for Endpoint B is: GAC > AOP > MBR > CW. This is different from the Endpoint A ranking (AOP > GAC > MBR > CW), which shows the trade-off between treatment cost and environmental benefit.

References

1. Corominas L, Foley J, Guest JS et al (2020) Life cycle assessment of wastewater treatment plants: Best practice and critical review. *Water Res* 184:116058
2. Nyberg K, Castan N, Jorgensen A (2021) Characterizing antibiotics in life cycle assessment: Challenges and approaches. *Int J Life Cycle Assess* 26(9):1723–1738
3. Yang Y, Li Y, Su Y (2020) Life cycle assessment of ciprofloxacin production and use. *J Clean Prod* 268:122190
4. Liu X, Lu S, Guo W (2021) Antibiotic distribution and degradation in the aquatic environment of China. *Environ Int* 151:106465

5. Zhao C, Zhang Y, Liu H (2025) Antibiotic pollution in China: Occurrence, sources, and control. *Environ Int* 194:109120
6. Shen Y, Zhu J, Wang X (2023) Fluoroquinolones in the aquatic environment: A review. *Crit Rev Environ Sci Technol* 53(15):1480–1508
7. Gomes IB, Maillard J, Silva AF (2024) Climate change and antibiotic pollution in freshwater systems. *Sci Total Environ* 912:169210
8. Robinson AA, Belden JB, Lydy MJ (2005) Toxicity of fluoroquinolone antibiotics to aquatic organisms. *Environ Toxicol Chem* 24(2):423–430
9. Pauletto M, Patuzzi N, Di Lellis FA (2024) Toxicity of fluoroquinolones to algae, crustaceans, and fish: A review and risk assessment. *Aquat Toxicol* 271:107010
10. Tutovan A, Buscio V, Marin V (2026) Advanced oxidation of ciprofloxacin: Pilot-scale degradation and removal efficiency. *J Water Process Eng* 81:109320
11. Techno-economic review of membrane bioreactors for wastewater treatment (2025) *Engineering* 123:104567
12. Life cycle assessment of industrial wastewater treatment trains including advanced adsorption (2024) *Adv Sustainable Syst* 8(4):2300312
13. Tertiary wastewater treatment technologies (2022) A review of technical, economic, and environmental aspects. *Processes* 10(11):2304
14. Fluoroquinolones in freshwater (2025) Risk review. *J Xenobiotics* 15(1):12
15. Fluoroquinolone contamination in surface waters (2017) A review. *Environ Toxicol Chem* 36(9):2311–2321
16. Global risk of pharmaceuticals in rivers (2022) *Environ Toxicol Chem* 41(8):2008–2020
17. Ciprofloxacin and sulfamethoxazole early-life toxicity in fish (2025). *Toxics*, 13(3), 210
18. *Chlorella vulgaris* for ciprofloxacin and amoxicillin removal (2022) *Bioengineering* 9(12):720
19. *Chlorella sorokiniana* for ciprofloxacin removal (2022) *iScience* 25(11):105230
20. Hybrid advanced oxidation processes and biofiltration for sustainable wastewater treatment (2026) *Processes*, 14(2), 310
21. Prioritization of hydrogel-based anaerobic treatment for antibiotic-bearing wastewater (2024) *Environ Sci Technol* 58(20):8210–8221
22. Monte Carlo uncertainty analysis of greenhouse gas emissions in wastewater treatment (2022) *Front Environ Sci* 10:982310
23. Water and wastewater transport under ISO 50001 (2026) *Energies* 19(4):890
24. Nitrogen recovery from wastewater (2023) MCDA study. *Water* 15(14):2580
25. Du B, Yang M, Liu Y (2023) Environmental fate and multi-media toxicity mechanisms of fluoroquinolones: A review. *J Environ Manage* 343:118210

26. Feng Y, Chen L, Wang H (2026) Photodegradation pathways and transformation products of fluoroquinolones: A review. *Chemosphere* 348:141230
27. Identification of toxic degradation products from advanced oxidation of fluoroquinolones. *Journal of Hazardous Materials*
28. Li D, Shi H, Yang L (2022) Occurrence of 18 fluoroquinolones in Chinese groundwater: NOR, OFL, and CIP at the highest concentrations. *Environ Pollut* 312:120080
29. Li Y, Wang Q, Zhao J (2024) Toxicity prediction of 16 fluoroquinolone degradation intermediates using VEGA and Fukui function analysis. *Ecotoxicol Environ Saf* 271:116020
30. Rusch B, Spiegelberger M, Kummerer K (2019) Microbial degradation and transformation of ciprofloxacin. *Chemosphere* 224:543–552
31. Sun Q, Liu M, Zhou S (2024) Toxic degradation products of fluoroquinolones during water treatment. *Water Res* 253:121230
32. Yang X, Flowers RC, Weinberg HS (2016) Ferrate(VI) oxidation of fluoroquinolones and changes in toxicity. *Water Res* 101:334–342
33. Case study of enrofloxacin life cycle assessment (2021) *J Environ Chem Ecotoxicol* 3(2):45–53
34. Modeling pharmaceutical emissions for life cycle assessment (2020) *Int J Environ Assess Manage* 22(3):210–228
35. Fertilizer N₂O emissions and life cycle impacts. *Nutrient Cycling in Agroecosystems*
36. Epoxy resin production life cycle assessment. *Journal of Cleaner Production*
37. Dejus B, Tedoldi EL, Dejus S, Kairisa L, Rajarao GK (2026) The Life Cycle Assessment of Filamentous Fungi in Pharmaceutical Bioremediation and Wastewater Management: A Critical Review. *ACS EST Water* 6:2637–2655
38. Pradhan L, Barik MR, Badamali SK (2025) Sunlight driven photocatalytic degradation of ciprofloxacin over a dual S-scheme based BiOCl/Bi₂WO₆/g-C₃N₄ ternary heterojunction. *RSC Advances*
39. Asad L, Khan ZUH, Ullah F (2026) Advancement in photocatalytic degradation of ciprofloxacin: mechanisms, materials and environmental remediation. *RSC Adv* 16:15119–15151
40. Nagy J, Thi D, Toth HT, A.J (2023) Life Cycle, PESTLE, and Multi-Criteria Decision Analyses of Novel Process for Nitrogen Recovery from Reject Water. *Water* 15(18):3231
41. Mazhar I, Afzaal M, Altaf M, Sohail M, Ashraf RS, Nizami A-S (2025) Structurally engineered monolithic catalyst for enhanced sunlight-driven degradation of ciprofloxacin in contaminated water systems. *Discover Sustain* 6:606
42. Ministry of Ecology and Environment of China (MEE) (2025) Announcement on 2024 National Power Carbon Footprint Factors. MEE, Beijing

Figures

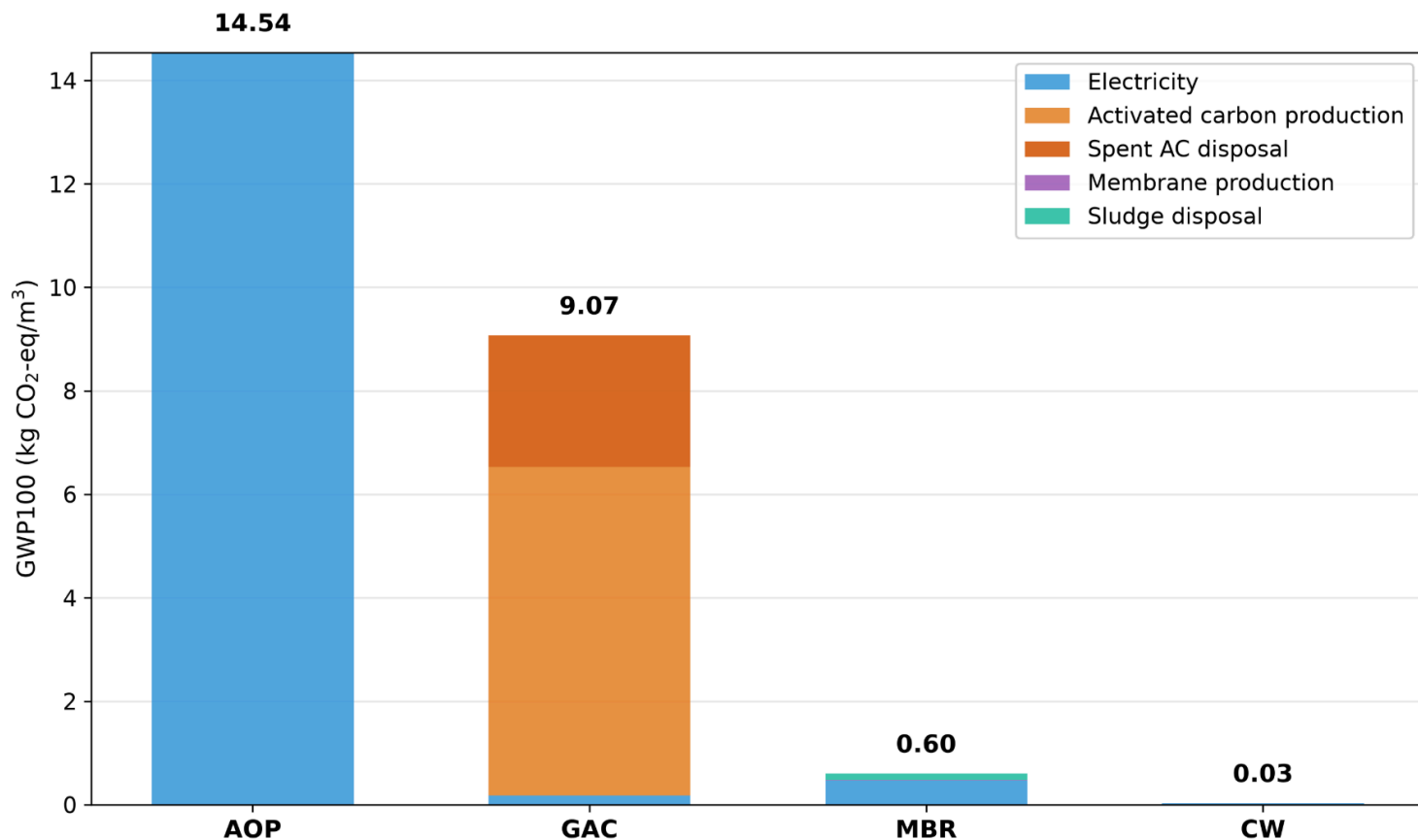


Figure 1

GWP contribution breakdown by treatment process (production wastewater scenario).

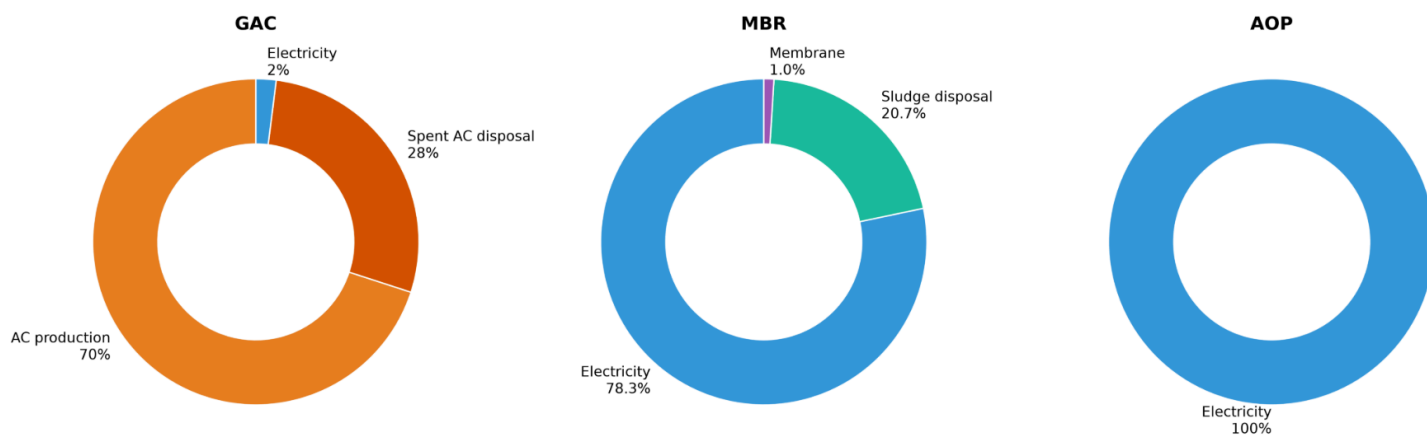


Figure 2

GWP contribution share for GAC, MBR, and AOP processes.

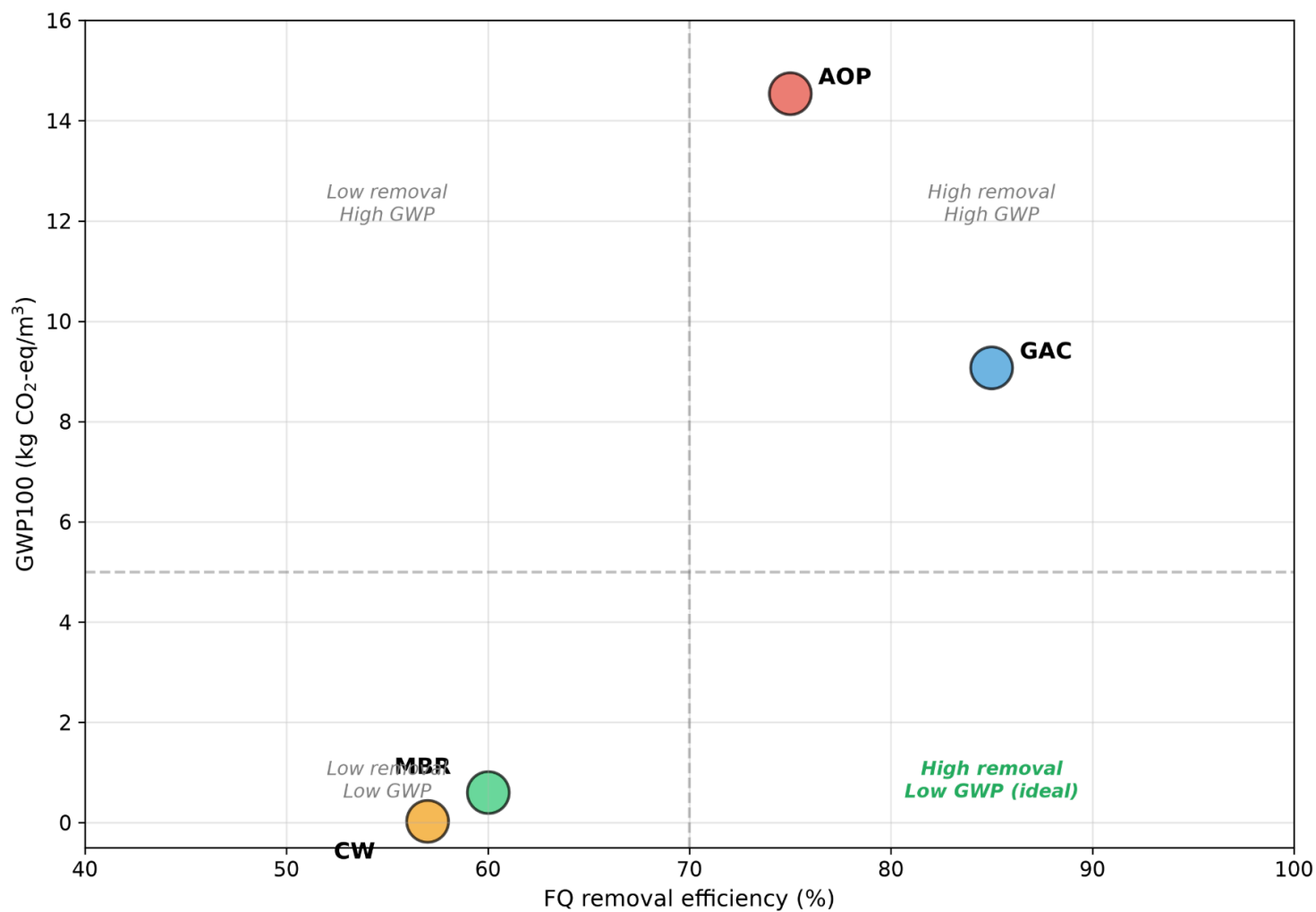


Figure 3

Trade-off analysis: removal efficiency vs GWP for four treatment technologies

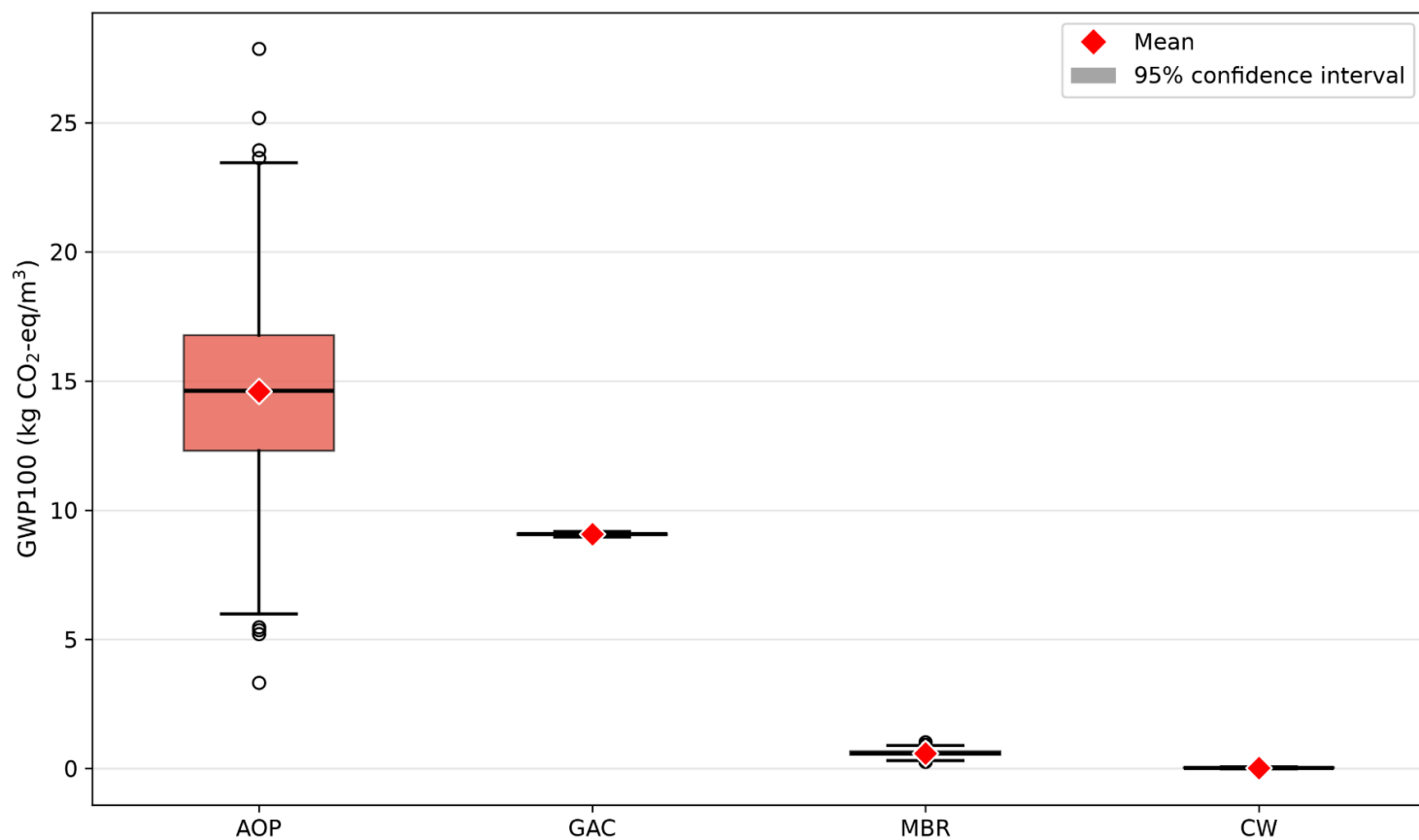


Figure 4

Monte Carlo uncertainty distribution (10,000 simulations) for GWP.

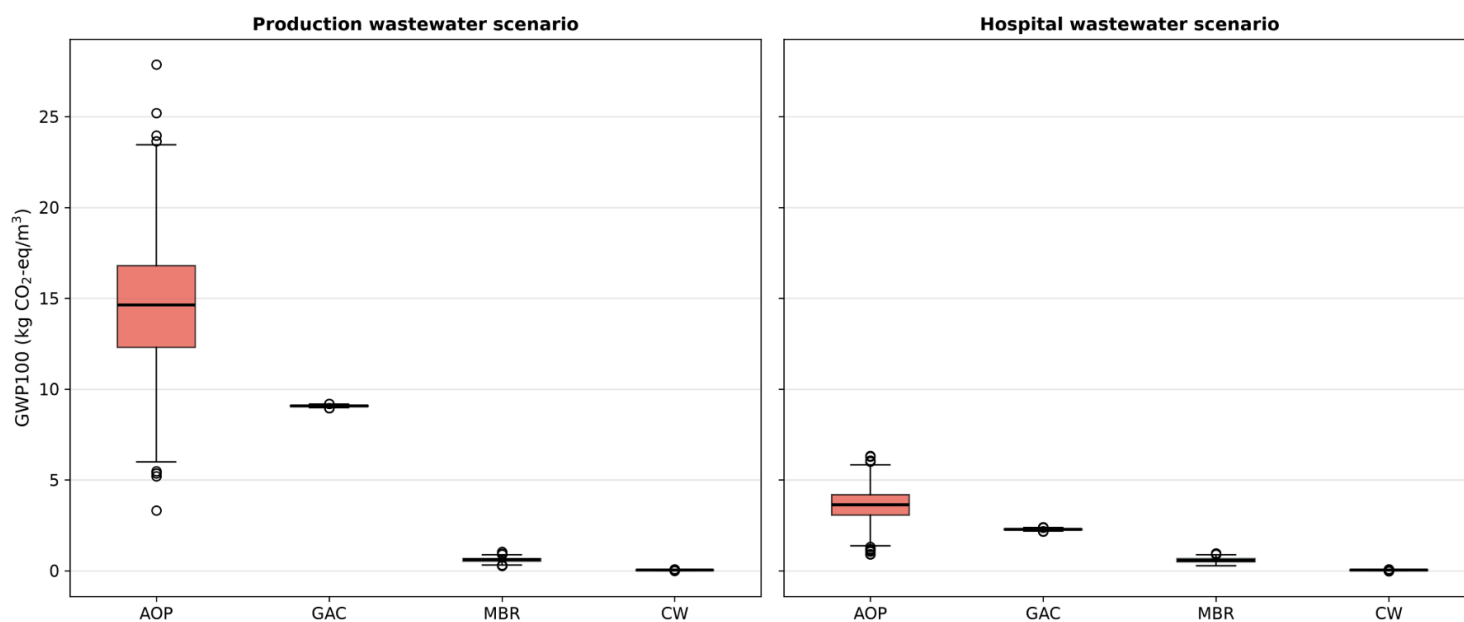


Figure 5

GWP uncertainty comparison across production wastewater and hospital wastewater scenarios.

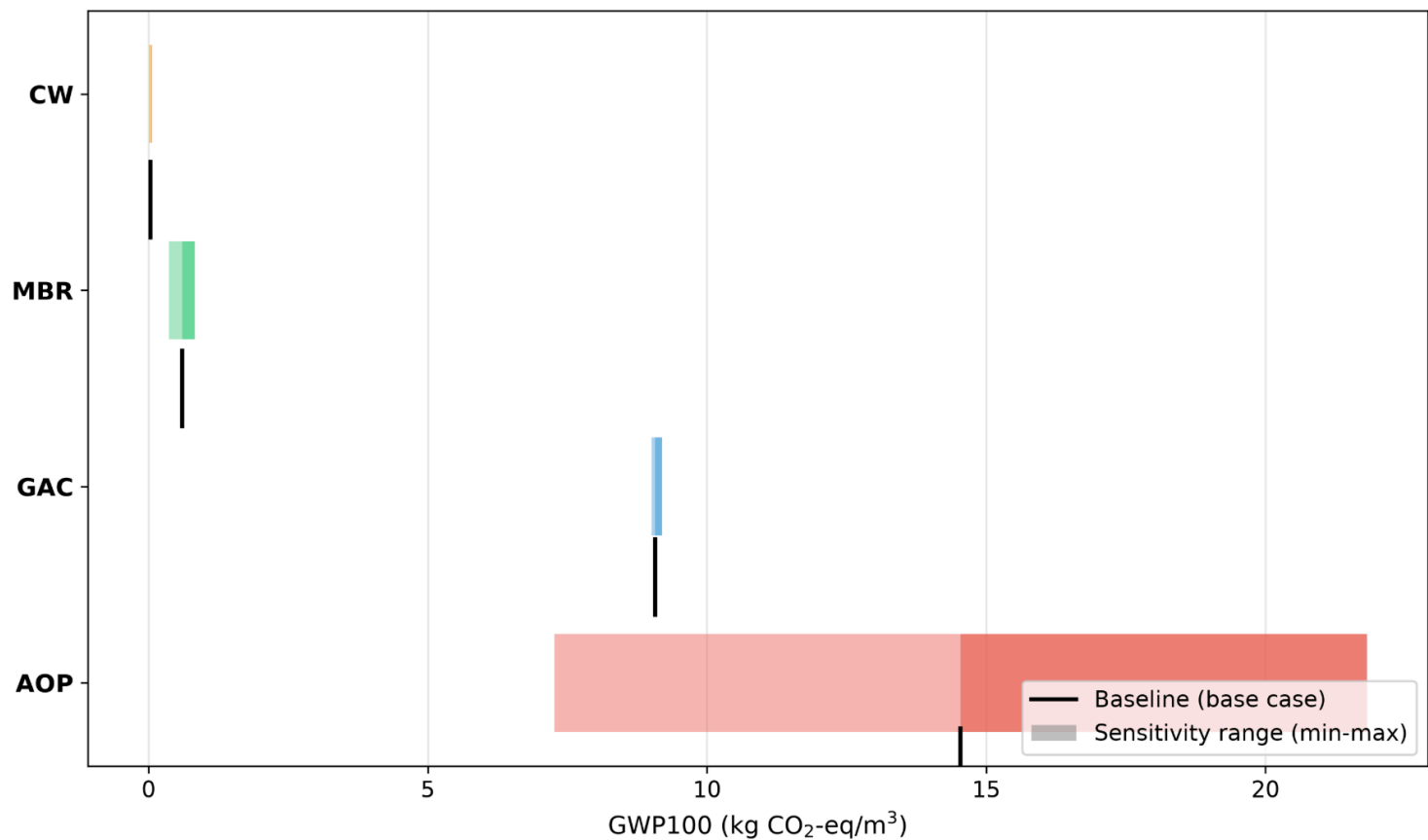


Figure 6

Sensitivity analysis tornado chart showing the impact of parameter variation on GWP.

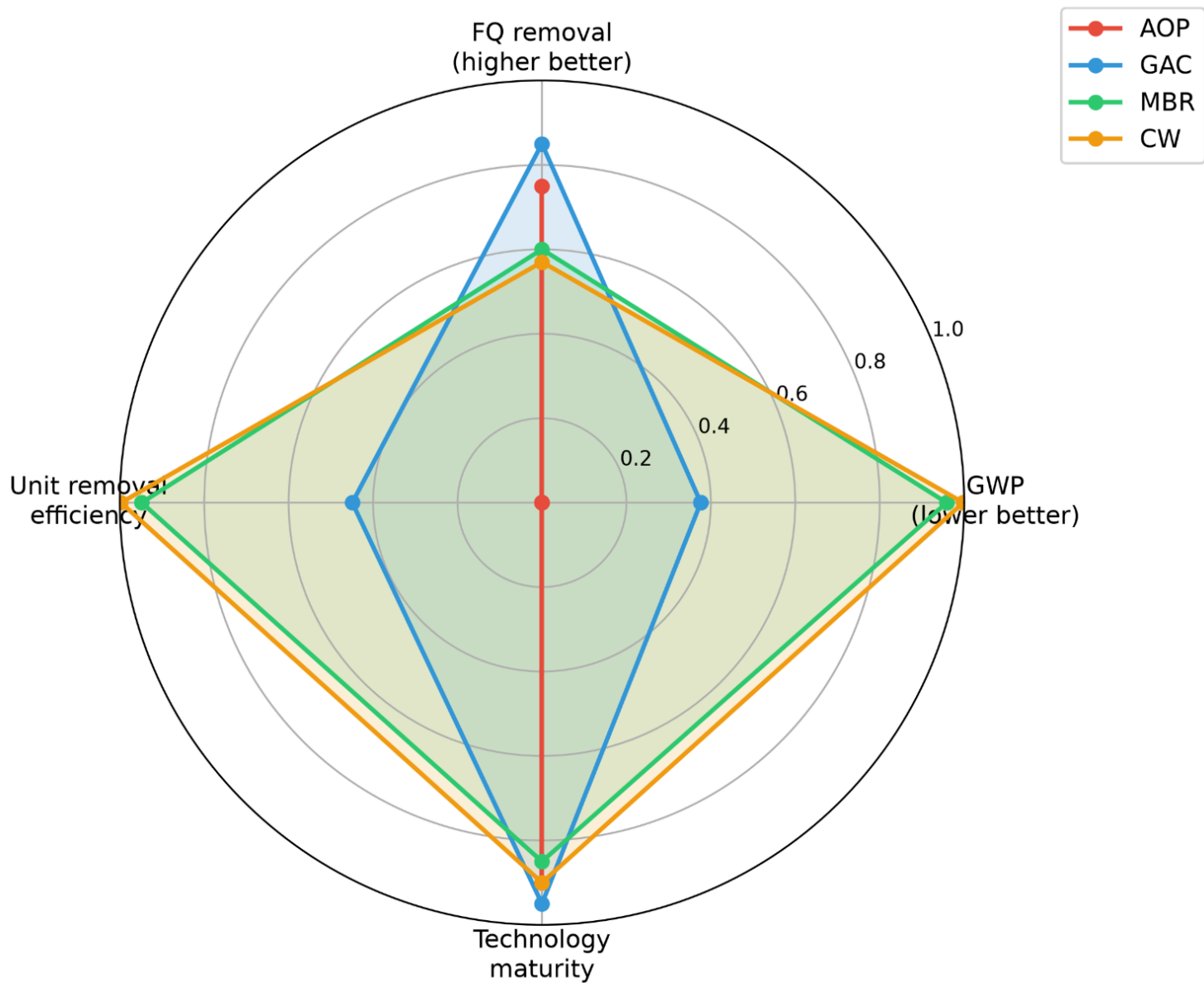


Figure 7

Multi-dimensional comparison of four treatment technologies across GWP, removal efficiency, unit removal efficiency, and technology maturity.