

Compensatory measures to reduce GHGs in wastewater treatment plants in Southern Italy

Ezio Ranieri^{a,*}, Gianfranco D'Onghia^a, Francesca Ranieri^b, Luigi Lopopolo^a, Sarah Gregorio^a, Ada Cristina Ranieri^{c,d}

^a *Universita' degli Studi di Bari, Dipartimento di Biologia, Bari, Italy*

^b *Universita' degli Studi di Foggia, Dipartimento di Dipartimento di Economia, Management e Territorio, Italy*

^c *Politecnico di Bari, Dipartimento Interateneo di Fisica, Bari, Italy*

^d *Universita' Internazionale Telematica Uninettuno, Roma, Italy*

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ABSTRACT

This study evaluates Greenhouse Gas (GHGs) emissions in 183 Wastewater Treatment Plants (WWTPs) located in the Apulia region in Southern Italy. All WWTPs examined treat municipal wastewater. GHGs from each treatment unit were estimated in the current situation and compared, for the same WWTPs, to those emitted after assuming structural compensatory measures to mitigate them. Total GHGs emissions in current estimation have been estimated equal to 83 kg CO₂eq/PE.y and equal to 62 kg CO₂eq/PE.y after upgrade. Some compensatory measures have been also discussed to lower GHGs emitted: the recirculation of sludge thickened in treatment secondary; reduction of biogas systems leakage, aerobic digester and thickener coverage and new system to recovery biogas from anaerobic digester generating energy. All upgrade systems considered result in electrical energy reduction and in significant GHGs emission reduction especially for anaerobic digestion based WWTPs.

1. Introduction

The primary objective of a wastewater treatment plant is to remove pollutants from water deriving by human activities aiming to respect effluent standards to safeguard the receiving water body and ecosystems. Throughout the treatment phases, WWTPs play a role in the release of greenhouse gases (GHGs), thereby contributing to climate change and air pollution [1–5, 88]. These emissions, depending on their origin, can be classified as direct or indirect. Direct emissions, such as nitrous oxide (N₂O), carbon dioxide (CO₂), and methane (CH₄), are primarily associated with biological processes. They are produced directly during the removal of C and N based compounds and on respiration of organic matter by bacteria [6–10, 89].

Indirect emissions refer to carbon dioxide related to energy for the operation within WWTPs, stemming from fossil fuels combustion [11–14] and WWTPs are important energy consumers [15,16]. Their emission to the atmosphere contributes to air pollution. In addition, N₂O and CH₄ have a global warming potential of 300 and 30 respectively of CO₂-equivalents over a 100-year time horizon [90], thus even a low emission contributes significantly to climate change.

The United States Environmental Protection Agency [91] estimated that N₂O from WWTPs accounts for approximately 3 % of N₂O from all national sources and ranks as the sixth largest contributor to GHGs emissions, while methane is estimated to account for approximately 5 % of total global emissions. In many European countries, urban water cycle accounts for 1–3 % of the total electric energy consumption [92] and 3–10 % of the Global Warming Potential (GWP) [17]. Otherwise, higher energy consumption is directly correlated with increased GHGs emissions [18,19].

However, during the last years, energy-saving and energy efficiency are progressively becoming more urgent issues, mainly due to higher requirements environmental standards on the quality of treated wastewater and due to the problems associated with the climate crisis [20–23]. In view of this pressure, the wastewater plants have been starting to make strides towards carbon-neutral operation [9, 24–26].

In the last years, several studies are conducted employing empirical modelling that relies on emission factors specific to treatment units [27], comparing models based on the process [28–30], analysing critical operational parameter to optimize the performance of the WWTP or energy optimization, especially on the processes of treatment as

* Corresponding author.

E-mail address: ezio.ranieri@uniba.it (E. Ranieri).

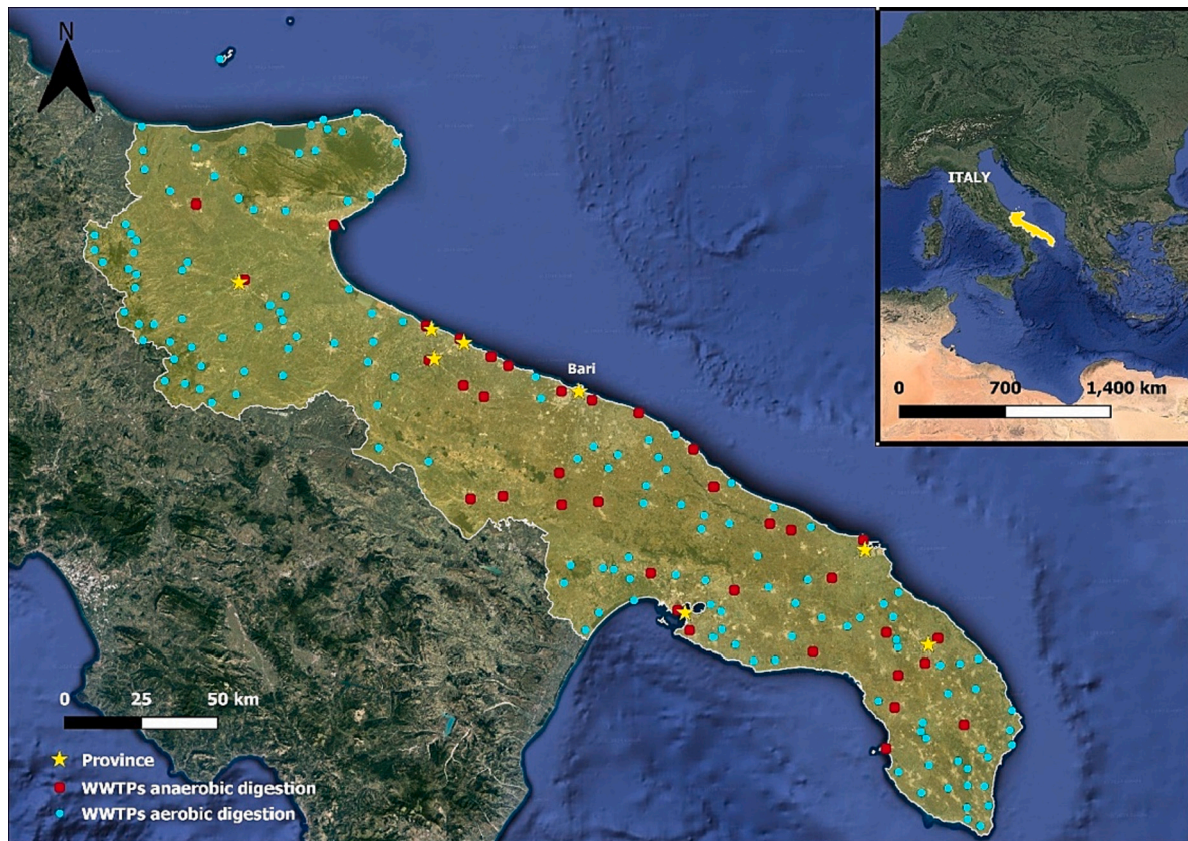


Fig. 1. Apulian WWTPs analysed.

aeration, pumping, mixing and analysis under severe climatic events with potential reduction of energy consumption [31,32].

The GHGs emissions associated with wastewater treatment plant (WWTPs) process can be effectively minimized by carefully choosing treatment technologies or improving the overall process and energy efficiency of WWTPs [33–39]. Also, under specific chemical oxygen demand (COD) conditions, the wastewater treatment process has the potential to decrease direct GHG emissions by 30 % [40].

Some compensatory measures such as: structures coverage, GHGs emissions capture; real time control system for process optimisation to minimise emissions; alternative process configurations with thickened sludge recirculation in denitrification treatment step, depending on site specific context [41–43, 88].

Lack of information exists about the quantification of GHGs emitted after compensatory measures [43–45].

The present study aims to evaluate GHGs emissions and the energy consumption from Apulian WWTPs (Fig. 1) before and after compensatory measures apt to reduce their accumulation in the atmosphere. CO₂, N₂O and CH₄ emissions have been quantified in each process units. In addition, a strategy of mitigation measures apt to reduce GHGs emission in order to improve the sustainability of the wastewater treatment systems, particularly for those treatment sections in which the emissions result critic.

Therefore, specific objective of this paper is to assess the GHGs emissions in all Apulian WWTPs and in each treatment section in terms of CO₂eq by N₂O, CH₄ and biogenic CO₂ fluxes emitted, determining

compensatory measures in the WWTP apt to reduce GHGs emissions.

2. Materials and methods

All plants analysed are managed by Italian Water Management Companies –Aqueduct Pugliese S.p.a. (AQP) and are all situated in Apulian region. According to the Köppen classification, the climate of the Apulian region is Mediterranean, the summers are hot and dry, and rainfall is concentrated between autumn and winter. The WWTPs are 183 out of which 140 possess an aerobic process for sludge management while 43 are equipped with anaerobic digestion sludge. Typical configuration is characterized by a wastewater line and a sludge line. Preliminary treatments, occasionally primary sedimentation and Conventional Activated sludge (CAS) constitute wastewater line and thickener, aerobic or anaerobic digester and dewatering unit constitute sludge line. Each of them is open tanks (except the anaerobic digester) and considered source of emissions. The potential biogas, produced in anaerobic plants, is not always recovered but burned on flare [46,47], generating and not saving CO₂. All operational data are average values that refer to five years of investigation (from 2018 to 2022). The average equivalent population of an Apulian WWTP is equal to 60,336 PE with an average capacity of 8476 m³/d.

Table 1 reports principal characteristic of the Anaerobic and Aerobic WWTPs in Apulia:

Anaerobic plants have larger capacities, with an average of 82,700 PE while aerobic based WWP have an average capacity of 10,543 PE.

Table 1
Anaerobic and aerobic WWTPs characteristics in Apulia.

	Person equivalent (PE)	Kwh/d (total)	Inflow (Q) m ³ /d	COD in mg/L	COD out mg/L	Nitrogen in mg/L	Nitrogen out mg/L
Anaerobic digestion	3,346,321	263,511	470,985	887	55	75	14
Aerobic digestion	1,517,781	237,684	210,853	798	48	78	13

Table 2
N₂O Emission factors for each sector of treatment in WWTP.

N ₂ O emission factors									
Units process	PRELIMINARY TREATMENTS	PRIMARY SETTLER	AEROBIC OXIDATION	SECONDARY SETTLER	THICK.	AEROBIC DIGESTER	AN. DIG	Note	References
-Oxidation ditch	0,2 gN ₂ O/d		4975 gN ₂ O/d	114,3 kgN ₂ O/d		1,7 × 10 ³ gN ₂ O/L		7 × 10 ⁴ m ³ /d	[54]
-Reversed A ² O	24,6 gN ₂ O/d		6718,1 gN ₂ O/d	829,2 kgN ₂ O/d				23 × 10 ⁴ m ³ /d	
-A ² O	24,6 gN ₂ O/d		9778,8 gN ₂ O/d	240,1 kgN ₂ O/d				23 × 10 ⁴ m ³ /d	
Activated sludge	1,6 × 10 ³ gN ₂ O/y		3,2 × 10 ⁴ gN ₂ O/L					11,000 PE	[86]
	1,6 × 10 ² gN ₂ O/y							1,1 × 10 ⁹ L/y	
Active sludge (15,000 PE)			0,00032 kgN ₂ O-N/ kgNH ₄ -N in					Nin:52,4 mg/ L. scarce efficiency	[55]
Italian CAS			0,027 g N ₂ O-N for each gram of N entering the plant						[56]
Netherlands CAS			0,25 g N ₂ O						
WWTP 1–6 (>15,000 PE)	2,6 × 10 ⁻⁴ kg N ₂ O /kgNrem		Value range 6,7 × 10 ⁻⁸ to 0,02 kg N ₂ O/kgNrem			8,9 × 10 ⁻⁸ kg N ₂ O/kgTS			[57]
WWTP 7–12 (<15,000 PE)									
Activated sludge plant (60.000 PE)			0,001 % N ₂ O/NLoad						[58]
Activated sludge plant (60.000 PE)			0,02 % N ₂ O/NLoad						[59]
CAS 1000 PE			0,01 %-0,08 % N ₂ O/NLoad						[60]
SBR with load >5000 PE			Range from 0,002 % to 1,29 % N ₂ O/TNin						[61]
COD ₁₂₀			0,025 kg N ₂ O/kgTN			0,00024 kg N ₂ O/kg N			[53]
						0,00023 kg N ₂ O-N/kg			[62]
		0,00055 kgN ₂ O/kgNrem							[17]

Table 3
Biogenic CO₂ Emission factors for each sector of treatment in WWTP.

CO ₂ emission factors									
Units process	PRELIMINARY TREATMENTS	PRIMARY SETTLER	AEROBIC OXIDATION	SECONDARY SETTLER	THICK.	AEROBIC DIGESTER	AN. DIG	Note	References
- oxidation ditch	2,1 kgCO ₂ /d		4128,3 kgCO ₂ /d	43,4 kgCO ₂ /d				7 × 10 ⁴ m ³ /d	[54]
-Reversed A ² O	78,3 kgCO ₂ /d		13,743,1 kgCO ₂ /d	181,7 kgCO ₂ /d				23 × 10 ⁴ m ³ /d	
-A ² O	78,3 kgCO ₂ /d		24,878 kgCO ₂ /d	211,4 kgCO ₂ /d				23 × 10 ⁴ m ³ /d	
A ² O	5,25gCO ₂ /m ³	0,28 gCO ₂ /m ³	168,65 gCO ₂ /m ³	0,52 gCO ₂ /m ³	0,07 gCO ₂ /m ³			CODin: 397 mg/L	[63]
AO	4,38gCO ₂ /m ³		167,99 gCO ₂ /m ³	0,41 gCO ₂ /m ³				CODin: 384 mg/L	
Oxidation ditch	5,45gCO ₂ /m ³	0,25 gCO ₂ /m ³	355,87 gCO ₂ /m ³	2,08 gCO ₂ /m ³				CODin: 488 mg/L	
-SBR	0,14gCO ₂ /m ³		343,86 gCO ₂ /m ³					CODin: 414 mg/L	
Aereated grit tank	3,9 × 10 ⁶ gCO ₂ /y		3,6x10 ⁸ gCO ₂ /y			2,1 × 10 ⁷ gCO ₂ /y		11,000 PE	[86]
Non areated grit tank	1,1 × 10 ⁶ gCO ₂ /y							1,1 × 10 ⁹ L/y	
WWTP 18000 PE	Value range							CODin:318 ton/y	[57]
WWTP 22000 PE	4,1 × 10 ⁻³ -0,1 kgCO ₂ /kgCODr							CODin:444 ton/y	
WWTP10000 PE								CODin:237 ton/y	
WWTP 1–6 (>15,000 PE)			Range CODin:432–2037 ton/y/y			1,3 × 10 ⁻³ kg CO ₂ /kgTS			[57]
WWTP 7–12 (<15,000 PE)			Range CODin:58–273 ton/y in:8,6–44 0,5 kgCO ₂ /kgCOD						[10]
						1,02 kgCO ₂ /kgCOD			[87]
							0		[53]

Table 4
CH₄ Emission factors for each sector of treatment in WWTP.

CH ₄ emission factors									
Units process	PRELIMINARY TREATMENTS	PRIMARY SETTLER	AEROBIC OXIDATION	SECONDARY SETTLER	THICK.	AEROBIC DIGESTER	ANAEROBI DIGESTER	Note	References
-Oxidation ditch	0,9 kgCH ₄ /d 18,3 kgCH ₄ /d		88 kgCH ₄ /d 147,7 kgCH ₄ /d	0 kgCH ₄ /d 0 kgCH ₄ /d				7 × 10 ⁴ m ³ /d 23 × 10 ⁴ m ³ /d	[54]
-Reversed A ² O -A ² O	18,3 kgCH ₄ /d		74,4 kgCH ₄ /d	0 kgCH ₄ /d				23 × 10 ⁴ m ³ /d	
(11,000 PE)	5,7 × 10 ⁴ gCH ₄ /y 9,2 × 10 ⁴ gCH ₄ /y	0.34 g CH ₄ /m ³	2,2 × 10 ⁵ gCH ₄ /y 0,075 kg CH ₄ /kgCOD			6,3 × 10 ⁴ gCH ₄ 0 kgCH ₄ /kgCOD	0,2	11,000 PE 1,1 × 10 ⁹ L/y Load COD influent (kg/PE/y)	[64]
	0.155 gCH ₄ /m ³	0.16 g CH ₄ /m ³						0.015 mgCH ₄ /L CH ₄	[65]
WWTP 1–6 (>15,000 PE)	Value range 1.3 × 10 ⁻⁴ – 1.5 × 10 ⁻³ kg CH ₄ /kgCODin		Value range 2.2 × 10 ⁻⁸ to 0.003 kg CH ₄ /kgCODin			3.8 × 10 ⁻⁷ kg CH ₄ /kgTS			[57]
WWTP 7–12 (<15,000 PE)		6,4 gCH ₄ /m ³	0, Assuming to work efficiently					COD influent 370 mg/L	[66]
						0.15 g CH ₄ /PE-d 0.0025 kg CH ₄ /kg CODslud	0.34 gCH ₄ /PE-d 3,44 g CH ₄ /m ³		[67]
									[62]
		1.15 g CH ₄ /m ³							[68]
		0,0018 kg CH ₄ /kgCOD							[96]
		0							[69]
		0,00084 kg CH ₄ /kgCOD removed							[17]
PE 169000 V = 2x5000m ³ CODin 16,961 kg/d							9100kgCOD/d -> 3185 m ³ CH ₄ /d Biogas From this 17m ³ CH ₄ /d emitted	Tot biogas produced: 4913gCH ₄ /(PE-y) Loss: 24,6gCH ₄	[70]
								0,38kgCO ₂ /kgCOD	[10]

Achieving a balance between these aspects is crucial for optimizing overall wastewater treatment effectiveness and sustainability.

The raw sewage presents following average influent characteristics: 857 mg COD/L and of 76 mg N/L. To quantify emissions from different stages of treatment, it has been calculated CH₄, N₂O, and CO₂ fluxes using GHGs Emission Factors (EFs) in relation to the percentage of COD and nitrogen removal, expressed in kilograms per day removed, measured for each treatment unit.

COD and N mass balance have been elaborated based on experimental values measured in the AQP facilities and compared to other similar contexts [48–52, 93, 94].

Primarily, CH₄ and N₂O emission factors for biological treatments, namely aerobic oxidation and sludge digestion in aerobic and anaerobic processes, were taken from [53], averaged with supplementary emission factors found in the literature (Tables 2-4).

EFs are plant-specific, as indicated by [10]. Consequently, a range of emission factor values has been obtained, serving as base for our estimations at each treatment stage. GHGs have been assessed using Eqs. (1), (2) and (3).

$$[\text{kg}]CH_4 = EF_{CH_4} \left(\frac{[\text{kg}]CH_4}{[\text{kg}]COD_{\text{removed}}} \right) \times [\text{kg}]COD_{\text{removed}} \quad (1)$$

$$[\text{kg}]N_2O = EF_{N_2O} \left(\frac{[\text{kg}]N_2O}{[\text{kg}]COD_{\text{removed}}} \right) \times [\text{kg}]N_{\text{removed}} \quad (2)$$

$$[\text{kg}]CO_2 \text{ biogenic} = EF_{CO_2} \left(\frac{[\text{kg}]CO_2}{[\text{kg}]COD_{\text{removed}}} \right) \times [\text{kg}]COD_{\text{removed}} \quad (3)$$

where: EF represents the amount of GHG emitted per unit of COD or N removed, measured in kilograms of GHG per kilogram of COD or N removed. The calculation involves multiplying the kilograms of COD removed (obtained from the raw influent multiplied by the percentage of carbon removal at each station) to obtain the carbon emissions from each unit. Similarly, for nitrogen, the kilograms of N removed are obtained by multiplying the kilograms of N in the raw influent by the percentage of N removal at each station. Finally, the emission factors are multiplied by the kilograms of COD or N removed from each unit. Additionally, to convert kilograms of GHG to kilograms of CO₂ equivalent (kgCO₂eq), CH₄, N₂O, and CO₂ are multiplied by 30, 300, and 1, respectively, in accordance with the Global Warming Potential (GWP). The quantity of indirect CO₂ is determined multiplied EF with electric consumption for each section of plants (kWh) (result of electric energy multiplied for its correspondent rate). Instead, EF of electric energy is taken from report of Acquedotto Pugliese [95]: 1 kwh = 0,406 kg CO₂.

Compensatory Measures for GHG reduction including recirculation

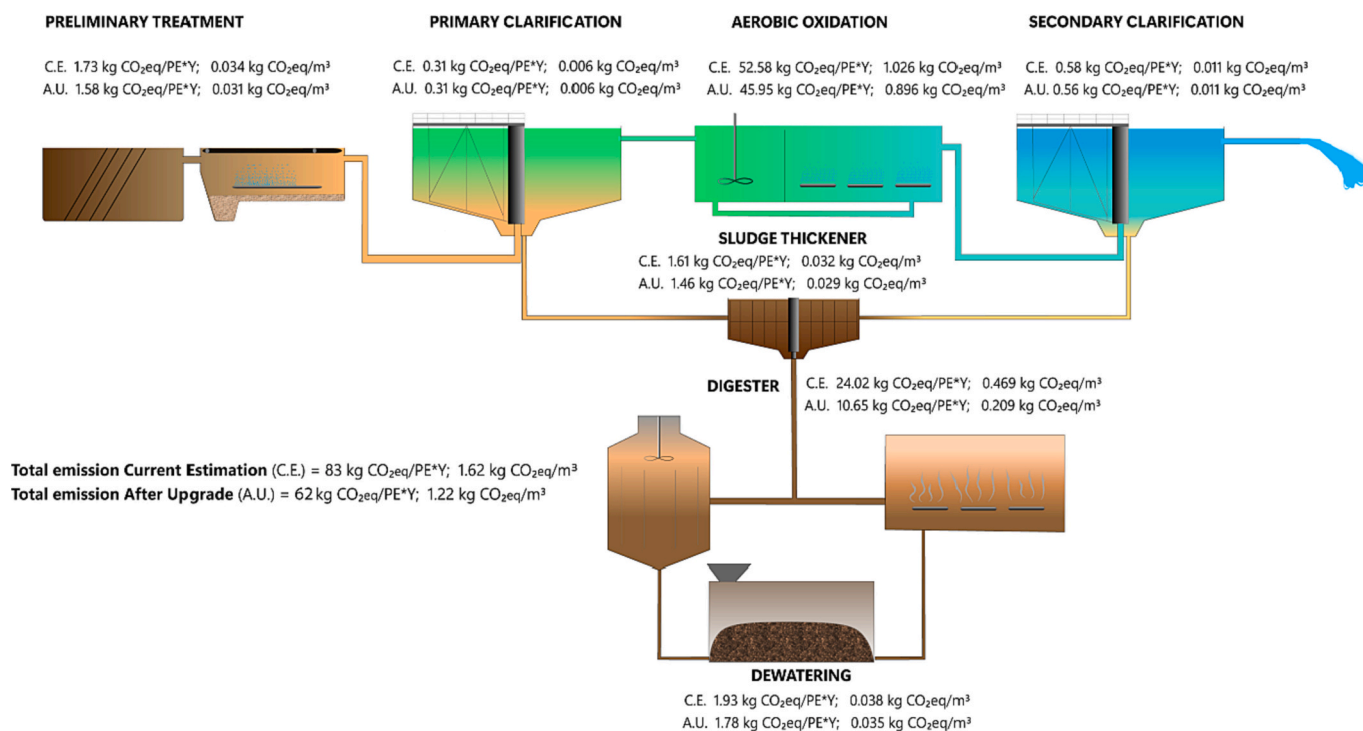


Fig. 2. Flowchart of Apulian WWTPs with relative emissions.

of sludge thickened flux in the denitrification step; covering with an alum structure the aerobic digester tank; use of inverters and Artificial Intelligence (AI) have been evaluated differentiating between anaerobic and aerobic WWTPs. In particular in anaerobic based WWTPs it has been estimated the amount of biogas converted in electric energy, so reducing, the total CO₂eq after upgrade. It has been better explained and added in the manuscript in Material and Methods sections. In the Results discussions it has been also added the percentage of electrical energy reduction (20 %) measured on field due to the use of inverters and new electromechanical equipment governed by AI [41,42,44,71].

3. Results and discussion

Mitigation measures are evaluated through a careful study of the current configuration of the Apulian plants: biological process and mechanical treatment, hydraulic and aeraulic connections and a new sludge line conceptualization. Same emission factors have been considered in the scenario after WWTP upgrade based on the upgraded process. The improvement focused on several WWTPs steps, where lower CO₂, N₂O and CH₄ emissions both in wastewater line and in sludge line are expected. So, it's concerned to hedging transactions aerobic digestion, to lock emissions resulting by endogenous respiration, enhance degradation process of organic matter degradation with recirculation of thickened sludge in anoxic basin prior entering in the biological basin to avoid N₂O formation.

In the anaerobic based WWTPs the upgrade concern anaerobic digester step, avoiding CH₄ losses and by converting CH₄ in heat and energy. This energy can be reused in same plant. Thus, this option allows valorising waste and by-products, turns out to be an alternative source of energy and save energy cost [72,73]. CH₄ emissions from the anaerobic digester are estimated to be 5 % of all CH₄ produced is fugitive and the remaining is considered as indirect CO₂ (because transformed from methane to electricity). The introduction of monitoring system governed by Artificial Intelligence (AI) specifically in the aeration tank and in the pumping, systems could drive to significant reduction of electric energy usage estimated in a reduction of 20 % [44,74, 88]. The estimation of total annual GHGs emissions by 183 AQP plants, after integration of

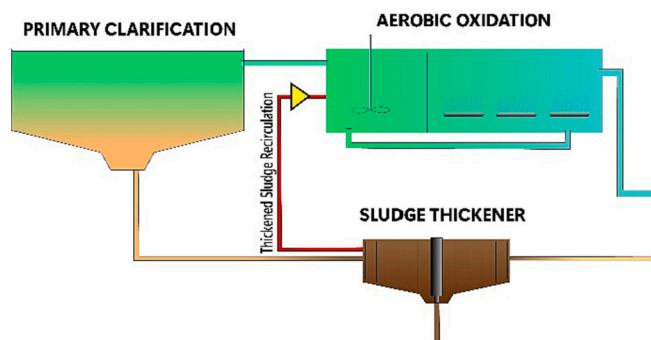


Fig. 3. Recirculation of thickened sludge in anoxic basin prior entering in the biological.

compensatory measure on specific sections is 62 kgCO₂eq/PEy or 1,22 kg CO₂eq/m³ starting to current situation in which is emitted 83 kgCO₂eq/PE.y. Values are referred to an average PE and were weighted on the size of the plants. In Fig. 2, the results of Current Estimation (C.E.) and After Upgrade (A.U.) GHGs estimation have been illustrated. The estimated emission introducing compensatory measures, in terms of kg CO₂eq/PE.y, amounts in preliminary treatments from 1.73 to 1.58, in aerobic oxidation from 52.58 to 45.95, in sludge thickener from 1.61 to 1.46, in digester from 24.02 to 10.65, in dewatering from 1.93 to 1.78.

Compensatory measures have been considered, mainly in biological processes as aerobic oxidation, aerobic and anaerobic digestion because are they emit GHGs more than in physical processes.

A possible mitigation strategy introduced in the Apulian WWTPs to reduce N₂O emissions was the recirculation of sludge thickened flux, that containing high C content directly in anoxic basin prior entering in the biological basin, as illustrated in Fig. 3. [75] quantify about 73.1 ± 5.6 % N₂O emissions only in aerobic oxidation and found higher N₂O emissions are principally due to insufficient carbon source and incomplete denitrification in the anoxic stage of the biological basin, causing more N₂O emissions [54,75]. The proposed internal recirculation is

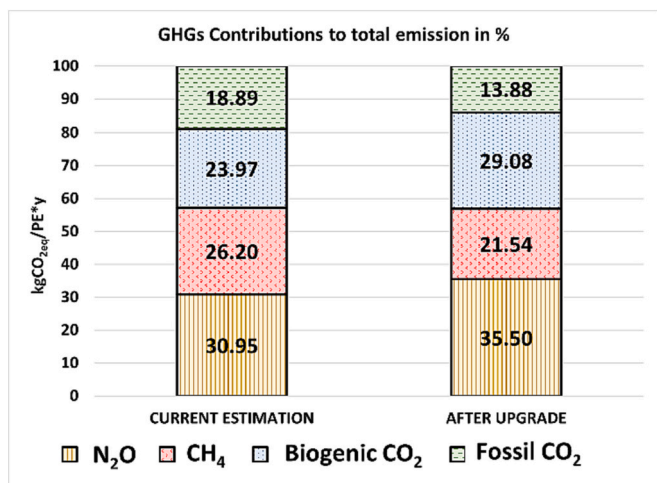


Fig. 4. GHGs contributions in % on Apulian WWTPs before and after upgrade.

shown to achieve nitrous oxide reductions of approx. 30 % in different time with an effluent quality improvement and an operational cost reduction by reducing energy consumption and improving wastewater nitrogen removal [43,76]. The recirculation can increase the C rate in the anoxic stage so less N₂O emissions are expected. The N₂O, biogenic CO₂ and CH₄ total fluxes are predominant in the WWTPs biological basin, particularly in anoxic/aerobic tank as a result of organic matter degradation process [64,77].

Another compensatory measure has been introduced by covering with an alum structure the aerobic digester tank in order to minimise emissions resulting by endogenous respiration.

The alum structure coverage also includes the aspiration of exhausted air and his treatment in biotrickling process with a reduced CO₂ emission into the atmosphere from the biotrickling.

In addition, the use of inverters and new electromechanical equipment governed by Artificial Intelligence with higher efficiency, would make it lower electricity consumption and therefore also the corresponding GHGs issued. In Europe annual GHG emissions, range between 7 and 108 kgCO₂eq/PE.y for 16 Scandinavian WWTPs [78] and 33–38 kgCO₂eq/PE.y in Romania WWTPs [85], quite lower than the values estimated in Apulia.

Fig. 4 illustrates the variation in the contribution of each greenhouse gas (GHG) to the total after the implementation of upgrade measures. N₂O contributions range from 30.95 % to 35.5 %, CH₄ contributions varies from 26.2 % to 21.54 %, biogenic CO₂ fluctuates from 23.97 % to

29.8 %, and fossil CO₂ shows a variation from 18.89 % to 13.88 %.

The total emission of current estimation is 83 kg CO₂eq/PE*y, the total emission after upgrade amount to 62 kg CO₂eq/PE*y. The emissions as found by the method used, are similar to those in the studies by Ranieri et al. (2023) and Parravicini et al. [79], in which emissions were estimated to range from 134 to 125/50 kgCO₂eq/PE.y C.E. to 63 kgCO₂eq/PE.y A.U.

Fig. 5 highlighted, respectively, the percentage contribution of single GHGs for each treatment stations in the current estimation and after upgrade. In all the treatment stations the major contribution is due to indirect CO₂ emission, except for digester and aerobic oxidation. Higher GHGs emissions decrease are reached, after upgrade, in the sludge line.

Both current emissions and estimated emissions following the upgrade of compensatory measures for biological oxidation stations and digesters appear to be similar when compared to emission factors reported in other studies such as those by [65], and [56]. [57]. Processing the data according to Eqs. (1), (2) and (3) and utilizing the emission factors similar emission results are obtained.

Fig. 6 reported the kgCO₂eq/PE.y of each GHGs for each treatment stations.

In anaerobic WWTPs, the digester section has a negative fossil CO₂ emission after upgrade because in all the plants the conversion from methane to energy has been reached saving energy cost and additionally, decreasing the global warming potential of the CO₂ emissions.

In USA and Germany WWTPs have already almost achieved 100 % electricity self-sufficiency [30,80]. So, net-zero electricity for WWTPs is a feasible option. By avoiding the emission from flare, the contribution of fossil CO₂ emissions, is resulted to be lowered of 13,88 %.

In addition, reduction energy consumption could be monitored with introduction system governed by Artificial Intelligence (AI) either in the anaerobic step, either in aeration tank and in the pumping (Ranieri et al., 2023).

However, anaerobic systems are almost always advantageous in terms of electricity consumption per m³ as they achieve >50 % saving than aerobic sludge system above a large size [16]. At the present a quite number of Apulian anaerobic based WWTPs are not optimal managed so a variable quantity of CH₄ is released in atmosphere as fugitive flux from battered pipes or due to leakage at the manhole and the cracks in the tank. This has been evaluated from 2 to 10 % of the total methane emissions that characterizes biogas step [81–83]. Good maintenance would make it possible to eliminate even the smallest parts, as taking into account in this study, in scenario after upgrade.

Fig. 7, reports the energy consumption per cubic meter of treated wastewater as a function of the size plant for all 183 WWTPs. It has been showed that the specific energy electric consumption is inversely

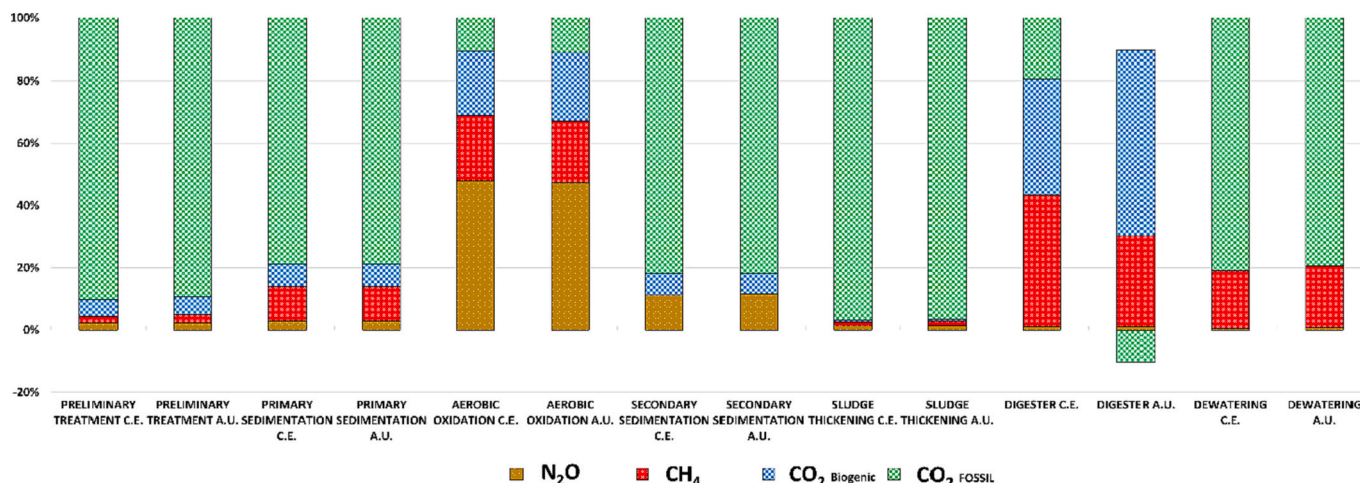


Fig. 5. Single GHGs contribution in current estimation (C.E.) and after upgrade (A.U.) for each treatment station.

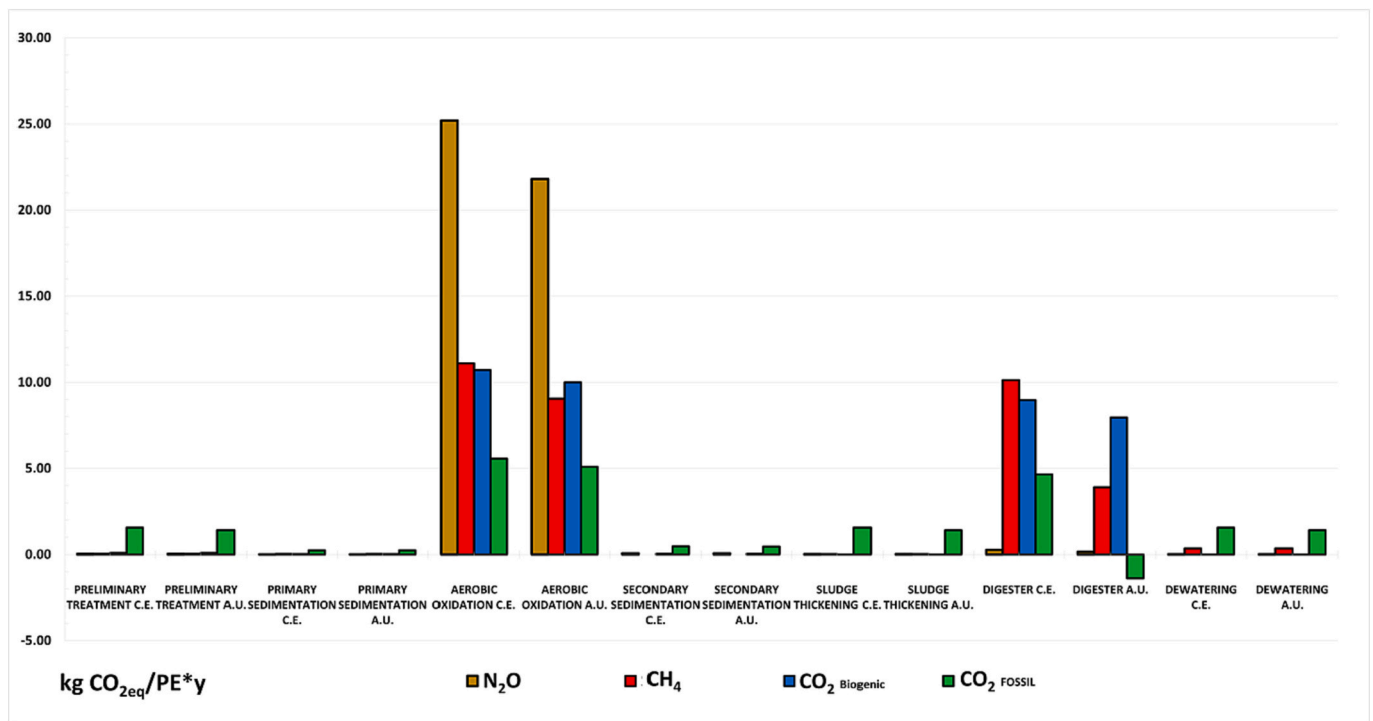


Fig. 6. Current estimation (C.U.) and after upgrade (A.U.) of single GHGs contribution in kgCO_{2eq}/PE*y for each treatment station.

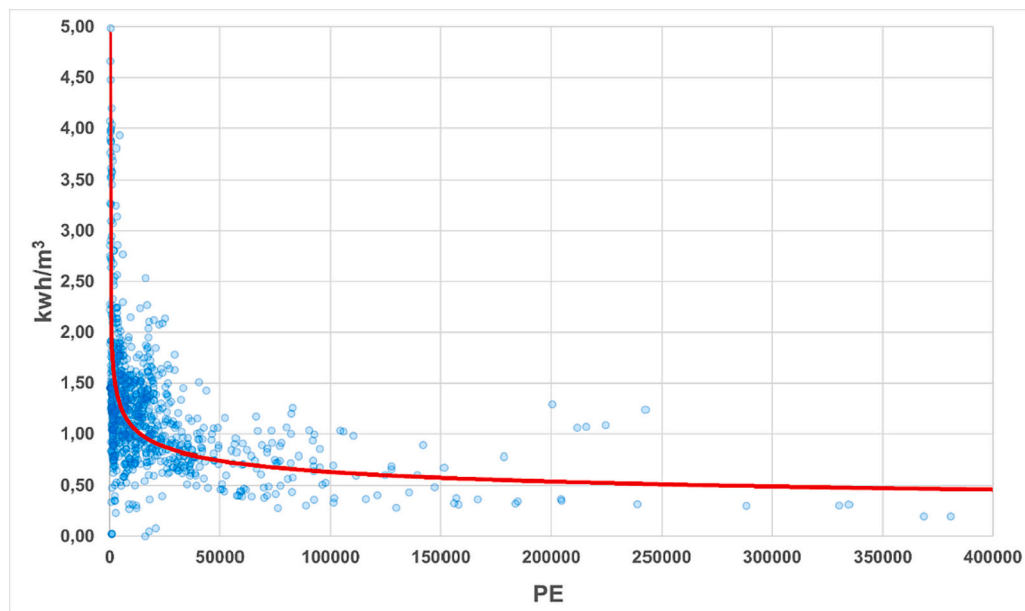


Fig. 7. Energy consumption (kwh/m³) related to size plant reported as Person Equivalent (PE).

proportional to the size of the WWTPs according to [15,16]. Moreover, large WWTPs are all anaerobic digestion based so, the upgrade measures should be better taken into consideration for large WWTPs to effectively lower either indirect emission (energy electric) either direct GHGs emission, particularly CH₄ emissions [84].

Summarising all mitigation strategy, it was designed that cover aerobic digestion involves a decrease of direct emissions, this application could also be designed for the preliminary sedimentation tank and thickener. In addition, recirculation of sludge thickened in anoxic tank of secondary treatment helps to decrease the formation of N₂O. The activation of cogeneration system in anaerobic plants, with an accurate

maintenance of tank, manhole and pipes could potentially achieve zero value of CH₄ emissions.

4. Conclusions

This study has been aimed to assess GHGs emissions from WWTPs situated in Southern Italy. It was found a contribute of 83 kgCO_{2eq}/PE-y with N₂O as the most significant part, about 31 % of emissions, followed by 26,2 % CH₄ emissions and about 24 % of biogenic CO₂ emissions, highlighting the need of targeted reduction strategies. To mitigate N₂O emissions, this study proposed a series of compensatory measures:

recirculation of thickened sludge from the thickener increasing the C/N ratio in the anoxic basin. Additionally, it has been implemented the integration of coverage of aerobic digester for which would get a significant reduction in direct and indirect emission realizing new machines and AI based equipment with higher specific yield and lower consumption.

The revamping of the biogas system and of the anaerobic digestion tank can significantly recover energy and reduce, GHG emissions, particularly CH₄. Finally, compensatory measures should be more advantageous especially if applied in large WWTPs based on anaerobic digestion.

Future investigations should highlight WWTP efficiency to identify potential areas for implement other effective compensatory measures which help to reduce GHG emissions, contributing to the climate change mitigation.

CRedit authorship contribution statement

Ezio Ranieri: Writing – original draft, Conceptualization. **Gianfranco D'Onghia:** Supervision. **Francesca Ranieri:** Formal analysis. **Luigi Lopopolo:** Data curation. **Sarah Gregorio:** Resources. **Ada Cristina Ranieri:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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