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Comparative analysis of calculation tools for estimating carbon footprint of wastewater treatment plants: methodologies and emission factors

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Abstract: Wastewater treatment plants (WWTPs) are significant sources of greenhouse gas (GHG) emissions, particularly methane (CH_4) and nitrous oxide (N_2O). This study compares two widely used carbon footprint (CF) calculation tools, CFCT and ECAM, and validates their results with a self-developed Validation Tool. The findings reveal substantial differences in CF estimates, with ECAM reporting emissions more than twice as high as those computed by CFCT. The Validation Tool, which incorporates site-specific empirical emission factors (EFs), estimates emissions approximately 80% lower than the other tools. The analysis identifies key methodological limitations, including the oversimplification of N_2O emissions in CF models, inconsistencies in EF selection, and the lack of standardized validation methodologies. The study underscores the need for refining CF methodologies by integrating real-world operational data and establishing harmonized validation frameworks to enhance the reliability of emissions accounting.

Abbreviations

AD – Anaerobic Digester
AR – Assessment Report
BEAM – Biosolids Emissions Assessment Model
BNR – Biological Nutrient Removal
BOD_5 – 5-day Biochemical Oxygen Demand
CF – Carbon Footprint
CFCT – Carbon Footprint Calculation Tool
CHP – Combined Heat and Power
COD – Chemical Oxygen Demand
CO_2e – Carbon Dioxide Equivalent
DEFRA – Department for Environment, Food & Rural Affairs
ECAM – Energy Performance and Carbon Emissions Assessment and Monitoring
EF – Emission Factor
FTIR – Fourier-Transform Infrared Spectroscopy
GHGs – Greenhouse Gases
GWP – Global Warming Potential
IPCC – Intergovernmental Panel on Climate Change
JHB – Johannesburg (BNR configuration)
N_{tot} – Total Nitrogen
PE – Population Equivalent
PWWTP – Poznan Wastewater Treatment Plant
PS – Primary Sludge
RS – Results Set
S1, S2, S3 – Scope 1, Scope 2, Scope 3
SDG – Sustainable Development Goal
TN – Total Nitrogen
v – Version
WaCCliM – Water and Wastewater Companies for Climate Mitigation Project
WAS – Waste Activated Sludge
WBCSD – World Business Council for Sustainable Development
WRI – World Resources Institute
WWT – Wastewater Treatment
WWTP – Wastewater Treatment Plant

Introduction

Wastewater treatment plants (WWTPs) play a crucial role in urban infrastructure by ensuring water quality and regulatory compliance (Zhang et al. 2024). However, they also contribute to environmental burdens due to high energy use and greenhouse gas (GHG) emissions, especially methane (CH_4) and nitrous oxide (N_2O), which strongly influence climate change. Reducing these two aspects while meeting strict regulations is a key challenge (Asadi et al. 2024). Emission levels vary due

Table 1. Scope 1 process emissions calculation completeness – comparison of the CF tools selected for the in-depth analysis

Tool name	Nitrogen-based calculations N_2O emission		Organics-based calculation CH_4 emission		Biogas-based calculation CH_4 emission		
	BNR	Recipient	BNR	Recipient	Combustion	Leakage	Upgrading Slip
CFCT v2014	$N_{denetrified}$ (removed)	TN effluent load	COD influent load	Not calculated	Calculated as Scope 1	Possibility of calculation as Scope 1 if needed	Calculated as default Scope 1
CFCT v2024	$N_{denetrified}$ (removed)	TN effluent load	COD influent load	BOD effluent load	Considered as biogenic	Possibility of calculation as Scope 1 if needed	Calculated as default Scope 1
ECAM	TN influent load	TN effluent load	BOD influent load	BOD effluent load	Considered as biogenicw	Calculated as default Scope 1	Possibility of calculation as Scope 1 if needed

TN – total nitrogen, COD – chemical oxygen demand, BOD – biochemical oxygen demand

to regional differences in plant design, operational practices, technologies and local conditions, making accurate assessment difficult (Toivonen and Räsänen 2024). The carbon footprint (CF) is a tool that is widely used to quantify and reduce WWTP emissions, supporting both operational optimization and policy objectives such as the European Green Deal. However, CF assessments often rely on default emission factors (EFs) and global warming potential (GWP) values, even in advanced scenario analysis.

Existing CF tools have notable limitations (Fighir et al. 2019), as many rely on fixed emission factors (EFs), causing inaccuracies under specific facility conditions. Inconsistencies with IPCC guidelines, including outdated GWPs and EFs, reduce credibility (Massara et al. 2017) and hinder cross-tool validation. Biogenic emissions, CH_4 leakages, and N_2O from biological treatment are often over- or underreported, leading to incorrect and incomplete CF estimates.

Current studies on WWTP GHG emissions reveal significant gaps (Toivonen and Räsänen 2024). There is no standardized framework for comparing CF outputs across different plant configurations (Huang et al. 2022), and limited validation using real-world data or regional traits (Faragò et al. 2022). The temporal effects of revised GWPs on CF assessments are underexplored (Wei et al. 2024). Research often focuses on specific technologies, overlooking broader CF tool relevance (Lotfikatouli et al. 2024). Furthermore, fugitive CH_4 and N_2O emissions remain underreported, and CF calculators lack empirical validation, limiting their decision-making utility. As a result, researchers rarely justify their choice of CF tools or compare outputs, leading to inconsistent conclusions (Tian et al. 2022).

Despite growing adoption of CF tools, gaps in standardization and validation persist. No unified framework exists for comparing outputs across WWTP types, and real-world data use is limited in regions with poor infrastructure. The influence of changing GWP values on long-term emission estimates remain unaddressed. This study addresses these issues by assessing open-access CF tools and proposing a refined validation framework. It incorporates site-specific EFs and updated GWPs to boost accuracy and adaptability. By improving CF methodologies, it enables more reliable reporting, aids tool selection, and supports the development of standardized calculators. The findings offer valuable guidance for utility managers, policymakers, and researchers in achieving globally consistent WWTP emission assessments.

Materials and methods

CF calculation tools

Supported by the broad adoption, two open-access CF tools were selected for comparison: Tool 1 - CFCT (versions 2014 and 2024) from Sweden (CFCT 2014, CFCT 2024), and Tool 2 - ECAM (WaCCliM 2024) from Germany. CFCT 2014 uses 2007 GWP values (Pachauri and Reisinger 2007) and allows users to modify calculations. CFCT 2024 incorporates updated EFs and GWPs (Lee and Romero 2023), but its equations and default factors are not user-editable. ECAM is a web-based tool employing default equations, EFs, and GWP values (Pachauri and Meyer 2014); however, users may request computation model changes via its developers. Both CFCT (Nejad 2020) and ECAM (Tian et al. 2022) have been widely used in research (Saidan et al. 2019). Table 1 presents a comparison of Scope 1 process emission components and EF considerations in both tools, with a particular focus on N_2O and CH_4 to highlight methodological similarities and differences.

CF validation tool

The CF algorithm for the municipal WWTP in this study follows the GHG Protocol guidelines (WRI, WBCSD 2014) and IPCC

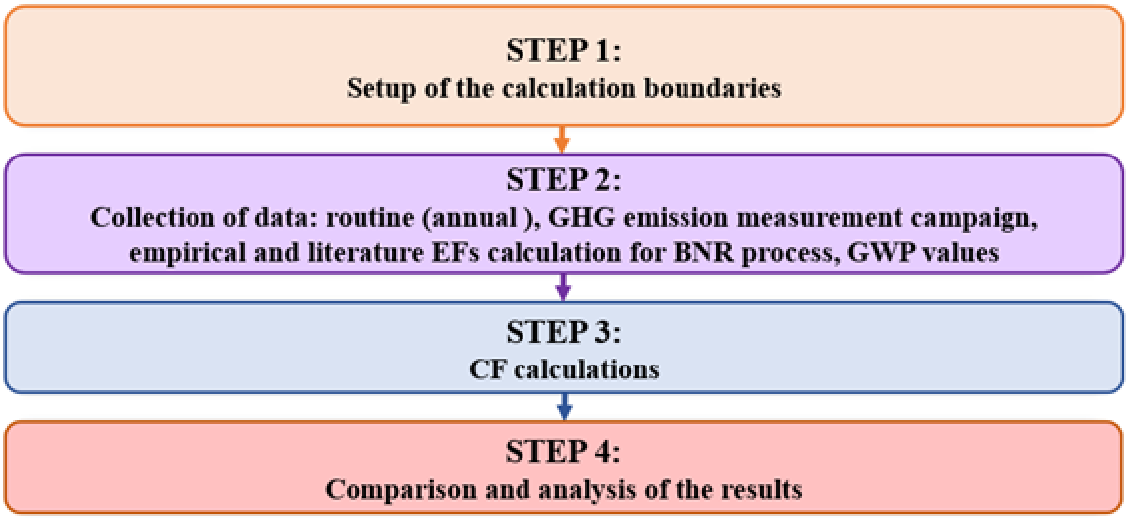

Figure 1. Study framework.

standards (IPCC 2019), aligning with EU requirements (EU 2022/2464). The new tool, customized for the facility, includes:

Scope 1 emissions:

a. N_2O from bioreactors and recipient,
b. CH_4 from bioreactors and recipient,
c. CH_4 from sludge management, biogas production, and on-site use.

Supporting activity emissions:

● Fossil fuel consumption in on-site power units

Scope 2: electricity consumption from external grid.

Fugitive Scope 1 emissions were calculated using total nitrogen (TN) load for N_2O and chemical oxygen demand (COD) load for CH_4. Emissions from biogas used for heat and electricity were excluded as renewable, but leakage losses and incomplete combustion were included.

Stepwise analysis procedure

A stepwise procedure was developed to compare the analyzed CF tools. Figure 1 presents the overall study structure, and Figure 2 illustrates the multi-stage evaluation approach. Six distinct CF

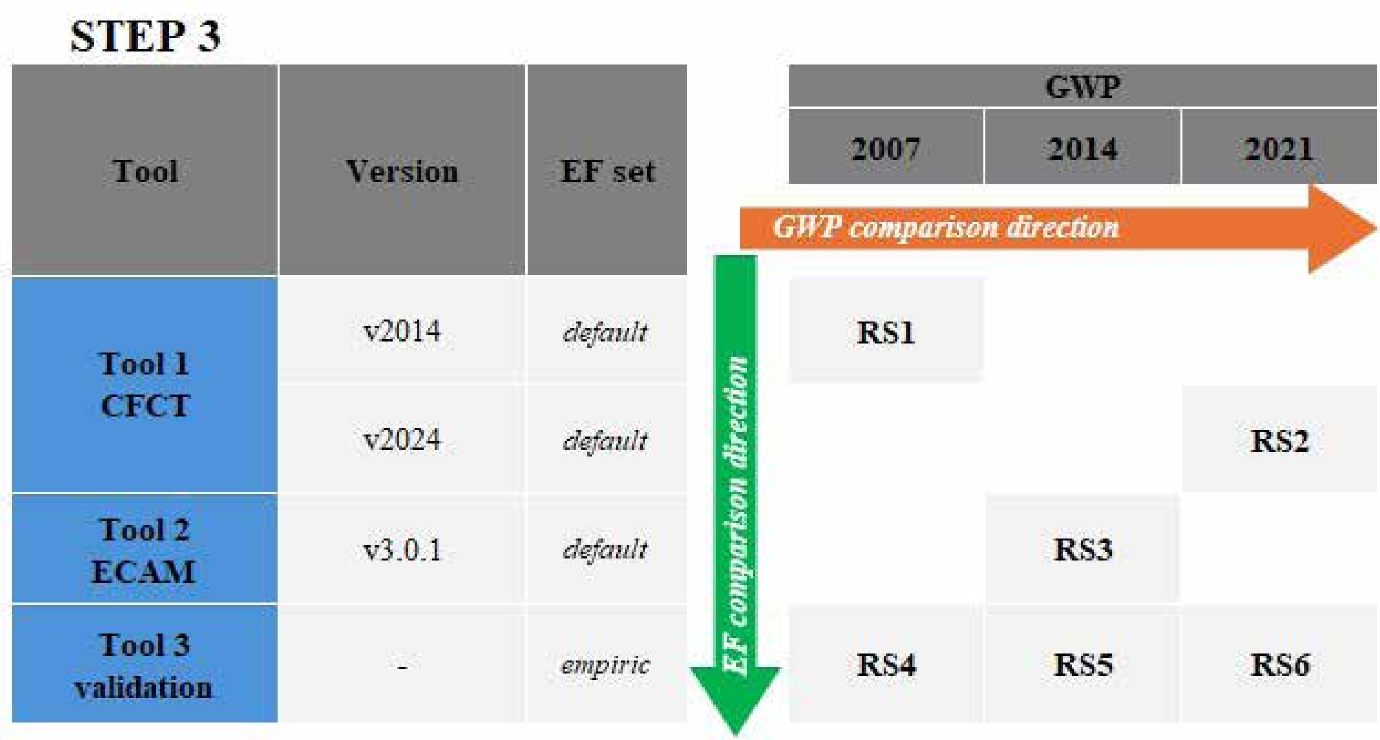

Figure 2. The concept of Step 3.

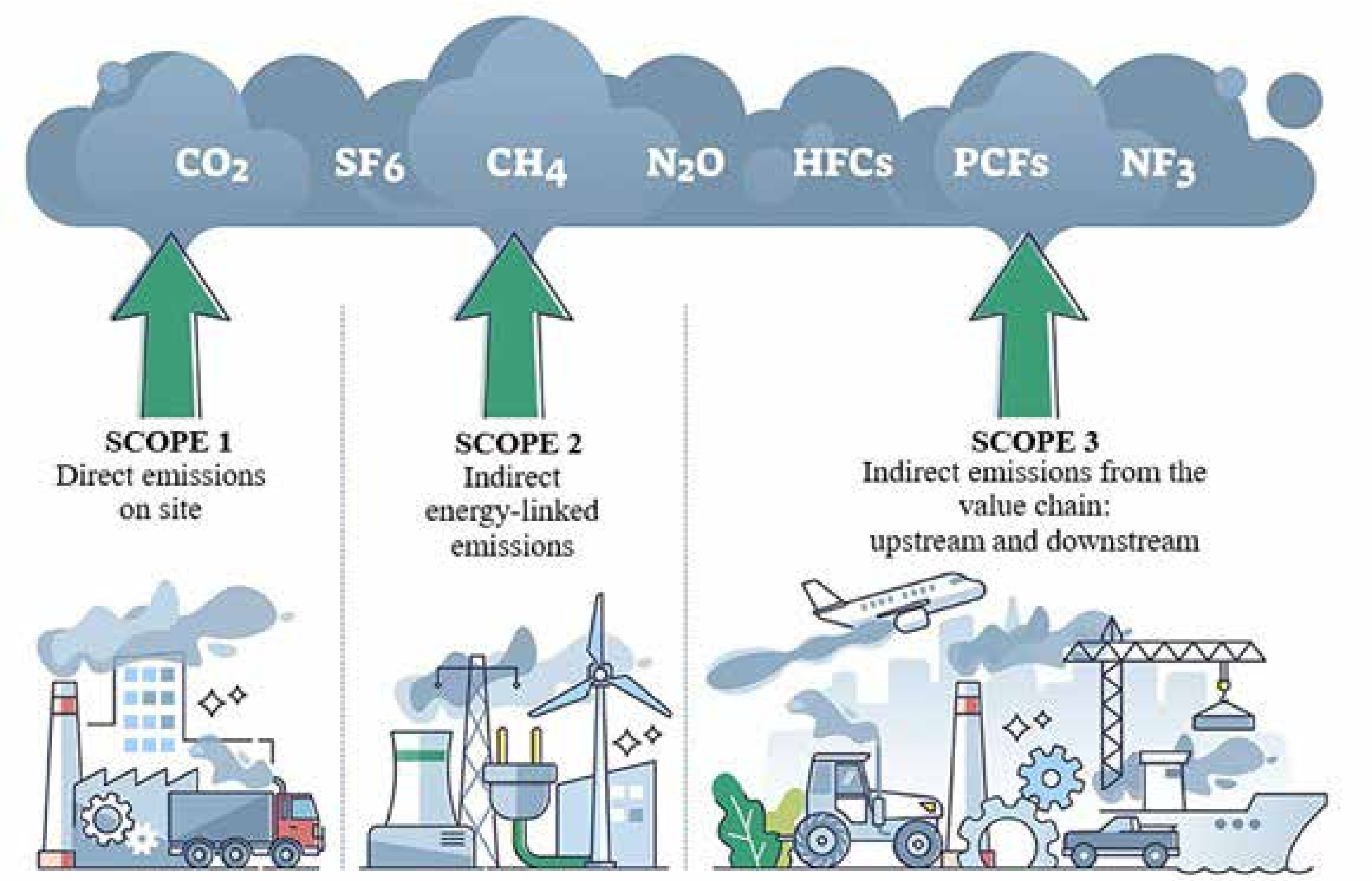

Figure 3. Overview of CF structure: scopes of GHG emission (based on [39]). Red dotted line presents calculation boundaries of this study.

results were generated, enabling comparison between default tool-based GHG emission factors (EFs) and those recalculated using updated and site-specific empirical EFs and GWPs. To validate these outputs, an independent algorithm developed by the authors was used. This structured comparison allowed the identification of key contributors to direct emissions (N_2O and CH_4), ensuring that the most impactful parameters inform the final methodological recommendations.

Step 1: Setup of the calculation boundaries (section 2.4)
The process begins with the setup of CF calculation boundaries. Each tool analyzed covers the scope of the analysis.
Step 2: Collection of data (section 2.6)
The tools incorporate a primary dataset comprising annual qualitative and quantitative operational data from the studied WWTP, ensuring consistent full-scale input. Additionally, a dedicated measurement campaign at the Poznań WWTP provided full-scale GHG emission data for estimating empirical EFs (N_2O and CH_4) specific to the facility's BNR (Biological Nutrient Removal) process.
Step 3: CF calculations and validation (section 3)
The selected CF tools and collected data were used to perform calculations. The comparison applied various CH_4 and N_2O GWP updates and default EFs to evaluate their impact on CF results. Each outcome was then verified using Tool 3, which incorporates EFs from the GHG measurement campaign and includes all GWP sets.
Step 4: Comparison and analysis of the results (section 4)
The structured comparison reveals that changes in EFs and GWPs significantly affect CF results, pinpointing key areas for optimizing GHG mitigation.

Step three, shown in Figure 2, is the study's critical phase. GWP values from IPCC reports: 2007 (Pachauri and Reisinger 2007), 2014 (Pachauri and Meyer 2014), and 2021 (Lee and Romero 2023), were combined with default EFs in the CF tools. The self-developed algorithm included all GWPs and empirical EFs. Two approaches were used: a horizontal comparison assessed the impact of GWP updates, while a vertical comparison evaluated results based on different EF values.

Setup of the calculation boundaries

Recently, CF has been used as a tool for controlling GHG impacts (Maktabifard et al. 2019). The GHG Protocol (WRI, WBCSD 2014) defines three CF scopes (Figure 3). Scope 1 (S1) includes direct emissions – particularly N_2O emissions from BNR processes, and CH_4 emissions from anaerobic stages and sludge treatment with biogas. Scope 2 (S2) covers emissions from purchased energy, while Scope 3 (S3) involves indirect emissions, such as those associated with chemical production or by-product disposal beyond the WWTP's value chain.

This research targets only S1 and S2 emissions within WWTP boundaries, as these are prioritized by regulations

Table 2. Summary of the WWTP's annual average characteristics (2021).

	Unit	Influent	Effluent
Flowrate	m^3/d	100,000	
COD	gO_2/m^3	1,240	49.9
BOD_5	gO_2/m^3	550	3.7
TN	gN/m^3	100	9.4
		Biogas CHP plant	External grid
Electricity used	kWh/a	15,200,000	5,750,000
Biogas produced/ consumed	Nm^3/a	7,760,000	-
Natural gas consumption	m^3/a		130,000

(EU 2022/2464, EU 2024/3019) and required for compliance (Burchart-Korol and Zawartka 2019). This boundary definition highlights how CF tool selection affects the composition and magnitude of WWTP GHG emissions (Awaitey 2021). S3 emissions, including those from chemical production and third-party transport, are excluded due to high uncertainty and limited controllability by WWTP operators (Ko et al. 2024).

Study site

The Poznań WWTP (PWWTP) is one of the largest wastewater treatment plants in Poland, treating about 100,000 m³/day

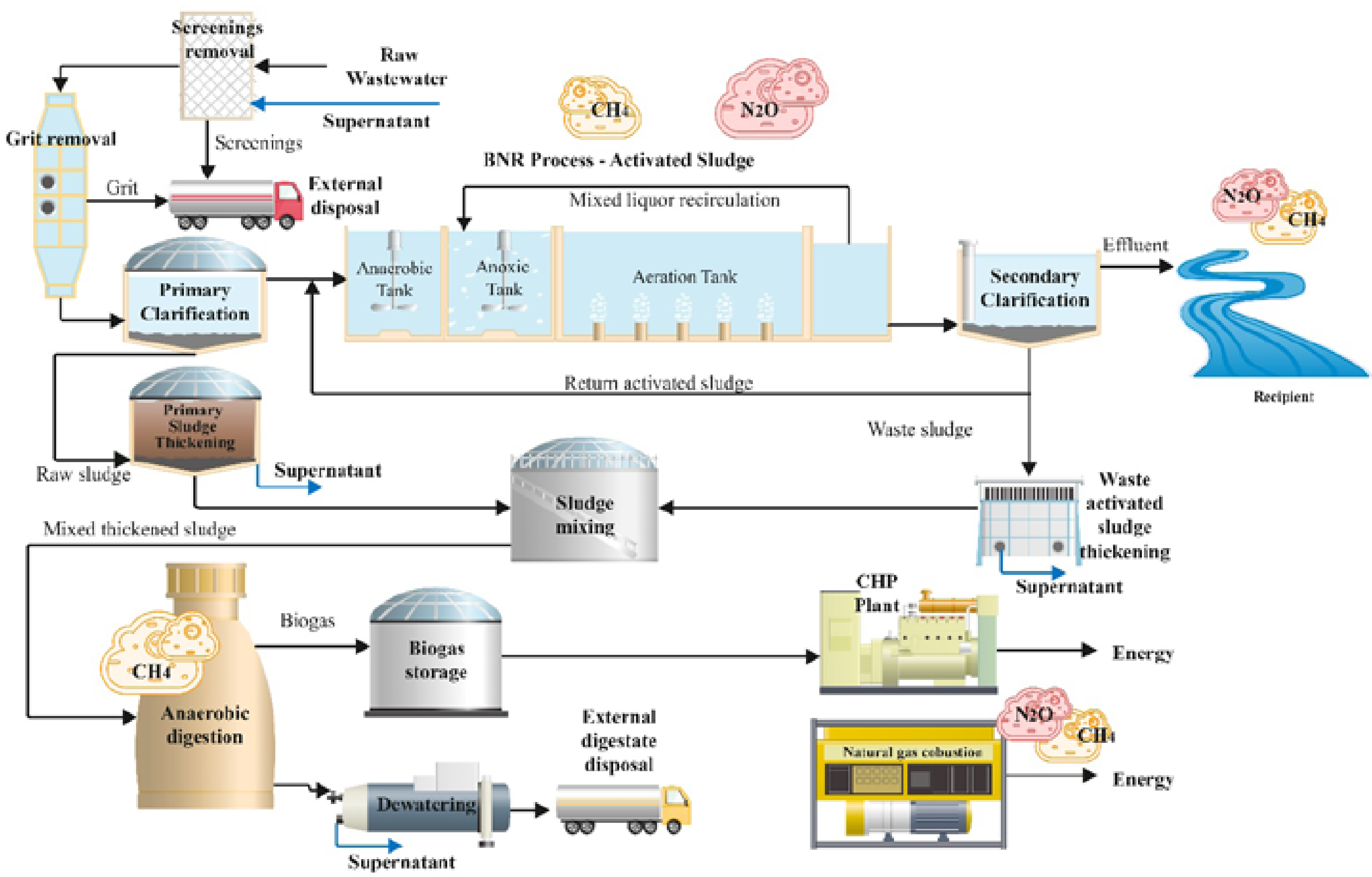

Figure 4. The idea of wastewater and sludge treatment processes employed in the investigated facility with GHG emission hotspots included in assessment.

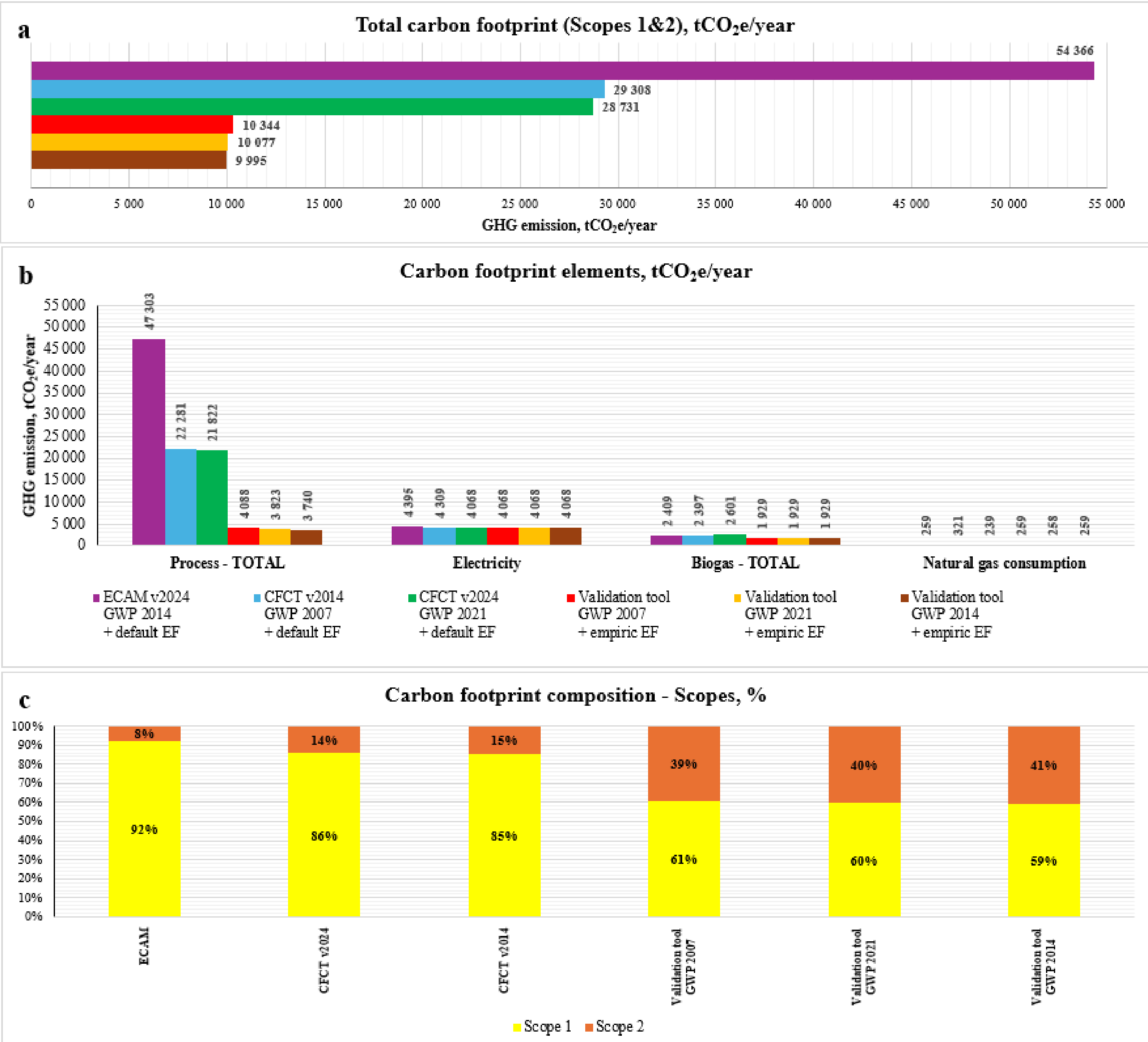

Figure 5. CF calculation results: a) Total CF (Scopes 1&2), tCO_2e/year; b) CF elements, tCO_2e/year c) Total CF composition - Scopes,%

of wastewater from Poznań and surrounding areas. It serves up to 1,000,000 population equivalents (PE; 1 PE = 60 g BOD_5). The plant operates using a Johannesburg (JHB) BNR configuration, consisting of six activated sludge bioreactors with a total volume of 25,500 m³ each. The treated effluent is discharged to the Warta River after secondary clarification. All facilities related to primary sludge management are hermitized and connected to dedicated biofilters. Primary and waste activated sludge are thickened and anaerobically digested at 35°C in digesters with a total volume of 29,760 m³. The digested sludge is then dewatered and incinerated externally. Biogas produced in the digesters is utilized in on-site combined heat and power (CHP) units to generate heat and electricity, with energy demand supplemented by the electrical grid and gas boilers. Figure 4 shows the PWWTP layout.

Data collection

Routine data

The CF assessments are based on the 2021 routine operational dataset from PWWTP (Table 2). Average influent and effluent concentrations of COD, BOD_5 and TN were provided by the plant operator, derived from biweekly sampling. Quantitative data on flow rates, fuel and biogas consumption, and energy production and use were obtained from water, gas, and electricity meters.

Emission factors

In September 2021, a -day full-scale measurement campaign was conducted at PWWTP. The campaign included routine data collection, sampling, laboratory analyses, and off-gas measurements in biological reactors. These data were used to calculate direct N_2O and CH_4 emission factors (EFs) and

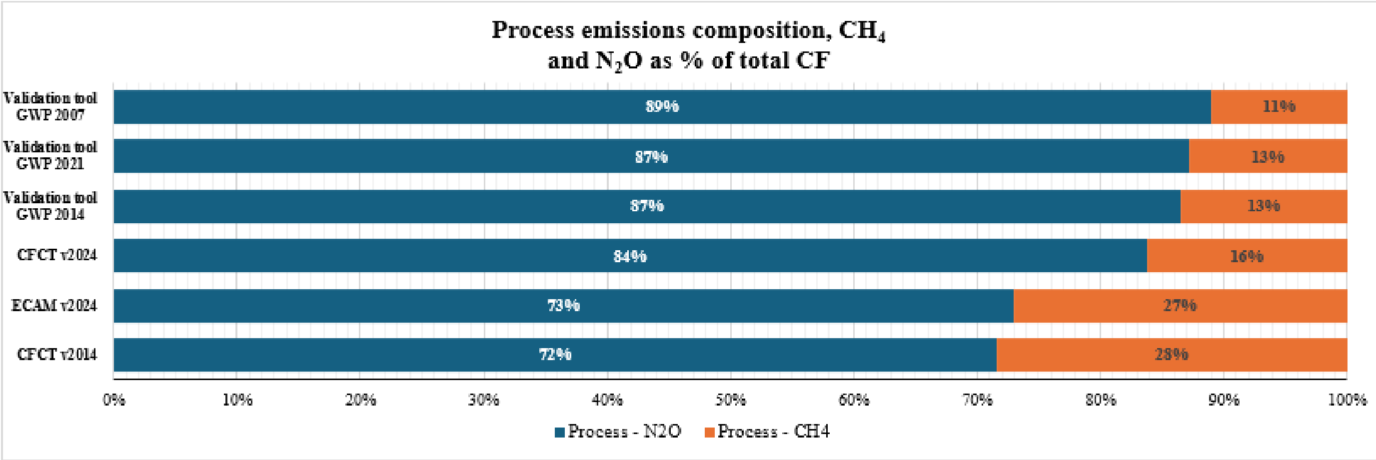

Figure 6. Process emission composition, CH_4 and N_2O as % of total (Scope1&2) CF

to apply them in Validation Tool 3. The PWWTP operates autonomously, with dissolved oxygen (DO) levels regulated through ammonia-based control. For this study, the average DO concentration was maintained at 1.0 ± 0.3 mg O_2/L and the average inflow rate was 600.0 ± 29.8 m³/h.

Emission factors were determined by measuring four points in the aerobic compartment for one hour each, at five-minute intervals, using a FTIR analyzer (Gasmet DX 4000) with a floating hood. Wastewater samples were collected at each measurement point, and the Gasmet was calibrated daily. To minimize uncertainty, the optimal GHG measurement point was identified prior to campaign. Final EFs, expressed as kg CO_2e per kg COD (for CH_4) and per kg TN (for N_2O), were weighted according to compartment area and gas flux.

Results

Figures 5 and 6 present CF results comparing the effects of GWP and EF variations. CFCT v2014 estimates 29,310 tCO_2e /year, slightly decreasing to 28,730 tCO_2e /year in v2024. ECAM reports a significantly higher 54,370 tCO_2e / year - more than twice the CFCT values. The Validation Tool, adjusted for three GWP scenarios, yields considerably lower results of 10,340-10,080 tCO_2e /year (Figure 5a). S1 fugitive emissions dominate the CF composition (Figure 5b), especially CH_4 and N_2O emissions from biological processes. In CFCT v2014, these account for 22,280 tCO_2e/year (76% of total), and 21,820 tCO_2e/year in v2024. ECAM estimates 47,300 tCO_2e/ year, representing over 87% of its total, with CH_4 from BNR and N_2O from effluent discharge being ~211% higher than in CFCT v2024. Biogas-related emissions, including CH_4 leakage and slip, are also critical. CFCT v2014 and v2024 estimate 2,400 and 2,600 tCO_2e /year, respectively; ECAM shows 2,410 tCO_2e/year, while the Validation Tool reports 1,930 tCO_2e / year across GWPs (Figure 5b). Natural gas-related emissions are smaller but vary slightly: CFCT v2014 reports 0.321 tCO_2e /year, v2024 shows 0.239 tCO_2e /year, and ECAM and Validation Tool each yield approximately 0.259 t CO_2e/year. Scope 2 electricity-related emissions are relatively consistent: 4.30 tCO_2e/year (CFCT v2014), 4.10 tCO_2e/year (v2024), and ~4.07 tCO_2e/year (ECAM, Validation Tool). GWP updates from 2007 to 2021 cause minor changes in total GHG emissions and in CH_4/N_2O contributions to CF, with EF variations exerting a stronger influence. Total CF trends align with IPCC's GWP revisions for N_2O. For example, when using the Validation Tool without EF changes, total CF decreased from 10,344 tCO_2e/year under GWP 2007 to 10,077 tCO_2e/year (-2.58%) under GWP 2021, and 9,995 tCO_2e/year (-0.81%) under GWP 2014 (Figure 5a). Comparing Tool 3 results (Figure 6), CH_4's share within S1 increased by 2%, corresponding to an 8.8% rise in its GWP value (from 25 to 27.2). Similarly, CFCT v2014 and v2024 show a 13% drop in total CF, from 54,366 t CO_2e/year (GWP 2021) to 47,303 t CO_2e/year (GWP 2014). The horizontal comparison evaluates the impact of default vs. empirical EFs on CF estimates. Using default EFs, CFCT (v2014, v2024) and ECAM v2024 consistently show higher process GHG emissions than Tool 3, which uses empirical EFs. Tool 1 and Tool 2 report significantly higher annual CFs - by 18,192, 16,718, and 17,068 tCO_2e, respectively - than the Validation Tool (Figure 5a). Within Tool 1, the difference between versions is small (459 t CO_2e/year), a 2.1% drop from v2014 to v2024. Figure 6 further illustrates how EF changes affect both CF magnitude and emission composition. ECAM v2024 uses BOD-based EFs, alternative recipient assumptions, and IPCC (2019) tier approaches, leading to higher CH_4 emissions. Its role differs further as CFCT v2014 omits emissions from the recipient. These differences highlight diverse approaches to biogenic process emissions. A distinct divergence in N_2O-related CF levels is seen between Tool 1 and Tool 2 (Figure 7). N_2O emissions strongly influence CF due to EF selection. CFCT versions use 2010 EFs (Foley et al. 2010), whereas ECAM applies IPCC 2019 values, which are 37.6% higher.

Discussion

CF estimates differ among the analyzed tools due to variations in emission factors (EFs), GWP constants, and calculation methods. S1 process emissions dominate the total GHG fluxes in all tools, particularly in CFCT (both versions) and ECAM, more than in the Validation Tool. S2 emissions, associated with purchased electricity, remain more consistent - showing only a 7.5% variation - due to uniformly applied grid-based EFs. These results show that EF selection and methodology differences exert a greater impact on calculated S1 emission levels than GWP updates. This underscores the need for developing standardized CF methods to enhance comparability and accuracy in WWTP assessments.

Heatmaps (Figures 7 and 8) visualize deviations from the mean CF estimates by category (tCO_2e/year), using a blue-to-red gradient to indicate negative to positive variations. Despite differences in accounting methods, CH_4 and N_2O emissions from recipients remain relatively consistent (Figure 7). CFCT v2014 excludes CH_4 from recipient pathways, resulting in slightly lower process-related CF values. ECAM's higher N_2O emissions suggest that its BNR-specific EFs cover more emission pathways. Both CFCT versions yield similar results, indicating minimal methodological or EF-related changes over the past decade. Conversely, Validation Tool results show that GWP updates have a smaller effect than EF adjustments, as CF values remain stable across the GWP scenarios.

Figure 8 illustrates how the CF associated with biogas combustion varies across the tools. CFCT v2014 links biogenic CO_2 to direct emissions, whereas CFCT v2024 and the other tools exclude it, based on IPCC (2019) guidelines. CFCT v2014 assumes a high biogas capture efficiency, showing the lowest CH_4 leakage, while v2024 shows moderate leakage, aligning more with operational realities. ECAM and the Validation Tool report higher leakage, stressing the significant contribution of fugitive CH_4 to total CF. Analysis of biogas slip emissions during upgrading reveals major methodological differences among CF tools. Both CFCT v2014 and v2024 show higher-than-average emissions, indicating alignment with Swedish WWTP operations, which are not captured in the other tools.

Figure 8. Heatmap of deviations from mean emissions by category - biogas, tCO_2e/year (2021).

ECAM and the Validation Tool, reflecting Central European norms, exclude biogas slip due to its limited presence in the region. Although CFCT v2014 covers a broader range of biogas-related categories, it reports the lowest total emissions, showing that broader boundaries do not necessarily yield higher CF values. In contrast, CFCT v2024 includes biogas slip, resulting in the highest reported emissions. ECAM and the Validation Tool consistently attribute emissions to leakage events, providing a more conservative estimate. The heatmap in Figure 8 underscores the need for site-specific EF adjustments supported by actual operational data. These differences highlight the importance of selecting CF tools that reflect a facility's actual biogas management scenario, supporting more accurate policy decisions and operational planning.

This study reinforces that CFCT and ECAM tools are highly sensitive to EF assumptions (De Haas and Andrews 2022). Observed emission levels and CF composition highlight the limitations of using uniform EFs, such as those provided by the IPCC, which can cause both overestimation (De Haas and Andrews 2022) and underestimation (Song et al. 2024) of fugitive emissions. These results support concerns about oversimplified N_2O calculations and demonstrate that relying on generic EFs fails to capture site-specific conditions, especially regarding nitrogen emissions (Maktabifard et al. 2021). Empirical BNR EFs derived in this study challenge the default value of 1.1% TN suggested by De Haas and Andrews (2022), showing instead ~0.11% TN for the investigated facility.

The tool comparison, which shows only minor variations in S2 emissions, confirms the relevance of CF for sustainable energy optimization (Szaja and Bartkowska 2024). Differences in anaerobic-related fugitive emissions support Fighir et al.'s (2019) recommendations for harmonized biogas integration in CF tools, as biomethane recovery is not fully accounted for. Findings align with previous research suggesting that energy-efficient upgrades, such as aeration systems, can reduce S2 emissions (Maktabifard et al. 2021). The tools show limitations in addressing regional and site-specific variability, causing potential biases in CF estimates. This study also confirms the dominance of N_2O in biological emissions (Maktabifard et al. 2021), with CH_4 and N_2O forming over 80% of S1 emissions (Smith et al. 2019). Persistent inconsistencies in CFCT and ECAM's treatment of sludge and biogas emissions highlight the need for flexible, region-specific EFs (Jiménez-Paute 2025) and updated GWPs to support accurate policy reporting.

The findings underscore the need for CF tools to adapt to site-specific conditions and evolving regulations, ensuring that emissions estimates accurately reflect operational data and align with policy goals. Given the discrepancies observed across tools, this study recommends a harmonized validation framework using site-specific EFs and updated GWPs to correct for generalized assumptions. Accounting for variability in fugitive emissions is essential to improve CH_4 and N_2O estimates, as these gases significantly influence WWTP CF. Enhancing CF tools to capture these trends will support more effective mitigation, reduce reporting uncertainty, and improve decision-making in WWTP operations.

This study provides valuable insights into CF estimations for WWTPs, yet there remain opportunities to expand and refine the analysis. Extending the dataset to multi years or facilites could better capture GHG variability. While this study focuses on Scope 1 and Scope 2 emissions, future work could incorporate Scope 3 emissions to assess a fuller environmental footprint. Including CF tools from additional regions, such as Australia, would further broaden the analysis. Differences in tool structure, input requirements, and output formats, complicate direct comparisons and highlight the need for methodological harmonization. Operational strategies, such as aeration regimes, which can affect emissions, were not fully explored. Integrating such factors could clarify how operations influence CF over time, improving assessment accuracy and offering practical guidance for sustainability and emissions management.

This research underscores the potential for adaptive CF tools using machine learning to calibrate EFs in real time based on operational data, thereby improving emission estimation accuracy. The use of real-time data enables long-term trend analysis, enhancing predictive insights and supporting operational planning. Site-specific EFs also enhance CF comparability across regions, facilitating the development of a shared emissions database that reflects the diversity of WWTP configurations, climates, and treatment efficiencies. Regional CF models should account for climate, treatment technologies, and regulations, including standardized methods for biogenic emissions accounting. The influence of climate change, such as extreme weather events, on CFs warrants further investigation, given its impact on treatment efficiency

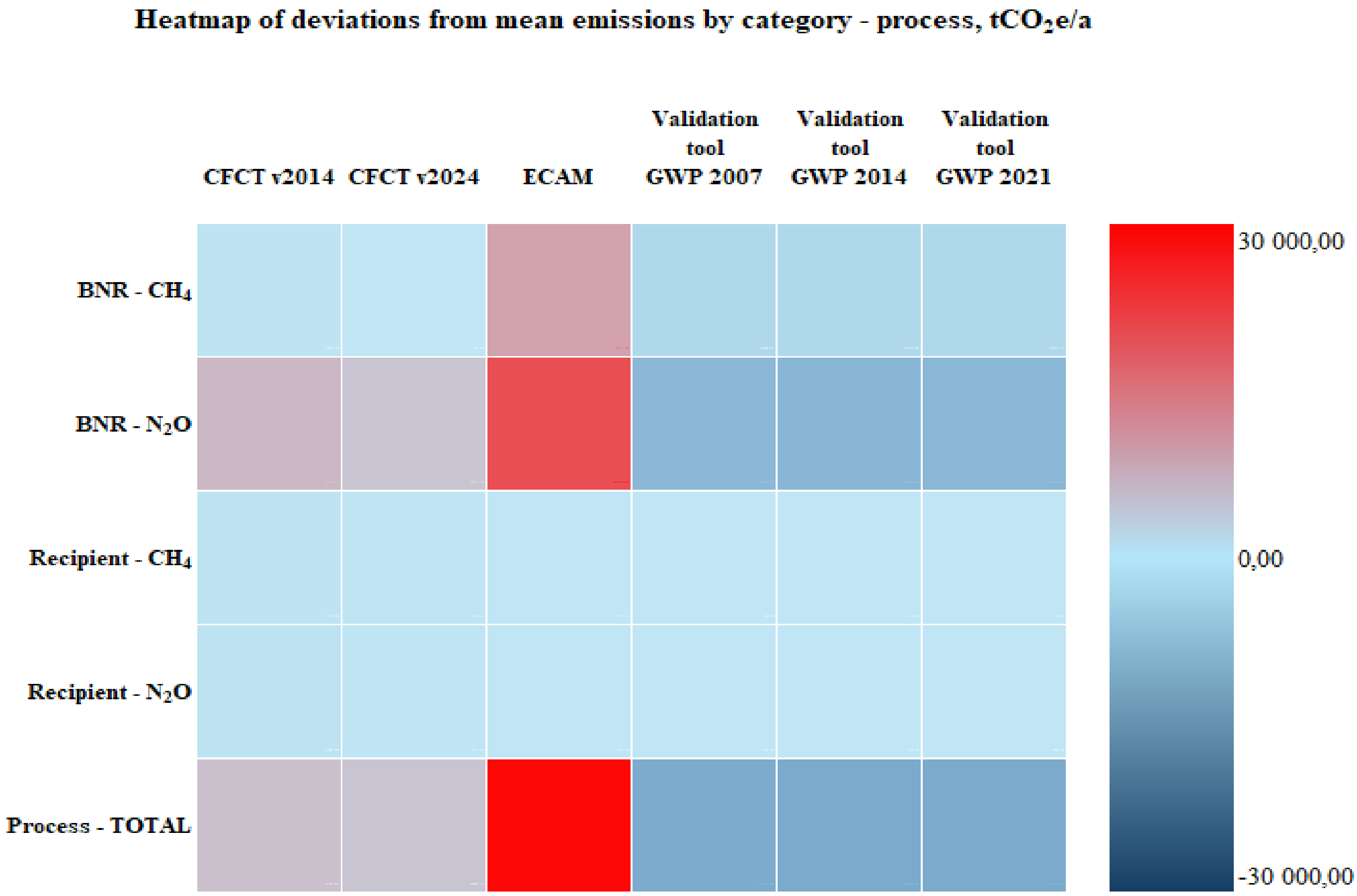

Figure 7. Heatmap of deviations from mean emissions by category - process, tCO_2e/a (2021).

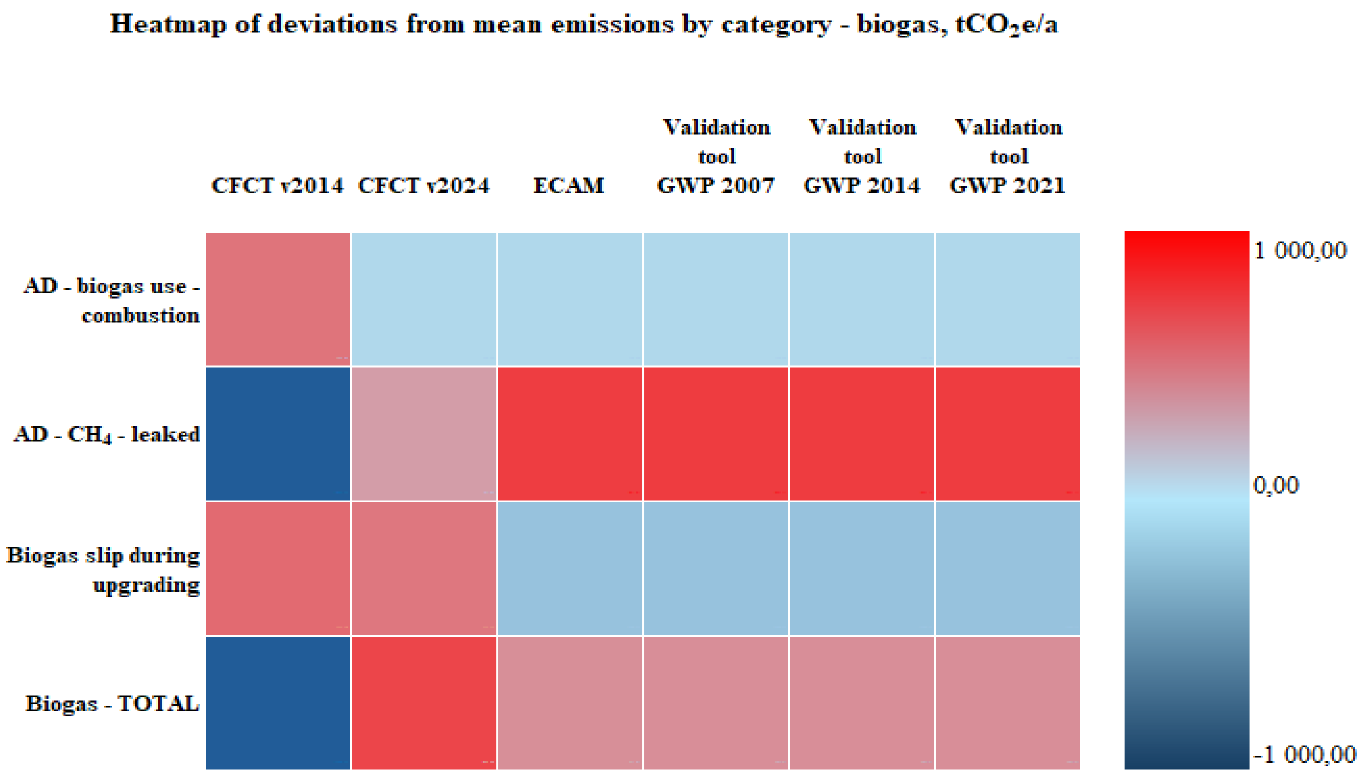

Figure 8. Heatmap of deviations from mean emissions by category - biogas, tCO_2e/a (2021).

and emissions. Additionally, in-situ measurements of biogas leakage are critical to establish more accurate benchmarks than those based on generalized assumptions.

Future research should investigate how resource recovery, particularly circular economy strategies, can contribute to reducing CF. The development of internationally recognized validation protocols is essential to standardize emissions reporting. Additionally, WWTPs could participate in carbon markets, using emission reductions achieved through biogas recovery to generate credits and support global decarbonization efforts.

Conclusions

This study highlights substantial discrepancies in CF estimates for WWTPs across different tools, primarily driven by variations in EFs, GWP values, and methodologies. Scope 1 (S1) emissions, especially from BNR processes and fugitive CH_4 and N_2O, dominate across all tools, whereas Scope 2 (S2) emissions from electricity remain relatively consistent. ECAM shows higher CFs due to its BOD-based approach, while the Validation Tool, using empirical EFs, reports lower values, demonstrating the value of real-world data.

The findings confirm concerns regarding the oversimplification of N_2O emissions and the limitations of default IPCC EFs, which can compromise CF accuracy. Although GWP updates from 2007 to 2021 affect results, the choice of EFs exerts a greater influence. Variability in biogas emissions across methods underscores the need for standardization. Overall, using empirical EFs notably improves CF accuracy, especially for BNR-related emissions. As this study is based on a single full-scale WWTP and does not consider Scope 3 emissions due to limited data availability, the findings should be interpreted within this specific context. Nevertheless, the methodology and results offer a valuable reference point for future studies across diverse wastewater treatment facilities.

Acknowledgements

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Analiza porównawcza narzędzi obliczeniowych do szacowania śladu węglowego oczyszczalni ścieków: metodologie i współczynniki emisji

Streszczenie. Celem artykułu była porównawcza analiza dwóch narzędzi do szacowania śladu węglowego (CF) oczyszczalni ścieków: CFCT (wersje 2014 i 2024) oraz ECAM (wersja 2024). Opracowano również narzędzie walidacyjne z wykorzystaniem współczynników emisji (WE) dla podtlenku azotu (N2O) i metanu (CH4) z procesu osadu czynnego wyznaczonych empirycznie. Praca miała charakter aplikacyjny - oceniano dokładność, spójność i przydatność narzędzi dla potrzeb raportowania równoważonego rozwoju. Analizie poddano oczyszczalnię ścieków (OŚ) w Poznaniu (100000 m^3/d, 1000000 RLM). Wykorzystano dane z 2021 roku oraz wyniki czterodniowej kampanii pomiarowej emisji N2O i CH4, wykonanej za pomocą spektrometru FTIR (spektrometria w podczerwieni z transformatą Fouriera, urządzenie pomiarowe Gasmet DX4000) ze specjalną pływającą kopułą pomiarową. Uzyskane WE wprowadzono do autorskiego narzędzia walidacyjnego. Porównanie oparto na specjalnie zaprojektowanej procedurze, umożliwiającej ocenę wpływu różnych wartości GWP (2007, 2014, 2021) oraz wartości WE (domyślnie wartości literaturowe versus empiryczne). CFCT (2014) zwrócił wynik 29 310 tCO2e/rok; 2024: 28 730 (−2%). ECAM: 54 370 (+88% względem CFCT 2024). Narzędzie walidacyjne: 10 344 (GWP 2007), 10 077 (2021), 9 995 (2014), czyli ~65% mniej niż ECAM. Zakres 1 (Z1) dominował względem Zakresu (Z2) (stanowiąc >75% sumy emisji Z1 oraz Z2). Wybór WE ma kluczowe znaczenie - domyślne wartości mogą zawyżać CF nawet o 200%. Stosowanie danych empirycznych znacząco zwiększa trafność analiz i umożliwia odzwierciedlenie rzeczywistych warunków pracy. Ujednolicenie metodyk i uwzględnienie lokalnych uwarunkowań stanowi warunek rzetelnego raportowania środowiskowego. Narzędzia CF powinny być walidowane empirycznie, zanim zostaną użyte do decyzji operacyjnych. Praca wspiera rozwój nowoczesnych, adaptowalnych narzędzi zgodnych z celami zrównoważonego rozwoju w obszarze OŚ.