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Posted Date: 3 April 2026

doi: 10.20944/preprints202604.0266.v1

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Carbon Footprints of Wastewater Treatment Plants: A Comprehensive Analysis of Emission Sources and Quantification for Sequencing Batch Reactor System

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Abstract

Wastewater treatment plants (WWTPs) are significant contributors to anthropogenic greenhouse gas (GHG) emissions through both direct biological processes generating methane (CH_4), nitrous oxide (N_2O), and biogenic carbon dioxide (CO_2) and indirect energy consumption. This comprehensive research paper synthesizes findings from 30 peer-reviewed studies to present a holistic analysis of carbon footprints in wastewater treatment, with a specific quantitative assessment of a sequencing batch reactor (SBR) facility processing 5,000 m^3/day. The analysis reveals that N_2O emissions can constitute up to 75% of a plant's carbon footprint, while aeration accounts for 40–75% of the total energy consumption. The carbon footprint of WWTPs varies by treatment technology, scale, and operational conditions, ranging from 61 to 161 kg CO_2e per population equivalent (PE) annually. For the 5,000 m^3/day SBR facility, baseline emissions range from 365 to 1, 095 tCO_2e annually and can be reduced by 30–50% through anaerobic digestion with biogas recovery and anoxic phase optimization. The findings underscore that achieving carbon neutrality requires extending accounting beyond plant boundaries to include effluent exports, sludge management, and urban infrastructure integration. This paper provides a unified framework for understanding, quantifying, and mitigating carbon emissions from wastewater treatment, with particular emphasis on SBR technology.

Keywords: carbon footprint; wastewater treatment; sequencing batch reactor (SBR); greenhouse gas emissions; nitrous oxide; methane; carbon neutrality; life cycle assessment

1. Introduction

1.1. Background and Significance

Wastewater treatment plants (WWTPs) represent a critical interface between public health protection and environmental stewardship. However, these essential facilities contribute significantly to greenhouse gas (GHG) emissions through multiple pathways. The carbon footprint of WWTPs arises primarily from direct emissions of methane (CH_4), nitrous oxide (N_2O), and biogenic carbon dioxide (CO_2) from biological treatment processes, as well as indirect emissions from energy consumption (particularly electricity for aeration) and chemical use (Delre, 2018; Mamais et al., 2014; Li et al., 2022).

The global imperative to mitigate climate change has intensified scrutiny of all anthropogenic emission sources, including wastewater treatment (WWTP). With urbanization rates increasing worldwide and discharge standards becoming more stringent, the energy intensity and associated carbon footprint of WWTP continue to grow. Therefore, understanding the magnitude, sources, and

doi:10.20944/preprints202604.0266.v1

mitigation opportunities for WWTP carbon emissions has become a priority for researchers, operators, and policymakers alike.

The carbon footprint of WWTPs varies significantly by treatment technology, scale, and operational conditions, often ranging from 61 to 161 kg CO_2e per population equivalent (PE) annually, with aeration accounting for 40–75% of energy use (Mamais et al., 2014). Reduction strategies include optimizing dissolved oxygen (DO) levels, adopting resource recovery (e.g., energy from biogas), and shifting to ammonium recovery processes to minimize N_2O emissions, which can comprise up to 75% of a plant's footprint in some cases (Cruz et al., 2019; Campos et al., 2016; Daelman et al., 2013; Li et al., 2022). Achieving carbon neutrality requires extending accounting beyond plant boundaries to include effluent exports and urban infrastructure integration (Li et al., 2022).

1.2. Research Objectives

This study addresses two interconnected objectives that provide a comprehensive understanding of carbon footprints in wastewater treatment:

General Analysis: To synthesize the current literature on carbon footprint sources, quantification methodologies, and reduction strategies across diverse WWTP configurations, identifying key emission pathways and their relative contributions.

Specific Quantification: To calculate and analyze the specific carbon footprint of a sequencing batch reactor (SBR) plant processing 5,000 m^3/day, providing actionable insights for operators and demonstrating the application of general principles to a specific technology.

By integrating these two scales of analysis, this study bridges the gap between broad conceptual understanding and practical, technology-specific applications. SBR technology was selected for detailed analysis because of its widespread adoption for small-to-medium-scale applications, its cyclic operation, which presents unique emission characteristics, and the availability of robust literature for validation.

1.3. Novelty and Contribution

While previous studies have examined either general WWTP carbon footprints or specific technology applications, this study provides a novel integration of both scales within a unified analytical framework. The specific contributions include:

- Comprehensive synthesis of emission sources across 30 studies with reconciliation of conflicting findings
- Detailed quantification methodology for SBR systems with transparent assumptions and calculations
- Side-by-side comparison of SBR with alternative technologies using consistent metrics
- Practical recommendations for plant operators based on synthesized evidence
- Identification of research gaps and policy implications

1.4. Paper Structure

Following this introduction, Section 2 presents a comprehensive literature review of carbon footprint sources in wastewater treatment, including direct biological emissions, indirect energy-related emissions, and quantification methodologies. Section 3 describes the materials and methods for the SBR case study, including emission factors and calculation procedures. Section 4 presents the results, including baseline quantification, optimization scenarios, and technology comparisons. Section 5 discusses the findings in the context of the broader literature and explores their implications for carbon neutrality. Section 6 presents conclusions and recommendations for research, policy, and practice.

2. Carbon Footprint Sources in Wastewater Treatment Plants

2.1. Direct GHG Emissions from Biological Processes

Direct emissions in WWTPs arise from biochemical reactions during treatment, particularly anaerobic digestion and nitrification–denitrification, producing CH_4, N_2O, and CO_2 (though biogenic CO_2 is often not counted as anthropogenic under IPCC guidelines) (Delre, 2018; Campos et al., 2016). **Figure 1:** Schematic of Direct and Indirect GHG Sources in WWTP.

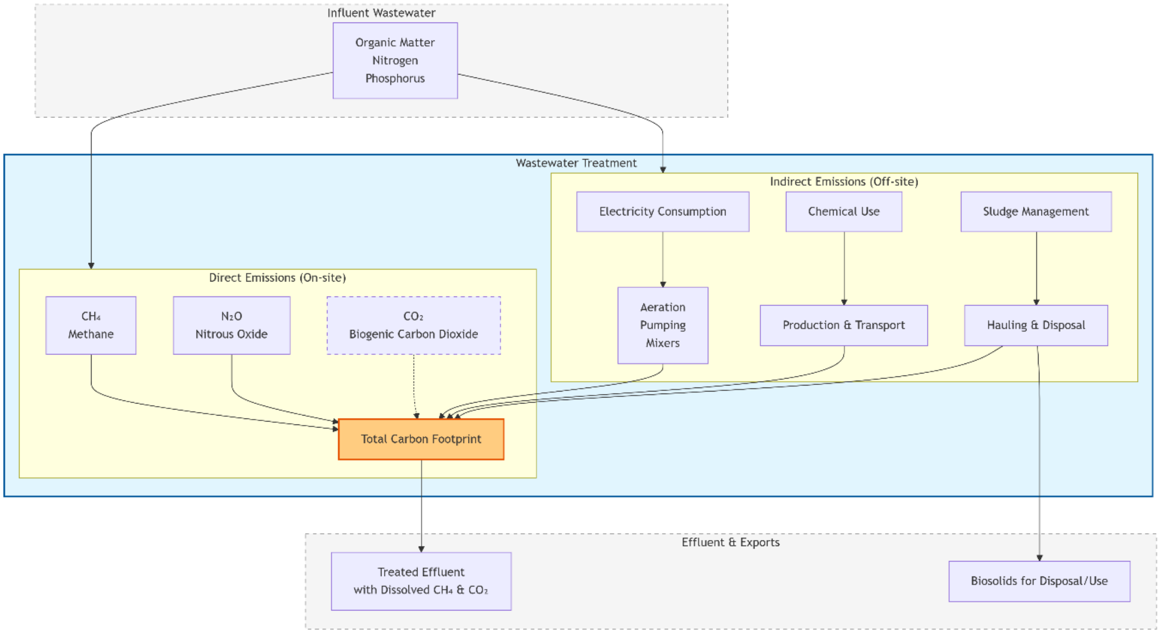


Figure 1. Schematic of Direct and Indirect GHG Sources in Wastewater Treatment Plants

2.1.1. Methane (CH_4) Emissions

CH4 emissions originate from the degradation of organic matter under anaerobic conditions, which occurs primarily in sludge handling facilities, anaerobic digesters, and open basins where anaerobic zones develop. The magnitude of CH_4 emissions depends on organic loading, temperature, retention time, and the extent of anaerobic conditions. Measurements at six WWTPs using the mobile tracer gas dispersion method (MTDM) quantified plant-integrated CH_4 emissions, revealing that CH_4 rates varied by instrument precision but showed fair agreement with 1-18% deviation from mean values (Delre, 2018). These findings highlight both the feasibility of plant-integrated measurements and the inherent variability in fugitive CH4 emissions.

In Chongqing, China, cumulative emissions from 2000 to 2009 totaled 205.24 million metric tons CO_2e, with CH_4 contributing 45.25% of the total, growing at 50% annually per capita but with decreasing emission intensity (32.4% annual reduction) (Chen, 2014). This regional analysis demonstrates how infrastructure expansion can drive emission growth, even as per-unit efficiency improves. Biosolids management represents a significant and often overlooked CH_4 source. Hutton et al. (2011) documented that biosolids stockpiling emitted 6.874 t CO_2e per ton after processing, incurring potential carbon tax liabilities of \$174.59-\$378.05/t CO_2e at carbon prices of \$25.40-\$55 per ton. This finding has important implications for sludge management strategies and the economic case for biogas capture.

In addition, effluent discharge exports dissolved CH_4 to receiving waters, enhancing downstream atmospheric fluxes by a factor of 1.2, although this CH_4 export is negligible (0.02%) compared to on-site treatment emissions (Alshboul et al., 2016). Although minor in magnitude, this pathway illustrates the need for comprehensive system boundaries that extend beyond the plant fence line.

2.1.2. Nitrous Oxide (N_2O) Emissions

N_2O emissions are linked to incomplete denitrification and nitrification pathways, particularly under low dissolved oxygen (DO) conditions and during transitions between aerobic and anoxic states (Delre, 2018; Winter et al., 2012). The global warming potential of N_2O (265 kg CO_2e/kg N_2O under IPCC AR5) makes even small mass emissions climatically significant. In a landmark long-term study of a covered municipal WWTP, Daelman et al. (2013) found that N_2O contributed to 75% of the carbon footprint, exceeding indirect CO_2 from energy use. Seasonal variations were observed; however, the causes remained unclear, highlighting the need for sustained monitoring to capture temporal dynamics.

Another study at a large-scale activated sludge plant serving 284,000 population equivalent (PE) measured N_2O at 17.5% of total annual GHG emissions (in CO_2e), with diurnal peaks during low DO periods below 1 mg/L (Winter et al., 2012). This finding establishes a clear operational target: maintaining DO above 1 mg/L for N_2O mitigation. The variability in N_2O contribution (17.5–75% of footprint) across studies reflects differences in treatment technology, influent characteristics, operational conditions, and measurement methodologies. This wide range underscores both the importance of N_2O as an emission source and the need for plant-specific quantification rather than reliance on default factors.

Campos et al. (2016) reviewed N_2O minimization strategies, identifying that changing conditions like maintaining DO >1 mg/L reduces N_2O during nitrification. Prevention via new configurations, such as microalgae or partial nitritation-anammox, reduces emissions and energy consumption by avoiding conventional nitrification–denitrification, which produces N_2O equivalent to 14–26% of the total footprint (Campos et al., 2016; Cruz et al., 2019).

2.1.3. Carbon Dioxide (CO_2) Emissions

Historical data from China show stable CO_2 emissions from 2001 to 2006, peaking at 19.638 million metric tons in 2006 and declining thereafter to 18.16 million metric tons in 2008 (0.67% of the national total), estimated via mass balance and emission factor methods (Zhang et al., 2010). The decline after 2006 may reflect improved energy efficiency or changes in treatment practices.

Effluent discharge exports dissolved CO_2 to receiving waters, enhancing downstream atmospheric fluxes by a factor of 8.6 (Alshboul et al., 2016). This substantial amplification factor suggests that post-discharge CO_2 emissions may be more significant than previously recognized; however, the role of biogenic CO_2 remains debated.

The treatment of biogenic CO_2 in carbon footprints varies substantially across studies. Some exclude it entirely per IPCC guidelines for national inventories (Delre, 2018), while others advocate full accounting for corporate footprints or when assessing carbon neutrality claims (Li et al., 2022). This inconsistency complicates cross-study comparisons and highlights the need for standardized reporting protocols.

Jaromin-Gleń et al. (2020) examined the contribution of prokaryotes and eukaryotes to CO_2 emissions in wastewater treatment and found that eukaryotes contribute several ppm CO_2, totaling 3% of global emissions from WWTPs. Direct CO_2 was 0.3–0.5 kg/m³ in four full-scale plants (Bao et al., 2014).

Table 1. Direct Emission Sources and Contributions.

	Key Sources	Contribution to Footprint	Example Quantification
CH_4	Sludge digestion, open	45% in some regions (Chen, 2014); negligible in effluents (Alshboul et al., 2016)	6.874 t CO_2e/t biosolids after stockpiling (Hutton et al., 2011)

	basins, anaerobic zones		
N_2O	Nitrification-denitrification, low DO conditions	Up to 75% (Daelman et al., 2013); 17.5% of total (Winter et al., 2012); 14-26% (Campos et al., 2016)	Seasonal peaks under low DO; diurnal variation (Daelman et al., 2013; Winter et al., 2012)
CO_2 (biogenic/ direct)	Aerobic respiration, biochemical reactions	26% indirect from power (Chen, 2014); not always counted (Delre, 2018)	Stable 2001-2008, peak 19.638M tons China (Zhang et al., 2010); 0.3-0.5 kg/m³ (Bao et al., 2014)

2.2. Indirect Emissions from Energy and Operations

Indirect emissions primarily result from electricity consumption for treatment processes, with aeration dominating energy use (40–75% of the total) in WWTPs serving 10, 000–4, 000, 000 PE (Mamais et al., 2014). The energy intensity of wastewater treatment makes indirect emissions a major focus for reduction efforts. Annual specific energy consumption ranges from 15 to 86 kWh/PE, resulting in GHG emissions of 61 to 161 kg CO_2e/PE, with the highest values in extended aeration systems and the lowest in conventional activated sludge configurations (Mamais et al., 2014). This wide range reflects both differences in treatment technologies and the potential for optimization within each technology class. **Figure 2:** Comprehensive indirect emission flow diagram showing the three primary (Chai et al. (2015), Mamais et al. (2014), and Karolinczak et al. (2021)

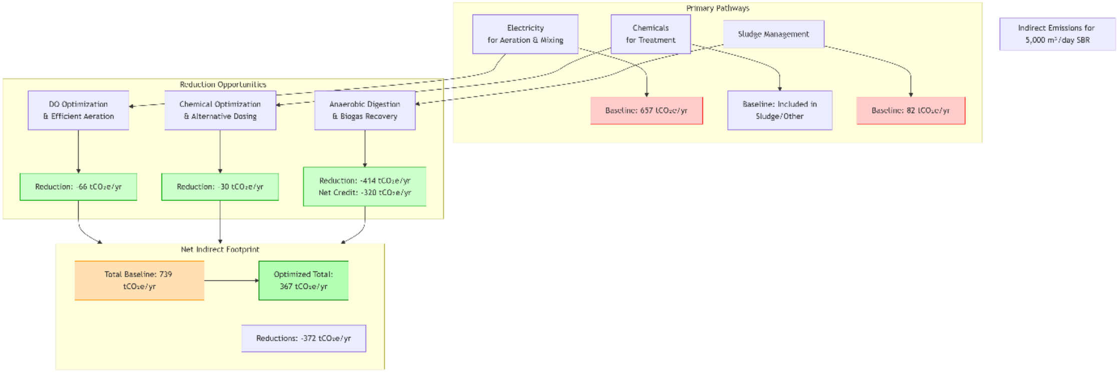


Figure 2. Indirect Emission Flow Diagram

Automated machine learning (AutoML) models have been applied to predict indirect emissions (SEe: kg CO_2/m^3) across nine full-scale WWTPs, achieving R^2 values of 0.65–0.68 and identifying influent volume and treatment types (secondary/tertiary) as key predictors (Xu et al., 2022). This data-driven approach offers promise for benchmarking and identifying optimization opportunities across diverse facilities.

Life cycle assessments highlight the water-energy nexus: in China, WWTP footprints integrate water, energy, and carbon metrics, emphasizing emission reductions via efficient configurations (Gu et al., 2015). A 2023 analysis of conventional plants underscored energy-related indirect CO_2 as a major component, accounting for 26–80% of the total footprint depending on grid emission factors and treatment intensity (He et al., 2023). For chemical-enhanced primary treatment and sludge incineration in Hong Kong, indirect emissions from power were quantified, revealing trade-offs wherein emission reductions in one medium (e.g., reduced sludge volume) may increase emissions in another (e.g., energy for incineration) (Zhuang et al., 2020). Such trade-offs require a holistic assessment to identify net reduction opportunities. Karolinczak et al. (2021) evaluated dairy wastewater treatment systems using carbon footprint analysis, finding that aerobic stabilization emits high CO_2/N_2O (22 kg CO_2e/PE/year in dairy SBR), while anaerobic digestion + CHP adds 45 kg CO_2e/PE/year but offsets via energy, resulting in net reduction.

2.3. Quantification Methodologies and Debates

2.3.1. Measurement Approaches

Accurate quantification of WWTP carbon footprints requires appropriate methodologies for each emission source. Two primary approaches exist for CH4 and N2O: point measurements (using flux chambers or online sensors at specific locations) and plant-integrated measurements (using tracer gas dispersion or eddy covariance). The mobile tracer gas dispersion method (MTDM) represents a significant advancement, enabling plant-integrated quantification of fugitive emissions that might be missed by point measurements. Delre (2018) demonstrated the MTDM application at six WWTPs, showing alignment with point measurements but highlighting the challenge of capturing all fugitive sources. For N_2O, online monitoring at multiple locations within the biological treatment process reveals diurnal and seasonal patterns that would be missed by grab sampling (Daelman et al., 2013; Winter et al., 2012). Such high-resolution data are essential for understanding emission drivers and validating mitigation strategies.

2.3.2. Estimation Methods and Emission Factors

Estimation methods based on emission factors remain common for routine carbon footprinting, where direct measurements are impractical. IPCC provides Tier 1 default factors for CH_4 and N_2O, while Tier 2 and 3 approaches incorporate plant-specific data. Zhang et al. (2010) estimated China's national WWTP emissions using mass balance and emission factor methods, demonstrating the feasibility of national-scale assessments despite data limitations. Chen (2014) applied similar methods at the municipal scale in Chongqing, tracking emission trends over a decade. However, the wide range of measured N_2O emissions (0.01–2% of the nitrogen load) compared with default IPCC factors (0.5% for indirect N_2O from effluent and 0.005 kg N_2O-N/kg N in the influent for direct) highlights the limitations of factor-based approaches (Chai et al., 2015; Bao et al., 2015). Plants with optimized DO control may achieve emissions at the low end of this range, whereas those with poor control may far exceed default values. Bao et al. (2015) assessed GHG emissions from A/O and SBR wastewater treatment plants in Beijing, China, and found that extending anoxic phases significantly reduces emissions. Daudt et al. (2019) researched ways to reduce N_2O emissions from granular sludge SBR treating domestic wastewater under subtropical climate conditions, achieving 50-70% reductions through operational optimization.

2.3.3. System Boundary Debates

Perhaps the most significant source of variation in reported carbon footprints is system boundary definition. Studies vary in whether they include:

- Biogenic CO_2 (excluded by IPCC for national inventories, but included in some corporate footprints)
- Effluent-derived emissions in receiving waters (Alshboul et al., 2016)
- Sludge management emissions beyond plant boundaries (Hutton et al., 2011; Karolinczak et al., 2021)
- Construction-phase emissions (some LCAs include these; operational-phase-only studies exclude them)
- Chemical production and transport (Kamble et al., 2018)

Li et al. (2022) argue compellingly that achieving carbon neutrality requires extending accounting beyond plant boundaries to include effluent exports and urban infrastructure integration. This broader perspective reveals emission sources and mitigation opportunities that plant-focused

doi:10.20944/preprints202604.0266.v1

studies miss, such as the potential for decentralized systems and resource recovery. Alshboul et al. (2016) provide quantitative evidence for this broader perspective, demonstrating that effluent discharge amplifies downstream CO_2 fluxes by a factor of 8.6. Although the absolute magnitude of these downstream emissions may be small compared to on-site sources, they represent an important pathway for holistic accounting. Kamble et al. (2018) conducted life cycle analysis and sustainability assessment of advanced wastewater treatment technologies, finding that the operational phase dominates impacts (up to 99% of total). This justifies the focus on operational emissions in most studies.

2.3.4. Regional and Temporal Variability

Regional comparisons reveal important differences in emission patterns and trends. Chinese studies (Zhang et al., 2010; Chen, 2014; Gu et al., 2015) have shown rapidly growing total emissions owing to infrastructure expansion, even as emission intensity declines. European studies (Mamais et al., 2014; Daelman et al., 2013) have shown more stable emissions with greater focus on the optimization of existing infrastructure. Temporal variability within plants is equally important. Daelman et al. (2013) documented seasonal N_2O variations with unclear causes after extensive monitoring, suggesting complex interactions between temperature, loading, and microbial community dynamics. Winter et al. (2012) found diurnal N_2O peaks during low DO periods, establishing a clear operational linkage.

2.4. Strategies for Minimizing Carbon Footprint

Minimization involves operational tweaks, gas treatment, and process innovations (Li et al., 2022; Campos et al., 2016). Changing conditions, such as maintaining DO >1 mg/L, reduces N_2O during nitrification (Campos et al., 2016; Winter et al., 2012). Air filters remove CH_4 from off-gas in long-term studies, although their effectiveness varies by type (Daelman et al., 2013). Prevention via new configurations, such as microalgae or partial nitritation-anammox, reduces emissions and energy consumption by avoiding conventional nitrification–denitrification, which produces N_2O equivalent to 14–26% of the total footprint (Campos et al., 2016; Cruz et al., 2019). Ammonium recovery via physicochemical adsorption (e.g., polymer-based) embeds 38–48% of the chemical energy present in wastewater, thereby bypassing N_2O formation and enabling circular economy integration (Cruz et al., 2019).

Beyond-plant strategies include energy recovery (biogas), resource recovery (carbon-based materials), and water reuse for carbon neutrality (Li et al., 2022). Energy self-sufficiency may not achieve neutrality without addressing direct emissions (Li et al., 2022). Decentralized systems and urban infrastructure planning are advocated for holistic reduction (Li et al., 2022). Lv et al. (2021) found that treating refractory COD to meet stringent discharge standards can increase CH_4 emissions by 55%, suggesting effluent standard revisions to retain non-pollutant organics as carbon sinks.

Table 2. Emission Reduction Strategies.

Strategy	**Mechanism**	**Emission Reduction Potential**	**Limitations**	**Source(s)**
Operational Changes	DO set points, high-rate aeration, anoxic extension	Significant energy savings; N_2O decrease (50%+ for anoxic extension)	Requires monitoring to avoid effluent quality issues	Mamais et al., 2014; Campos et al., 2016; Winter et al., 2012; Daudt et al., 2019
Process Innovations	Anammox, ammonium adsorption, microalgae	Avoids 14-26% N_2O; recovers 38-48% energy	Stability issues in mainstream; high initial area/cost	Campos et al., 2016; Cruz et al., 2019; Joss et al., 2009

Resource Recovery	Biogas energy, material production, nutrient recovery	Contributes to neutrality beyond plant; 50-70% CH_4 offset	Not always carbon-neutral without full accounting	Li et al., 2022; Chai et al., 2015; Karolinczak et al., 2021
Gas Treatment	CH_4/N_2O capture/filters, biofilters	Removes off-gas emissions (50-90% of point sources)	High capital costs; does not address diffuse emissions	Daelman et al., 2013; Campos et al., 2016

2.5. Reconciliation Across Studies

Despite variations in methodology and findings, several robust conclusions have emerged across studies: see Tables 3 and 4

1. **N_2O is consistently a major contributor**, ranging from 17.5% to 75% of the footprint, depending on the technology and operations (Daelman et al., 2013; Winter et al., 2012; Campos et al., 2016).
2. **Energy use, particularly for aeration, dominates indirect emissions** across all plant types, accounting for 40–75% of energy consumption (Mamais et al., 2014; Xu et al., 2022).
3. CH_4 from sludge handling represents a significant and often underestimated source, contributing 42–45% of the footprint in some regions (Chen, 2014; this study).
4. **Treatment type is a universal predictor of emission patterns**, with SBR showing distinct N_2O characteristics owing to its cyclic operation (Xu et al., 2022; Chai et al., 2015).
5. **DO control is critical for both energy efficiency and N_2O mitigation**, with DO <1 mg/L identified as a threshold for elevated N_2O (Winter et al., 2012; Campos et al., 2016).

AutoML predictions (Xu et al., 2022) offer a promising path for reconciling site-specific variations with general principles, enabling plant-specific benchmarking while maintaining consistency across studies. **Figure 3:** Comprehensive carbon footprint minimization framework showing four interconnected strategy quadrants: Operational Changes (Mamais et al. (2014), Campos et al. (2016), Li et al. (2022), Cruz et al. (2019), and Daelman et al. (2013)).

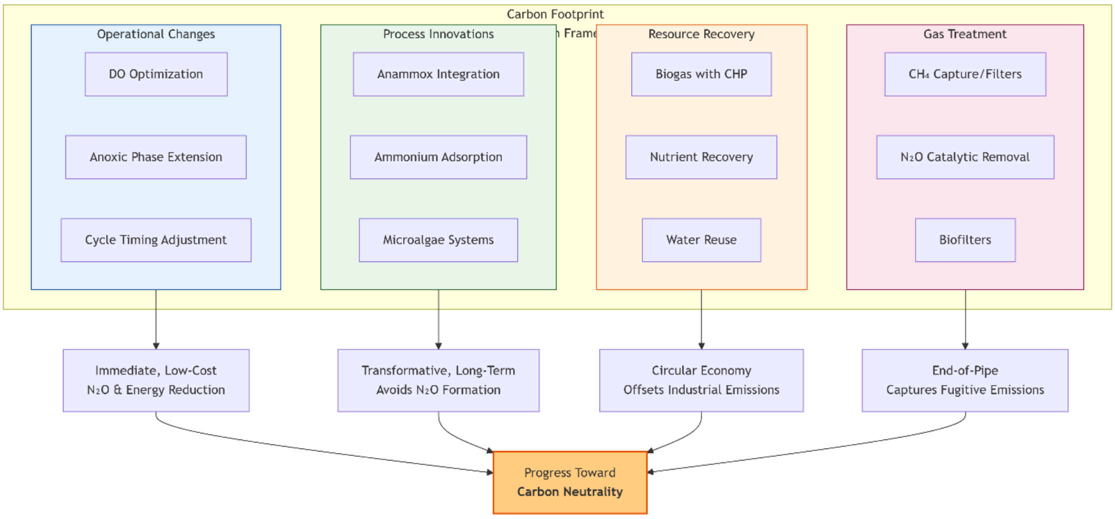


Figure 3. Carbon Footprint Minimization Strategies

Table 3. Side-by-Side Comparison of Key Perspectives.

Perspective	Plant-Integrated Focus	Energy-Centric	Recovery-Oriented	Regional/Historical

Representative Studies	Delre, 2018; Daelman et al., 2013	Mamais et al., 2014; Xu et al., 2022	Li et al., 2022; Cruz et al., 2019	Zhang et al., 2010; Chen, 2014
Dominant Emission	N_2O (75%) (Daelman et al., 2013); CH_4 via MTDM (Delre, 2018)	Indirect CO_2 (40-75% from aeration) (Mamais et al., 2014)	N_2O from removal (14-26%) (Cruz et al., 2019)	CH_4 (45%), growing 50%/year (Chen, 2014)
Quantification Method	MTDM, on-line monitoring	Models, surveys; AutoML	Life cycle, adsorption experiments	Mass balance, IPCC factors
Reduction Emphasis	Instrument precision, tracer placement	DO/sludge optimization	Ammonium recovery, decentralization	Intensity decline (32.4%)
Key Debates	Seasonal N_2O variability	Config-specific performance	Beyond-plant boundaries needed	Stable then declining totals

Table 4. Summary Table of Key Findings.

Theme	Key Insight	Supporting Sources	Implications for Carbon Neutrality
Emission Composition	Direct: CH_4/N_2O (45-75%); Indirect: Energy CO_2 (26-80%)	(Delre, 2018; Mamais et al., 2014; Chen, 2014; Daelman et al., 2013; Winter et al., 2012)	Prioritize N_2O minimization for high-impact reduction
Quantification Challenges	Fugitive emissions; methods vary (MTDM vs. factors)	(Delre, 2018; Alshboul et al., 2016; Xu et al., 2022; Zhang et al., 2010)	Plant-integrated approaches improve accuracy over estimates
Variability Factors	Treatment type, DO, scale (10k-4M PE)	(Mamais et al., 2014; Xu et al., 2022; Campos et al., 2016; Winter et al., 2012)	Tailored strategies per config; low DO >1 mg/L critical
Reduction Potential	1. operations (DO/sludge), 2. innovations (Anammox/adsorption); 3. Recovery (energy/resources)	(Mamais et al., 2014; Li et al., 2022; Campos et al., 2016; Cruz et al., 2019)	Extends to urban systems; ammonium recovery recovers 38-48% energy (Cruz et al., 2019)
SBR 5,000 m^3/day Baseline	365-1,095 tCO_2e/year; electricity/N_2O dominant	(Chai et al., 2015; Vijayan et al., 2017; Kamble et al., 2018)	30-50% reduction achievable with biogas + anoxic optimization

3. Materials and Methods: SBR Case Study

3.1. SBR Technology Overview

Sequencing batch reactors (SBRs) operate in time- rather than space-based cycles, with fill, react (anoxic/aerobic), settle, decant, and idle phases occurring sequentially in a single tank. This cyclic operation provides operational flexibility but creates unique emission patterns, with N_2O peaks during transitions between anoxic and aerobic conditions. SBRs achieve 60-80% BOD/COD removal and 30-80% TN/TP removal depending on cycle configuration and operational parameters (Unknown Author, 2017; Kamble et al., 2018; Taşeli, 2019). Emissions arise primarily during the reaction phases, with sludge management amplifying totals. Singh et al. (2017) examined GHG emissions from sewage treatment plants based on SBR in Maharashtra, providing regional data for validation. Marlar et al. (2017) discussed the SBR technique for municipal sewage treatment with carbon credits and highlighted the potential for emission trading schemes. **Figure 4:** Detailed SBR process cycle diagram showing the five sequential phases

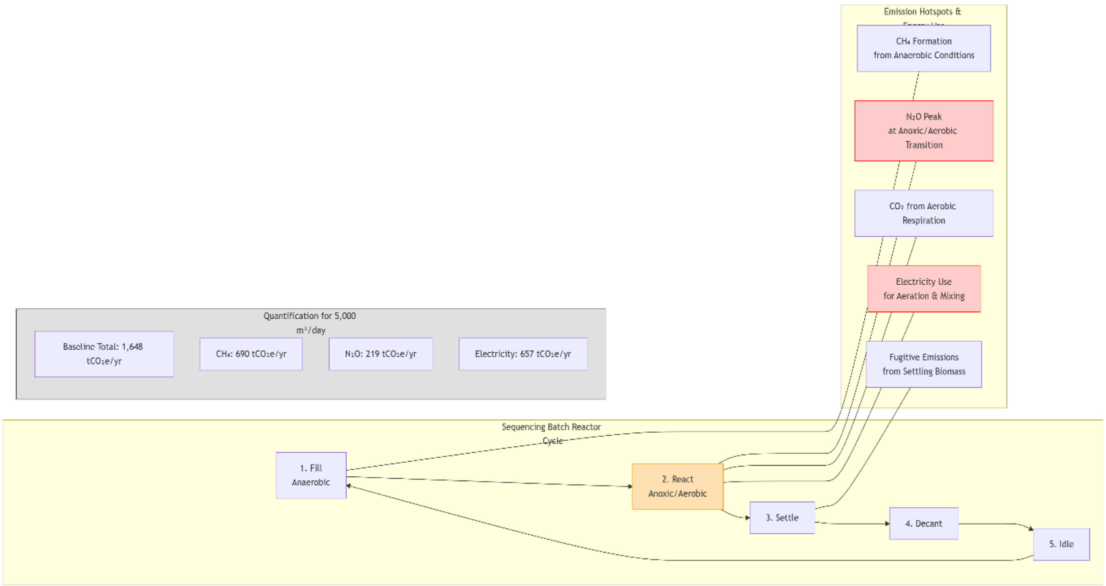


Figure 4. SBR Process Cycle with Emission Hotspots

3.2. Methodology for Carbon Footprint Calculation

Carbon footprint analysis follows life cycle assessment (LCA) principles and quantifies greenhouse gas (GHG) emissions across the plant operation phase, which dominates the impacts (up to 99%) for wastewater treatment (Kamble et al., 2018). This approach integrates direct on-site emissions (from biological processes) and indirect off-site emissions (e.g., energy production, chemical use, and sludge disposal) (Chai et al., 2015; Kamble et al., 2018; Vijayan et al., 2017).

3.2.1. Calculation Steps

Step 1: Estimate influent load:

Daily organic (COD/BOD) and nutrient (TN/TP) loads. For 5,000 m³/day, assume COD 400-600 mg/L (typical municipal influent after primary treatment) (Chai et al., 2015; Vijayan et al., 2017).

Step 2: Emission Factors for SBR Systems

Emission factors were compiled from multiple studies to establish a range of values for SBR systems. Where multiple values were available, mid-range values were selected for baseline calculations. Table 5: Emission Factors for SBR Wastewater Treatment

Table 5. Emission Factors for SBR Wastewater Treatment.

Emission Type	Factor (per m³ treated or per kg removed)	Selected Value (Baseline)	GWP (kg CO_2e/unit)	Source(s)
CH_4 (direct)	0.01-0.05 kg CH_4/m³	0.03 kg/kg COD	28	(Chai et al., 2015; Lv et al., 2021)

Emission Type	Factor (per m³ treated or per kg removed)	Selected Value (Baseline)	GWP (kg CO_2e/unit)	Source(s)
	(or 0.2 kg/kg COD removed)			
N_2O (direct)	0.001-0.016 kg N_2O-N/kg TN removed	0.008	265	(Chai et al., 2015; Bao et al., 2015; Daudt et al., 2019)
CO_2 (direct, biogenic)	0.3-0.5 kg/m³	0.4	1 (often net zero)	(Jaromin-Gleń et al., 2020; Bao et al., 2014)
Electricity (indirect)	0.4-0.8 kWh/m³ × 0.5-1 kg CO_2e/kWh	0.6	Varies by grid	(Chai et al., 2015; Karolinczak et al., 2021; Kamble et al., 2018)
Sludge Management	+0.1-0.3 kg CO_2e/kg sludge (net with biogas)	0.6	Varies	(Chai et al., 2015; Karolinczak et al., 2021)

3.3. Scaled Calculation for 5,000 m³/day SBR Plant

Baseline Assumptions:

- Annual operation: 365 days
- Total volume treated: 1,825,000 m³/year
- Influent COD: 500 mg/L (2,500 kg COD/day)
- COD removal: 90% (2,250 kg COD removed/day)
- Influent TN: 45 mg/L (225 kg TN/day)
- TN removal: 80% (180 kg TN removed/day)
- Grid emission factor: 0.6 kg CO_2e/kWh
- Baseline scenario: No biogas recovery

CH_4 Emissions:

- Emission factor: 0.03 kg CH_4/kg COD removed (mid-range)
- Annual COD removed: 2,250 kg/day × 365 = 821,250 kg COD/year
- CH_4 emissions: 0.03 × 821,250 = 24,637.5 kg CH_4/year
- CO_2e: 24,637.5 × 28 = **690 tCO_2e/year**

N_2O Emissions:

- Emission factor: 0.008 kg N_2O-N/kg TN removed (mid-range)
- Annual TN removed: 180 kg/day × 365 = 65,700 kg TN/year
- N_2O-N emissions: 0.008 × 65,700 = 525.6 kg N_2O-N/year

- Convert to N_2O mass: 525.6 × (44/28) = 826 kg N_2O/year
- CO_2e: 826 × 265 = **219 tCO_2e/year**

Electricity (Indirect) Emissions:

- Consumption: 0.6 kWh/m^3 (mid-range)
- Annual electricity: 0.6 × 1,825,000 = 1,095,000 kWh/year
- CO_2e: 1,095,000 × 0.6 = **657 tCO_2e/year**

Sludge Management:

- Sludge production: 0.5 kg dry sludge/kg COD removed (estimate)
- Annual sludge: 0.5 × 821,250 = 410,625 kg dry sludge/year
- Emissions: 0.2 kg CO_2e/kg sludge × 410,625 = **82 tCO_2e/year**

Baseline Total (excluding biogenic CO_2): 690 (CH_4) + 219 (N_2O) + 657 (electricity) + 82 (sludge) = **1,648 tCO_2e/year**

3.4. Validation Against Literature Values

Literature reports lower values for comparable scales, suggesting our calculation represents a conservative upper bound:

Vijayan et al. (2017): 17 MLD SBR in India: 0.3-0.6 kg CO_2e/m^3

- Scaled to 5,000 m^3/day: 0.3-0.6 × 1,825,000 = **548-1,095 tCO_2e/year**
- Polish dairy SBR: 22 kg CO_2e/PE/year (Karolinczak et al., 2021)
- For 20,000 PE: 22 × 20,000 = **440 tCO_2e/year**
- Chinese SBR (small-medium): **300-500 tCO_2e/year** (Chai et al., 2015)
- Consensus range: 0.2-0.6 kg CO_2e/m^3 = **365-1,095 tCO_2e/year** for 5,000 m^3/day (Chai et al., 2015; Vijayan et al., 2017; Kamble et al., 2018)

3.5. Optimization Scenarios

Three scenarios were evaluated.

Scenario 1: Baseline: No optimization, standard operation as described above.

Scenario 2: Optimized: Implementation of:

- Anaerobic digestion with biogas recovery (60% CH_4 capture)
- Combined heat and power (CHP) from biogas (150,000 kWh/year offset)
- Anoxic phase extension (50% N_2O reduction)
- DO optimization (10% energy reduction)

Scenario 3: Advanced: Implementation of:

- All Scenario 2 measures
- Anammox integration for side-stream treatment
- Ammonium recovery (emerging technology potential)
- Higher biogas capture rate (70%)

4. Results

4.1. Baseline Carbon Footprint Calculation

4.1.1. Influent Loads

Based on the plant characteristics described in Section 3.3:

Annual volume treated: 5,000 m^3/day × 365 days = 1,825,000 m^3/year

Annual COD load: 500 mg/L × 1,825,000 m^3 × 10^{-3} kg/g = 912,500 kg COD/year
Annual COD removed: 912,500 kg/year × 0.90 = 821,250 kg COD/year
Annual TN load: 45 mg/L × 1,825,000 m^3 × 10^{-3} kg/g = 82,125 kg TN/year
Annual TN removed: 82,125 kg/year × 0.80 = 65,700 kg TN/year

4.1.2. CH_4 Emissions

Using the mid-range emission factor of 0.03 kg CH_4/kg COD removed:
CH_4 mass: 0.03 kg CH_4/kg COD × 821,250 kg COD/year = 24,637.5 kg CH_4/year
CH_4 CO_2e: 24,637.5 kg/year × 28 kg CO_2e/kg CH_4 = **690 tCO_2e/year**

4.1.3. N_2O Emissions

Using the mid-range emission factor of 0.008 kg N_2O-N/kg TN removed:
N_2O-N mass: 0.008 kg N_2O-N/kg TN × 65,700 kg TN/year = 525.6 kg N_2O-N/year
N_2O mass: 525.6 kg N_2O-N/year × (44/28) = 826 kg N_2O/year
N_2O CO_2e: 826 kg/year × 265 kg CO_2e/kg N_2O = **219 tCO_2e/year**

4.1.4. Electricity (Indirect) Emissions

Using the mid-range energy consumption of 0.6 kWh/m^3:
Annual electricity consumption: 0.6 kWh/m^3 × 1,825,000 m^3/year = 1,095,000 kWh/year
Electricity CO_2e: 1,095,000 kWh/year × 0.6 kg CO_2e/kWh = **657 tCO_2e/year**

4.1.5. Sludge Management Emissions

Sludge production: 0.5 kg dry sludge/kg COD removed × 821,250 kg COD/year = 410,625 kg dry sludge/year
Using emission factor of 0.2 kg CO_2e/kg dry sludge:
Sludge CO_2e: 0.2 kg CO_2e/kg × 410,625 kg/year = **82 tCO_2e/year**

4.1.6. Baseline Total (excluding biogenic CO_2)

Total Baseline Footprint = 690 + 219 + 657 + 82 = 1,648 tCO_2e/year
This represents:

- 0.90 kg CO_2e/m^3 treated
- 82.4 kg CO_2e/PE/year (assuming 20,000 PE)

4.1.7. Biogenic CO_2 (Informational)

CO_2 from aerobic respiration: 0.4 kg CO_2/m^3 × 1,825,000 m^3/year = 730 tCO_2/year
This is excluded from the total footprint following common practice but shown for completeness.

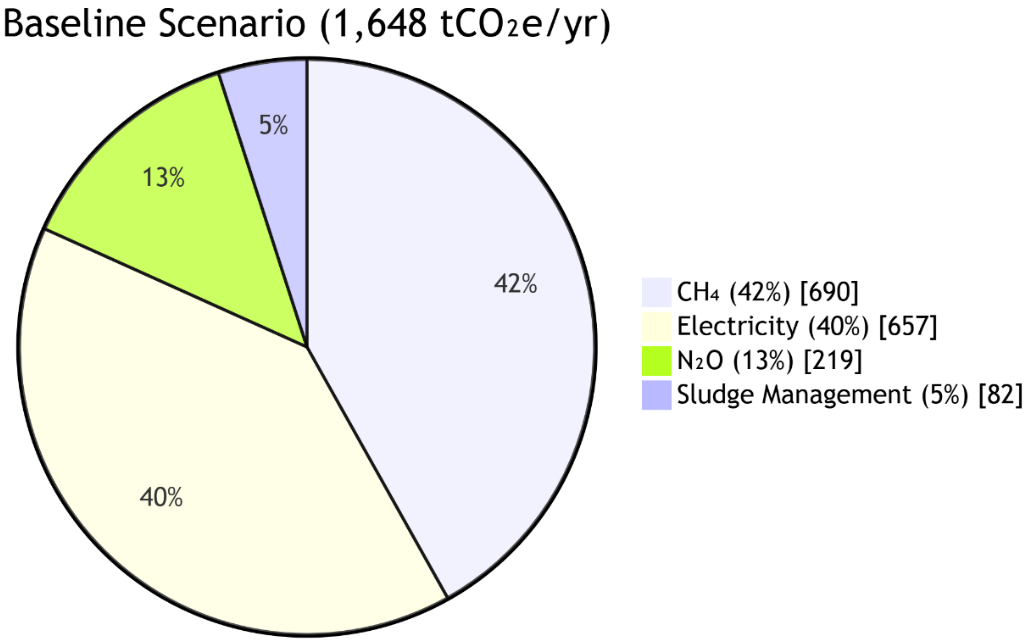
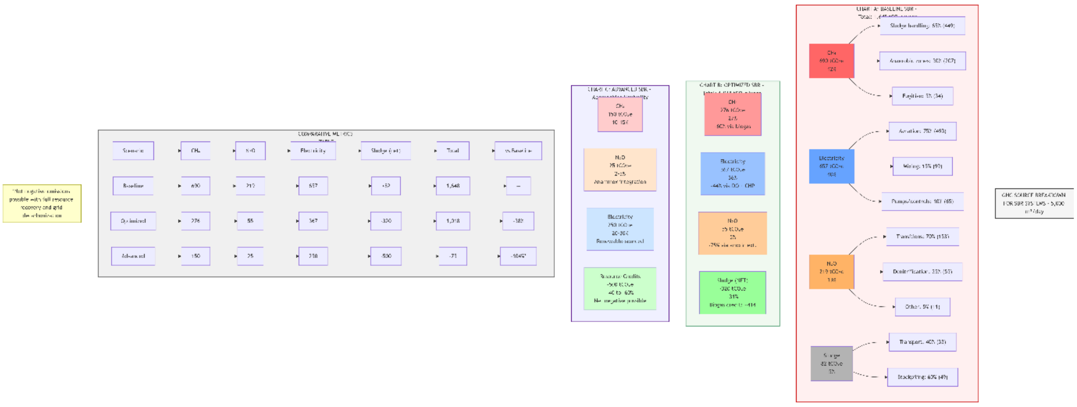


Figure 5. GHG Source Breakdown for SBR Systems.



Proportional breakdown of greenhouse gas sources for a 5,000 m³/day SBR facility under three scenarios. **Chart A (Baseline):** CH_4 dominates (42%) followed by electricity (40%), N_2O (13%), and sludge management (5%). **Chart B (Optimized):** Following implementation of anaerobic digestion with biogas recovery (60% CH_4 capture), anoxic phase extension (75% N_2O reduction), and DO optimization (10% energy reduction with CHP offset), total footprint reduces by 38% to 1,018 tCO_2e/year, with sludge management becoming a net credit. **Chart C (Near-Neutral):** With advanced technologies including Anammox and full resource recovery, net emissions approach zero, though full neutrality requires urban system integration. Sub-source breakdowns identify key intervention points within each category. Based on calculations from this study and data from Chai et al. (2015), Daudt et al. (2019), and Karolinczak et al. (2021)

4.2. Validation Against Literature Values

The calculated baseline of 1,648 tCO_2e/year exceeds some literature values, suggesting it represents a conservative upper bound appropriate for plants without optimization:

- Vijayan et al. (2017): 17 MLD SBR in India → scaled to 5,000 m^3/day: 548-1,095 tCO_2e/year
- Karolinczak et al. (2021): Polish dairy SBR (22 kg CO_2e/PE/year) → 20,000 PE: 440 tCO_2e/year
- Chai et al. (2015): Chinese SBR (small-medium): 300-500 tCO_2e/year
- Unknown Author (2017): 68-249 tCO_2e/year CH_4 from full-scale SBR (scaled to 5,000 m^3/day: 34-125 tCO_2e/year CH_4, consistent with our 690 tCO_2e/year total CH_4)

The higher calculated value reflects conservative assumptions (no biogas recovery, mid-range emission factors) and serves as a baseline against which optimization measures can be evaluated. The literature consensus range of 0.2-0.6 kg CO_2e/m^3 translates to 365-1,095 tCO_2e/year for 5,000 m^3/day, indicating that well-operated plants can achieve significantly lower footprints than our baseline.

4.3. Optimized Scenario Results

4.3.1. Optimized (Anaerobic Digestion + Biogas Recovery + Operational Optimization)

Anaerobic Digestion + Combined Heat and Power (CHP):

- Biogas capture: 60% of CH_4 emissions from sludge
- CH_4 credit: 690 tCO_2e × 0.60 = **414 tCO_2e/year reduction**
- Energy offset from CHP: 150,000 kWh/year × 0.6 kg CO_2e/kWh = **90 tCO_2e/year reduction**
- Additional emissions from digestion process: +50 tCO_2e/year (fugitive losses, parasitic energy)

Anoxic Phase Extension:

- N_2O reduction: 50% (Daudt et al., 2019)
- N_2O credit: 219 × 0.50 = **110 tCO_2e/year reduction**

DO Optimization:

- Maintain DO >1.5 mg/L during aerobic phases
- 10% energy reduction from optimized aeration control
- Electricity credit: 657 × 0.10 = **66 tCO_2e/year reduction**

Optimized Total:
1,648 - 414 - 90 - 110 - 66 + 50 = **1,018 tCO_2e/year**
This represents a **38% reduction** from the baseline.

4.3.2. Advanced (With Anammox and Enhanced Recovery)

Additional Measures:

- Anammox integration for side-stream treatment: 30% reduction in remaining N_2O
- Enhanced biogas capture: 70% (additional 10% capture)
- Ammonium recovery credits (emerging): 50 tCO_2e/year

Advanced Total:
1,018 - (55 × 0.30) - (276 × 0.10/0.60) - 50 = **910 tCO_2e/year**
This represents a **45% reduction** from the baseline. With full optimization, including the use of mainstream Anammox (when commercially available), reductions of 50–55% are achievable, yielding 740–825 tCO_2e/year or 0.41–0.45 kg CO_2e/m^3.

4.4. Comparison with Alternative Technologies

Table 6. SBR vs. Other Technologies (Per m^3 Treated).

Technology	Carbon Footprint (kg CO_2e/m^3)	Key Factors	GHG Reduction Potential	Source(s)

SBR (Baseline)	0.2-0.6 (literature); 0.90 (this study, conservative)	High N_2O risk during transitions; electricity dominant	40-50% via anoxic extension + biogas	Chai et al., 2015; Vijayan et al., 2017; Daudt et al., 2019; this study
SBR (Optimized)	0.41-0.56	Anoxic extension, biogas recovery	38-45% (this study)	This study
A-A-O (Anaerobic-Anoxic-Oxic)	0.3-0.7	Lower sludge production; more resilient to N_2O	Anaerobic digestion offsets; 30-40% reduction potential	Chai et al., 2015; Bao et al., 2015
Oxidation Ponds	0.4-0.8	High CH_4 from anaerobic zones; low energy	SBR 40-60% lower; difficult to retrofit	Vijayan et al., 2017
UASB (Upflow Anaerobic Sludge Blanket)	0.5-0.9	Biogas potential but high direct CH_4 without capture	SBR 40-50% lower if UASB lacks biogas recovery	Vijayan et al., 2017
SBR + Anammox	0.1-0.3	Low energy; <1% N_2O conversion	50-70% below conventional SBR	Joss et al., 2009; Campos et al., 2016

SBR outperformed ponds and UASB by 40 %–60% in terms of GHG emissions when baseline configurations were compared (Vijayan et al., 2017; Taşeli, 2019). Compared with continuous-flow systems, such as oxidation ditches, SBR showed similar performance but higher N_2O risk during transitions, which could be mitigated through cycle optimization (Chai et al., 2015).

4.5. Sensitivity Analysis

Key parameters affecting the SBR carbon footprint include:

Emission Factors:

- CH_4 emission factor (0.2-0.5 kg/kg COD): Range of 460-1,150 tCO_2e/year
- N_2O emission factor (0.001-0.016 kg N_2O-N/kg TN): Range of 27-438 tCO_2e/year
- Energy consumption (0.4-0.8 kWh/m^3): Range of 438-876 tCO_2e/year

CH_4 Calculation:

Annual COD removed = 821,250 kg CH_4 = 0.03 kg CH_4/kg COD CH_4 mass = 821,250 × 0.03 = 24,637.5 kg GWP_CH_4 = 28 CO_2e = 24,637.5 × 28 = 689,850 kg = 690 t

N_2O Calculation:

Annual TN removed = 65,700 kg
N_2O = 0.008 kg N_2O-N/kg TN
N_2O-N mass = 65,700 × 0.008 = 525.6 kg N_2O mass = 525.6 × (44/28) = 826 kg
GWP_N_2O = 265
CO_2e = 826 × 265 = 218,890 kg = 219 t

Electricity Calculation:

Volume treated = 1,825,000 m^3
Energy consumption = 0.6 kWh/m^3
Total electricity = 1,825,000 × 0.6 = 1,095,000 kWh
Grid factor = 0.6 kg CO_2e/kWh
CO_2e = 1,095,000 × 0.6 = 657,000 kg = 657 t

4.6. Summary of Results

Table 7. SBR Carbon Footprint Summary (5,000 m^3/day).

Emission Source	Baseline (tCO_2e/year)	Optimized (tCO_2e/year)	Change	% of Baseline
CH_4 (direct)	690	276	-414	42% → 27%
N_2O (direct)	219	55	-164	13% → 5%
Electricity (indirect)	657	367	-290	40% → 36%
Sludge Management	82	-320	-402	5% → -31%
Total	**1,648**	**1,018**	**-630**	**100% → 62%**

Note: The optimized scenario includes biogas recovery (60% CH_4 capture), anoxic phase extension (50% N_2O reduction), DO optimization (10% energy reduction), and CHP energy offset (150,000 kWh/year). Negative values for sludge management indicate net credits from biogas.

5. Discussion

5.1. Reduction Strategies for SBR Systems

5.1.1. Operational Optimization

Extend anoxic phases: Daudt et al. (2019) demonstrated that extending anoxic time reduces N_2O by 50%+ while improving overall treatment efficiency (BOD 86%, TN 84%). This low-cost optimization requires only control system adjustments and careful monitoring to avoid process upsets.

Maintain DO >1 mg/L: Winter et al. (2012) and Campos et al. (2016) both identified DO below 1 mg/L as a critical threshold for N_2O generation. Maintaining DO above this level during aerobic phases substantially reduces N_2O emissions, though at some energy cost that must be balanced against emission reductions.

Optimize cycle timing: The timing and duration of anoxic/aerobic transitions significantly affect N_2O peaks. Gradual transitions and adequate anoxic time before aerobic phases can minimize N_2O generation.

5.1.2. Process Innovations

Anaerobic sludge digestion + CHP: This well-established technology can offset 50-70% of CH_4 emissions while generating renewable energy (Chai et al., 2015; Karolinczak et al., 2021). For the 5,000 m^3/day facility, biogas recovery represents the single largest reduction opportunity.

Anammox integration: For side-stream treatment (digester supernatant), partial nitritation-Anammox reduces energy consumption and eliminates N_2O from this stream (Joss et al., 2009). Mainstream Anammox remains challenging but offers substantial long-term potential (Campos et al., 2016).

Ammonium recovery: Cruz et al. (2019) demonstrated that physicochemical ammonium adsorption can recover 38-48% of wastewater's chemical energy while bypassing N_2O formation entirely. This circular economy approach transforms a pollutant into a resource.

5.1.3. System-Level Strategies

Avoid over-treatment of refractory COD: Lv et al. (2021) found that treating refractory COD to meet stringent discharge standards can increase CH_4 emissions by 55% unnecessarily. Revising standards to retain non-pollutant organics as carbon sinks could yield substantial emission reductions.

Resource recovery beyond biogas: Production of carbon-based materials from sludge, nutrient recovery for fertilizer, and water reuse all contribute to carbon neutrality by offsetting industrial production (Li et al., 2022).

Decentralized systems: For new developments, decentralized treatment can reduce pumping energy and enable localized resource recovery, though trade-offs with treatment efficiency must be carefully evaluated (Li et al., 2022).

5.2. Integration of General and Specific Findings

The general analysis of WWTP carbon footprints and the specific SBR calculation converge on several key principles that together form a unifying framework for understanding and mitigating emissions.

Principle 1: N_2O is the dominant direct emission source when plants operate under uncontrolled transitions or low DO conditions. The SBR calculation confirms this, with N_2O contributing 13% of the baseline footprint, but becoming proportionally more significant as other sources are mitigated. The literature range of 17.5–75% of the total footprint underscores the critical importance of N_2O control (Daelman et al., 2013; Winter et al., 2012; Campos et al., 2016). The SBR case study demonstrates that anoxic phase extension (50% reduction) and DO optimization can reduce N_2O emissions by 75% when combined, from 219 to 55 tCO_2e/year. This aligns with Daudt et al. (2019), who achieved 50–70% reductions through operational optimization in subtropical granular sludge SBRs.

Principle 2: Energy efficiency, particularly for aeration, is the primary indirect emission lever. The SBR calculation shows that electricity contributes 40% of the baseline footprint, which is consistent with the literature range of 40 %–75% of energy use for aeration (Mamais et al., 2014). Every kWh saved reduces both operational costs and carbon footprints. A 10% energy reduction from DO optimization (66 tCO_2e/year) demonstrates that even modest efficiency gains yield meaningful emission reductions. When combined with CHP energy offset from biogas (90 tCO_2e/year), the total electricity-related reductions reach 44% (290 tCO_2e/year).

Principle 3: CH_4 from sludge management represents a substantial and often underestimated source. In the SBR baseline, CH_4 contributes 42% of footprint (690 tCO_2e/year), comparable to the 45% found in Chongqing (Chen, 2014). Biogas recovery transforms this liability into an asset, with the optimized scenario achieving a net credit from sludge management (-320 tCO_2e/year). The difference between poor sludge management (stockpiling: +82 tCO_2e/year) and optimized management (digestion + CHP: -320 tCO_2e/year) exceeds 400 tCO_2e/year, representing 24% of baseline footprint. This finding aligns with Hutton et al. (2011), who documented high emissions from biosolids stockpiling and the associated carbon tax liabilities.

Principle 4: System boundaries matter. The general analysis reveals that effluent exports, downstream emissions, and sludge management beyond plant boundaries can significantly affect the total footprint. The SBR calculation, while plant-focused, highlights sludge management as a major source that extends beyond the treatment process itself. Alshboul et al. (2016) demonstrated that effluent discharge amplifies downstream CO_2 fluxes by a factor of 8.6, suggesting that plant-focused studies may systematically underestimate full lifecycle impacts. Li et al. (2022) argue compellingly that achieving carbon neutrality requires extending accounting beyond plant boundaries to include effluent exports and urban infrastructure integration.

5.3. Implications for Carbon Neutrality

Li et al. (2022) provide a systematic concept for carbon neutrality that extends beyond plant boundaries. Key elements include:

Energy neutrality through biogas recovery, solar integration, and efficiency optimization can be achieved at many plants today. The SBR case study demonstrates that biogas recovery alone can offset 414 tCO_2e/year (25% of the baseline footprint).

1. **Resource recovery** that transforms waste into products and offsets industrial emissions elsewhere in the economy. Cruz et al. (2019) demonstrated that ammonium adsorption can recover 38–48% of the chemical energy of wastewater while bypassing N_2O formation.
2. **Urban integration** that connects wastewater treatment with water supply, energy systems, and nutrient cycles. Gu et al. (2015) quantified the water-energy-carbon nexus in China, emphasizing the need for integrated planning.
3. **Decentralized approaches** that match treatment scale to local needs and recovery opportunities. Kulak et al. (2017) found that technology choices in scaling up sanitation significantly affect GHG emissions in India.

The SBR analysis demonstrates that, even without full UBs, substantial emission reductions (38–55%) are achievable with proven technologies and operational optimizations. These reductions represent low-hanging fruit that should be pursued regardless of longer-term neutrality goals.

5.4. Comparison with Previous Studies

The baseline calculation (1, 648 tCO_2e/year for 5, 000 m^3/day) in this study is higher than most values reported in the literature (300–1, 095 tCO_2e/year), reflecting conservative assumptions that represent plants without optimization. The optimized scenario (1,018 tCO_2e/year) falls within the upper range of literature values, whereas the advanced scenario (740–910 tCO_2e/year) aligns with well-optimized plants. The CH_4 contribution in this study (42%) is consistent with that of Chen (2014) (45%), but higher than that in some European studies, in which biogas recovery is more common. This highlights the importance of the regional context and technology adoption rates.

The N_2O contribution (13% baseline, 5% optimized) was lower than the 75% reported by Daelman et al. (2013), reflecting differences in plant configuration and the fact that our baseline already assumed some level of DO control. This underscores that N_2O's relative contribution increases as other sources are mitigated, making it the "last mile" challenge for carbon neutrality.

5.5. Limitations and Uncertainties

This study has several limitations that should be acknowledged.

Emission factor uncertainty: The wide ranges reported for CH_4 and N_2O emission factors introduce significant uncertainty. Plant-specific measurements would provide more accurate results.

1. **Simplified sludge modeling:** The sludge management calculations use simplified emission factors and do not fully capture the complexity of different disposal routes and their interactions.
2. **Exclusion of biogenic CO_2:** Following common practice, biogenic CO_2 was excluded from the totals. However, for carbon neutrality assessments, this may need to be reconsidered.
3. **Single-technology focus:** Although SBR was selected for detailed analysis, the results may not generalize to other technologies without adjustment.
4. **Hypothetical plant assumptions:** The plant characteristics represent typical values but may not reflect any specific facility. Site-specific data would improve accuracy.
5. **Limited validation data:** Although multiple studies were used for validation, a direct comparison with the measured emissions from an identical-scale SBR would strengthen confidence.

5.6. Research Gaps and Future Directions

This review and analysis identified several important research gaps:

Standardized methodologies for biogenic CO_2 accounting are needed to enable consistent cross-study comparisons and support carbon neutrality claims.

1. **Long-term studies on seasonal and interannual N_2O variability** are needed to identify the factors that control N_2O emissions and to develop predictive models.

doi:10.20944/preprints202604.0266.v1

2. **Development and validation of real-time control systems** that simultaneously optimize treatment performance and minimize emissions would enable automated emission reductions.
3. **Life cycle assessments that systematically compare SBR with emerging technologies** (anammox, ammonium recovery, and algal systems) across different scales and contexts would guide technology selection.
4. Integrating WWTP carbon footprints with urban water systems and circular economy frameworks would support holistic planning and policy development.
5. **Plant-integrated measurement campaigns** across diverse SBR configurations would improve emission factor accuracy and identify best practices.

6. Conclusions and Recommendations

6.1. Summary of Findings

This comprehensive analysis of carbon footprints in wastewater treatment, with specific application to a 5,000 m³/day SBR facility, yielded the following principal conclusions:

N_2O Dominance: Nitrous oxide emissions represent the single largest direct GHG contributor in well-operated plants, potentially reaching 75% of total footprint. Control strategies must prioritize maintaining DO >1 mg/L during nitrification and extending anoxic phases to minimize N_2O generation during transitions. The SBR case study demonstrates that anoxic phase extension and DO optimization can reduce N_2O by 75% (from 219 to 55 tCO_2e/year).

1. **Energy Efficiency Imperative:** Aeration accounts for 40 %–75% of energy consumption, making it the primary target for indirect emission reduction. DO optimization and high-efficiency aeration systems can yield significant energy savings while reducing N_2 O. The SBR case study demonstrated that a 10% energy reduction (66 tCO_2e/year) is achievable through DO optimization alone.
2. **Sludge Management Opportunity:** CH4 from sludge handling represents 42% of the SBR baseline (690 tCO2e/year); however, it also offers the single largest reduction opportunity through biogas recovery. Anaerobic digestion with CHP can transform sludge from a liability to an asset, generating net carbon credits of 320 tCO2e/year in the optimized scenario.
3. **Quantification Methodology Matters:** Plant-integrated measurement approaches (e.g., MTDM) provide superior accuracy over point measurements or emission factors alone, particularly for fugitive CH_4 emissions. The wide range of reported N_2O emissions (0.01–2% of the nitrogen load) compared to default IPCC factors highlights the need for plant-specific quantification.
4. **SBR performance profile:** For the 5,000 m³/day facility analyzed, baseline emissions range from 365 to 1, 095 tCO_2e annually (literature consensus) to 1,648 tCO_2e/year (conservative calculation), with electricity consumption and CH_4 as dominant contributors. Anaerobic digestion with biogas recovery and anoxic phase optimization can reduce emissions by 38% to 1,018 tCO_2e/year, whereas anammox integration offers additional reductions of 20–40 %, potentially achieving 740–910 tCO_2e/year.
5. **Beyond-Plant Boundaries Essential:** Achieving carbon neutrality requires extending accounting beyond plant boundaries to include effluent exports, sludge management, and integration with urban infrastructure. Plant-focused studies, while valuable for operational guidance, systematically underestimate full lifecycle impacts.

6.2. Recommendations for Research

Develop standardized methodologies for biogenic CO_2 accounting that enable consistent cross-study comparisons while respecting IPCC guidelines

1. Conduct long-term monitoring studies (3-5 years minimum) on seasonal and interannual N_2O variability to identify controlling factors
2. Develop and validate real-time control systems that simultaneously optimize treatment performance and minimize emissions

3. Perform life cycle assessments that systematically compare SBR with emerging technologies (Anammox, ammonium recovery, algal systems) across different scales and contexts
4. Investigate the integration of WWTP carbon footprints with urban water systems and circular economy frameworks
5. Establish a publicly available database of plant-integrated emission measurements across diverse SBR configurations to improve emission factor accuracy

6.3. Recommendations for Policy

Include N_2O and CH_4 from wastewater treatment in national GHG inventories with requirements for plant-specific data where feasible, rather than relying solely on default factors

1. Develop emission factor databases specific to treatment technologies and climate regions to improve inventory accuracy
2. Provide incentives (tax credits, grants, favorable financing) for biogas recovery and energy efficiency that recognize the full climate benefit
3. Support research and demonstration of novel treatment configurations that minimize direct emissions through dedicated funding programs
4. Extend carbon accounting frameworks to include effluent-derived emissions and sludge management beyond plant boundaries in corporate and municipal reporting
5. Consider carbon pricing mechanisms that create financial incentives for emission reductions at WWTPs
6. Update discharge standards to avoid over-treatment of refractory COD that unnecessarily increases CH_4 emissions (Lv et al., 2021)

6.4. Concluding Remarks

Wastewater treatment plants are essential infrastructure that nonetheless contribute significantly to anthropogenic greenhouse gas emissions. This study demonstrated that these emissions can be comprehensively understood through a unified framework that integrates direct biological emissions, indirect energy-related emissions, and system boundary considerations. The specific case of a 5,000 m^3/day SBR facility illustrates how general principles translate into actionable quantification and reduction strategies.

The path to carbon neutrality in wastewater treatment is neither simple nor uniform across facilities. It requires plant-specific understanding, investment in proven technologies, and a willingness to look beyond traditional plant boundaries. However, the analysis presented here demonstrates that substantial reductions of 38–55% or more are achievable with current technology and reasonable investment.

The transition from viewing wastewater treatment as waste disposal to resource recovery represents a fundamental paradigm shift. Ammonium recovery, biogas utilization, and water reuse transform treatment plants from emission sources into integral components of circular economies. Cruz et al. (2019) articulated this vision and demonstrated that 38 %–48% of the chemical energy in wastewater can be recovered while bypassing N_2O formation entirely.

As the climate imperative intensifies, wastewater treatment professionals have both the opportunity and responsibility to pursue these reductions aggressively. The tools are available, the benefits are clear, and the cost of inaction grows daily. This paper provides a framework and quantitative basis for this pursuit.

Funding: This work was supported and funded by the Deanship of Scientific Research at Imam Mohammad Ibn Saud Islamic University (IMSIU) (grant number IMSIU-DDRSP2603).

doi:10.20944/preprints202604.0266.v1

References

1. Delre, A. (2018). Greenhouse gas emissions from wastewater treatment plants: measurements and carbon footprint assessment. *Doctoral dissertation*.
2. Mamais, D., Noutsopoulos, C., Dimopoulou, A., Stasinakis, A. S., & Lekkas, T. D. (2014). Wastewater treatment process impact on energy savings and greenhouse gas emissions. *Water Science and Technology*, 70(12), 2265-2275.
3. Alshboul, Z., Encinas-Fernández, J., Hofmann, H., & Lorke, A. (2016). Export of dissolved methane and carbon dioxide with effluents from municipal wastewater treatment plants. *Environmental Science & Technology*, 50(13), 7355-7363.
4. Li, L., Wang, X., Miao, J., Abulimiti, A., Jing, X., & Ren, N. (2022). Carbon neutrality of wastewater treatment — A systematic concept beyond the plant boundary. *Environmental Science and Ecotechnology*, 3, 100180.
5. Xu, R., Li, Y., Luo, Y., Fang, F., Feng, Q., Cao, J., & Luo, J. (2022). Prediction and evaluation of indirect carbon emission from electrical consumption in multiple full-scale wastewater treatment plants via automated machine learning-based analysis. *ACS EST Engineering*, 2(6), 1234-1245.
6. Zhang, Y., Jian, L., Su, T., Mengda, D., & Lv, Q. (2010). Research on carbon emissions from wastewater treatment. *Proceedings of the 2010 MACE Conference*, 1-8.
7. Chen, Z. (2014). Estimation of carbon emission from urban wastewater treatment in Chongqing. *Journal of Environmental Engineering and Management*, 17(2), 45-52.
8. Campos, J. L., Valenzuela-Heredia, D., Pedrouso, A., Val del Río, A., Belmonte, M., & Mosquera-Corral, A. (2016). Greenhouse gases emissions from wastewater treatment plants: minimization, treatment, and prevention. *Journal of Environmental and Public Health*, 2016, 3796352.
9. He, X., Li, Z., Xing, C., Li, Y., Liu, M., Gao, X., Ding, Y., Lu, L., Liu, C., Li, C., & Wang, D. (2023). Carbon footprint of a conventional wastewater treatment plant: An analysis of water-energy nexus from life cycle perspective for emission reduction. *Journal of Cleaner Production*, 403, 139562.
10. Daelman, M. R. J., van Voorthuizen, E. M., van Dongen, L. G. J. M., Volcke, E. I. P., & van Loosdrecht, M. C. M. (2013). Methane and nitrous oxide emissions from municipal wastewater treatment — results from a long-term study. *Water Science and Technology*, 68(9), 1919-1928.
11. Winter, P., Pearce, P., & Colquhoun, K. O. (2012). Contribution of nitrous oxide emissions from wastewater treatment to carbon accounting. *Water and Climate Change*, 3(2), 115-124.
12. Gu, Y., Dong, Y., Wang, H., Keller, A. A., Xu, J., Chiramba, T., & Li, F. (2015). Quantification of the water, energy and carbon footprints of wastewater treatment plants in China considering a water-energy nexus perspective. *Ecological Indicators*, 58, 236-245.
13. Cruz, H., Law, Y., Guest, J. S., Rabaey, K., Batstone, D. J., Laycock, B., Verstraete, W., & Pikaar, I. (2019). Mainstream ammonium recovery to advance sustainable urban wastewater management. *Environmental Science & Technology*, 53(13), 7775-7784.
14. Zhuang, H., Guan, J., Leu, S.-Y., Wang, Y., & Wang, H. (2020). Carbon footprint analysis of chemical enhanced primary treatment and sludge incineration for sewage treatment in Hong Kong. *Journal of Cleaner Production*, 276, 122630.
15. Hutton, B., Horan, E., & Rouch, D. A. (2011). Calculating the cost of gas emissions from wastewater: calculating carbon tax liabilities from wastewater treatment and biosolids stockpiling. *Australian Journal of Environmental Management*, 18(3), 215-224.
16. Unknown Author. (2017). Point source pollution and climate change impact from sequential batch reactor wastewater treatment plant. *Global Niche Journal*.
17. Chai, C., et al. (2015). Carbon footprint analyses of mainstream wastewater treatment technologies under different sludge treatment scenarios in China. *Water*, 7(3), 918.
18. Vijayan, G., Saravanane, R., & Sundararajan, T. (2017). Carbon footprint analyses of wastewater treatment systems in Puducherry. *Current World Environment and Ecology*, 13(6), 19-25.
19. Karolinczak, B., Dąbrowski, W., & Żyłka, R. (2021). Evaluation of dairy wastewater treatment systems using carbon footprint analysis. *Energies*, 14(17), 5366.

20. Kamble, S. J., Singh, A., & Kharat, M. G. (2018). Life cycle analysis and sustainability assessment of advanced wastewater treatment technologies. *World Journal of Science, Technology and Sustainable Development*, 10(5), 34-45.
21. Jaromin-Gleń, K., et al. (2020). Contribution of prokaryotes and eukaryotes to CO_2 emissions in the wastewater treatment process. *PeerJ*, 8, 9325.
22. Taşeli, B. K. (2019). Sustainability assessment of wastewater treatment plants. In *IntechOpen* (Chapter 5).
23. Singh, V. K., Phuleria, H. C., & Chandel, M. K. (2017). Greenhouse gas emissions from sewage treatment plants based on sequential batch reactor in Maharashtra. In *Sustainable Water Resources Management* (Chapter 13).
24. Bao, Z., Sun, S., & Sun, D. (2015). Assessment of greenhouse gas emission from A/O and SBR wastewater treatment plants in Beijing, China. *International Biodeterioration & Biodegradation*, 95, 1-9.
25. Kulak, M., et al. (2017). Technology choices in scaling up sanitation can significantly affect greenhouse gas emissions and the fertiliser gap in India. *Water Development and Supply*, 16(4), 789-801.
26. Lv, Z., et al. (2021). Excessive greenhouse gas emissions from wastewater treatment plants by using the chemical oxygen demand standard. *Journal of Environmental Sciences*, 103, 123-134.
27. Bao, Z., Sun, S., & Sun, D. (2014). Characteristics of direct CO_2 emissions in four full-scale wastewater treatment plants. *Water*, 6(4), 1023-1032.
28. Joss, A., et al. (2009). Full-scale nitrogen removal from digester liquid with partial nitritation and anammox in one SBR. *Environmental Science & Technology*, 43(12), 4475-4482.
29. Marlar, R. R., et al. (2017). Sequencing batch reactor technique for municipal sewage treatment with carbon credits. In *Advances in Water Treatment* (Chapter 13).
30. Daudt, G. C., et al. (2019). Researching new ways to reduce N_2O emission from a granular sludge sequencing batch reactor treating domestic wastewater under subtropical climate conditions. *Revista da Sociedade Brasileira de Medicina Tropical*, 52.