Application of strategies for sanitation management in wastewater treatment plants in order to control/reduce greenhouse gas emissions

Margarita Préndez[a,*], Scarlette Lara-González[b]

[a] *Universidad de Chile, Facultad de Ciencias Químicas y Farmacéuticas, Olivos 1007, Santiago, Chile*
[b] *Universidad de Chile, Magíster en Gestión y Planificación Ambiental, Avda. Diagonal Paraguay 265, of. 801, Santiago, Chile*

Abstract

Greenhouse gases (GHG), basically methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O), occur at atmospheric concentrations of ppbv to ppmv under natural conditions. GHG have long mean lifetimes and are an important factor for the mean temperature of the Earth. However, increasing anthropogenic emissions could produce a scenario of progressive and cumulative effects over time, causing a potential "global climate change". Biological degradation of the organic matter present in wastewater is considered one of the anthropogenic sources of GHG.

In this study, GHG emissions for the period 1990–2027 were estimated considering the sanitation process and the official domestic wastewater treatment startup schedule approved for the Metropolitan Region (MR) of Santiago, Chile. The methodology considers selected models proposed by the Intergovernmental Panel on Climate Change (IPCC) and some others published by different authors; these were modified according to national conditions and different sanitation and temporal scenarios.

For the end of the modeled period (2027), results show emissions of about 65 Tg CO_2 equiv./year (as global warming potential), which represent around 50% of national emissions. These values could be reduced if certain sanitation management strategies were introduced in the environmental management by the sanitation company in charge of wastewater treatment.

Keywords: Strategies for sanitation management; Wastewater treatment plants; Greenhouse gas emissions

1. Introduction

The greenhouse effect is a natural process produced when solar radiation crosses the atmosphere modifying its long waves, impacts the terrestrial surface again modifying its long waves and returns to space. In this process, part of the infrared radiation coming from the Earth is trapped by the clouds and certain gases in the atmosphere, called greenhouse gases (GHG), and returns to the Earth. GHG, mainly carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), occur at low concentrations in the atmosphere under natural conditions and have long mean lifetimes (10–200 years); they are essential to maintaining the temperature of the planet (Table 1).

The sustained increase in anthropogenic emissions beginning with the industrial revolution could generate a scenario of potential progressive and cumulative effects, which may cause a potential "global climate change" over time.

1.1. Principal greenhouse gases

The most important GHG is CO_2; it is the most abundant in the atmosphere (360 ppmv), has a high calorific power and is easily generated by human activities, essentially by the burning of fossil fuels and wood. CO_2 is the greenhouse gas of reference, and the other gases are stated in units of CO_2.

The atmospheric concentration of CH_4 is relatively low (1.72 ppmv), but its calorific power is 63 or 21 times greater than that of CO_2 over a horizon of 20 and 100 years, respectively (Intergovernmental Panel on Climate Change

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[*] Corresponding author. Tel.: +56 2 978 2806; fax: +56 2 978 2809.
E-mail address: mprendez@ciq.uchile.cl (M. Préndez).

Table 1
Characteristics of the principal greenhouse gases

Gas	Mean life (years)	Pre-industrial C concentration	Concentration in 1990	GWP[a] (%)	Annual increase (%)[b]	Caloric equivalencies[c] with respect to CO_2
CO_2	50–200	280 ppmv	360 ppmv	45–61[d]	1.5[e]	1[f,g]
CH_4	10	790 ppbv	1720 ppbv[f]	16[e]	1.3[e]	63–21[g]
N_2O	130–200[d]	288 ppbv	312 ppbv[h]	5[e]	0.25[d]–0.3[e]	310–320[f,g]

[a] GWP: global warming potential.
[b] Annual increase calculated for the 90s.
[c] Caloric equivalencies in a 20- and 100-year scenario, respectively.
[d] Ref. Lexmond and Zeeman (1995).
[e] Ref. Mackenzie (1998).
[f] Refs. Houghton (1997) and Houghton (1991).
[g] Refs. IPCC (1997a, b, c).
[h] Ref. Keller (2002).

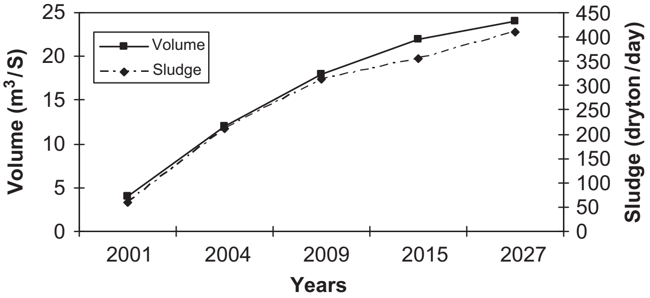

Fig. 1. Projection of wastewater and sludge volume produced and treated in the Metropolitan Region from 2001 to 2027 (Aguas Andinas, 2000).

(IPCC), 2000). CH_4 is emitted mainly from rice cultivation, ruminant digestive processes, anaerobic management of solid waste and biomass burning.

N_2O has different emission sources. It is generated by microbial activity in wastewater, soils and oceans during the degradation of nitrated organic matter (Mackenzie, 1998; IPCC, 2002). Mackenzie (1998) recognizes an increasing amount of N_2O emissions due to microbial transformation of the nitrogen contained in wastewater. N_2O has a calorific power equivalent to 310–320 times that of CO_2 in a 100-year scenario (Lexmond and Zeeman, 1995; IPCC, 1997a).

Biological degradation of the organic matter present in wastewater is considered one of the anthropogenic sources of GHG; emissions from this source correspond to about 0.18% of total emissions from any country (UNFCCC, 2002).

Fig. 1 shows the domestic wastewater treatment program schedule for the Metropolitan Region (MR) (Aguas Andinas, 2000). This planning considers the treatment of domestic wastewater generated by the city of Santiago and surrounding towns, increasing by 23% during 2001 (using 1990 as a baseline) and reaching a 75% increase in 2004 and a projected 100% increase in 2009. Sludge will be stabilized and essentially digested through anaerobic processes, generating quantified GHG concentrations.

The main goal of this study is to estimate GHG emissions from domestic wastewater treatment in the MR during the period 1990–2027, incorporating different sanitation management scenarios.

2. Materials and methods

The methodology used for the estimation of the GHG potentially emitted from the treatment of domestic wastewater generated from the MR was: (1) analysis of the type of environmental management to be used for the treatment, (2) choice of the conceptual work model and (3) selection, adaptation and application of different models for estimating GHG.

The information on national values was obtained from the sanitation sector and was organized and used according to the recommendations contained in the IPCC methodological guidelines for "anthropogenic wastes" (IPCC, 1997a, b, 2000). In absence of the required parameters, default values were used. Excel 2000, v.9.0 software was used as database administrator. Partial estimations for each gas, in different scenarios, consider different management strategies. Individual gas estimations were expressed in CO_2-equiv. units in order to estimate the global warming potential for MR wastewater in the different modeled scenarios.

Fig. 2 shows the scheme of the conceptual model for three emitting sources: (i) treated wastewater (WWT), (ii) sewage sludge treated and disposed of (SST), (iii) surface drainage and land application of untreated wastewater in a wastewater treatment plant, but through an *on site* method (NTWW).

The mathematical models used are based on linear equations relating sanitation activity information to design parameters, emission factors and the biochemical process for organic matter decomposition in wastewater and sludge (Lara-González, 2003). Emissions through the "water line"

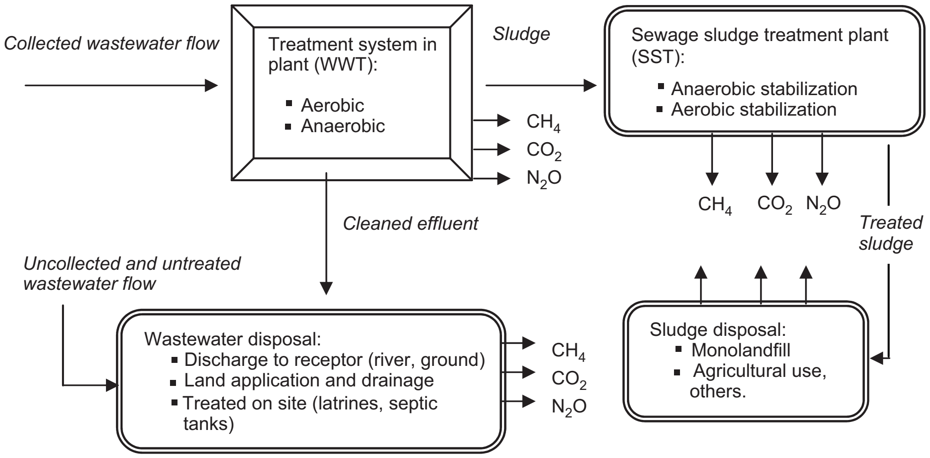

Fig. 2. Conceptual model for greenhouse gas emissions from domestic wastewater (Lara-González, 2003).

are estimated from activity data ((*AD*) population served, treated volume, organic loading and so on); this information is multiplied by the fraction of treated wastewater in treatment plants (*Fr*) (aerobic or anaerobic processes) or by another design parameter (*DP*) and then multiplied by the specific emission factor (*EF*) for each gas (default value), generating an estimation of the emitted gas. Occasionally, a conversion factor is used (*CONVF*) to standardize the calculation units. The simplified general algorithm is shown in Eq. (1):

$$\text{Gas emission (Tg/year)} = AD * Fr * DP * EF * CONVF. \tag{1}$$

The USEPA (1997) and the IPCC (2000) apply this methodology for CH_4 and N_2O estimations, respectively, for calculating emissions from the "wastewater line".

The CH_4 and the CO_2 emitted from the "sludge line" were calculated using the methodology suggested by Lexmond and Zeeman (1995). Biogenic CO_2 emission was not considered. This methodology incorporates emission factors and energy requirements (Lexmond and Zeeman, 1995) and includes the biochemical process and energy used for the treatment process. In the case of CH_4 emission, input data such as quantity of generated sludge, sludge treatment efficiency, fraction of treated sludge, organic loading and maximum CH_4 production capacity, among other factors, were used.

The methodology suggested by the IPCC (2000) was used for N_2O emissions from sludge. Both calculation methods are similar to the algorithm shown in Eq. (1), but they incorporate additional information, such as quantity of generated sludge, sludge treatment efficiency, fraction of treated sludge, nitrogen content in protein consumption and nitrogen content in the remaining sludge. The nitrogen content was determined analytically to be between 15.7 and 28.4 gN/kg sludge (Aguas Andinas, 2000).

Emissions from "untreated wastewater" were estimated in a way similar to that indicated in Eq. (1) but also considering the population for which domestic wastewater is not treated in a treatment plant. In the case of N_2O, the inclusion of nitrogen content in per capita protein consumption (Lara-González, 2003) was also needed and analytically determined (Aguas Andinas, 2000) (CH_4 and N_2O estimations were calculated according to the IPCC (1997a, b, c, 2000), Doorn and Liles (1999) and the USEPA (1997)). The biogenic CO_2 generated from this source was not considered because the IPCC reports that, in the case of surface drainage water, this gas is in equilibrium with its atmospheric content (IPCC, 1997b).

CH_4 estimations were made using the following models:

IPCC-US1WWT-CH_4: This model was used to estimate CH_4 emissions from domestic wastewater treated in wastewater treatment plants. It was based on the IPCC default methodology (IPCC, 2000), modified according to the USEPA (1997) to incorporate specific values from each facility. The model incorporates the CH_4 recycled in the facilities as an additional parameter.

LZ1SST-CH_4: In this model, the IPCC (2000) incorporates the information reported by Lexmond and Zeeman (1995) to estimate CH_4 emissions from sludge treated and disposed of at the plant facilities or a monolandfill site.

IPCC-DLUS1NTWW-CH_4: This model was developed to estimate CH_4 emissions from the drainage and disposal of wastewater treated *on site* (but not in a wastewater treatment plant). The basic methodology corresponds to that suggested by the IPCC (1997a, b, c, 2000) and by Doorn and Liles (1999). The information was systematized as suggested by the USEPA (1997) and the NGGIC (1998). We considered the following aspects: (i) estimation of the population not connected to the sewage system and the population not yet connected to a treatment plant, (ii) the total organic loading per person per year (kg BOD/person/year) and (iii) the BOD which is degraded under anaerobic conditions.

CO_2 estimations were made using the following models:

LZ1WWT-CO_2 and LZ2SST-CO_2: Both models were developed by Lexmond and Zeeman (1995) to estimate CO_2 emissions from treated wastewater and sludge and include the use of the emission factor using electric energy and the requirement energy factor to remove the organic loading. In this study, the biogenic emission of CO_2 was not considered as per the suggestions of the IPCC. The model assumes that, in the cases when the recovery of the biogas is possible in the treatment plant, the CO_2 can be discounted since the energy necessary to recover biogas (Kwh) also can be calculated. In this study, these calculations were made for Conventional Activated Sludge plants. It is necessary to note that, in Chile, treatment plants do not generate their own energy, but electrical energy is provided by a central interconnected electrical system, as in commercial, domestic and industrial facilities. Electricity is supplied indifferently from hydro-electrical and/or thermo-electrical generation with fossil fuels.

N_2O estimations were made using the following models:

DLUS3WWT-N_2O: This model corresponds to an adaptation of the Doorn and Liles (1999) model. The modification permits the incorporation of specific information from each treatment plant.

IPCC3SST-N_2O: This model corresponds to the IPCC (1997a, b, 2000) method using default information, but modified to consider N_2O emissions associated with sludge treatment and final disposal thereof on the soil or at a monolandfill site.

SLGSSTN$_2$O: This model estimates the emissions from sludge treated and disposed of at a treatment plant, according to the type of sludge generated and the treatment technology. N_2O is produced from the remaining nitrogen content of the sludge (analytically determined) that has been digested and disposed of at a monolandfill site; the same emission factors suggested by the IPCC (2000) were used.

DL-IPCC3NTWW-N_2O: This model was adapted from Doorn and Liles (1999) and the USEPA (1997) in order to estimate N_2O emissions generated from the drainage and disposal of untreated water. It is based on the determination of the population that either is not connected to a sewage system or, even if connected, is not yet using a treatment facility; it corresponds to the default methodology suggested by the IPCC (1997a, b).

The GWP from all GHG released to the atmosphere from the MR was calculated over a 20-year horizon, considering the calorific equivalencies for CO_2—such as $CO_2 = 1$, $CH_4 = 63$ and $N_2O = 310$—and using the equation suggested by Lexmond and Zeeman (1995) adapted for this study in order to incorporate the corresponding N_2O values, as shown in Eq. (2):

$$GWP = (E_{CO_2} * GWP_{CO_2}) + E_{CH_4} * GWP_{CH_4}) + E_{N_2O} * GWP_{N_2O}, \tag{2}$$

where E_{CO_2}, E_{CH_4} and E_{N_2O} correspond to the annual emission for each gas.

3. Calculation

The models were used for different environmental management scenarios and periods of time, including different management strategies, related to the control and mitigation of GHG within treatment plant facilities, on the one hand and to a change of technology, on the other hand. These scenarios are shown in detail in Table 2, considering emissions as CH_4 when the biogas is not recycled. In this study, anaerobic systems correspond to lagoons.

Calculations for the period 1990–2027 were made according to the schedule of the sanitation company in charge, namely Aguas Andinas (2000) as indicated in Fig. 1.

The global trend followed by CH_4 for the different management strategies (Scenarios S1–S6) applied to the total wastewater and sludge treated in the MR treatment plants during the period 1990–2027 are shown in Fig. 3. Note that, before 2002, only 2% of wastewater was treated by means of stabilization ponds (around 89%) and oxidation ditch and biofilter processes (around 11%). CH_4 released after 2002 dropped so much because Sanitation Planning in the sanitation company considered

Table 2
Management scenarios with the specific treatment processes and different strategies considered

Scenario	Wastewater treatment	Sludge treatment	Biogas reuse (%)
S1	90%/10% aerobic/ anaerobic	100% anaerobic	None
S2	S1	S1	50
S3	S1	S1	75
S4	100% aerobic	100% anaerobic	75
S5	50%/50% aerobic/ anaerobic	100% anaerobic	75
S6	100% anaerobic	100% anaerobic	75

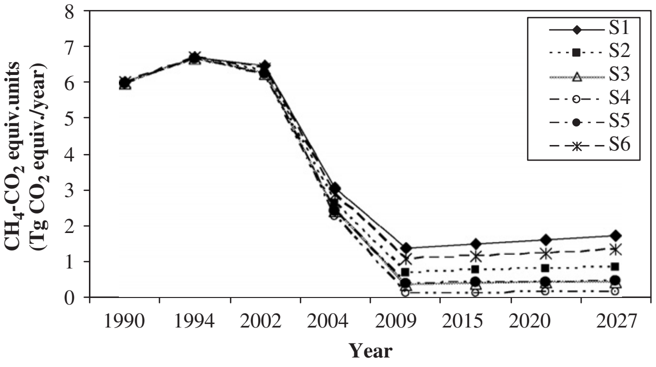

Fig. 3. Total methane emitted, as CO_2-equiv. units, from domestic wastewater and sludge managed in the Metropolitan Region, for the different management scenarios (S1–S6) for the period 1990–2027.

treating increasingly massive volumes of untreated wastewater using aerobic processes such as activated sludge and oxidation ditches. All management strategies produce a reduction in CH_4 emissions after treatment, with emissions arriving at values below the base value (1990) and the best strategy for GWP reduction corresponding to Scenario S4.

The global trend followed by CO_2, as shown in Fig. 4, indicates that 100% aerobic treatment with 75% biogas reuse (S4) would generate a more positive scenario than that projected for S1. Maximum CO_2 reduction would occur for the mixed treatment (aerobic/anaerobic) Scenario S5. However, 50% or 75% biogas reuse for Scenarios S2 and S3 would produce an important reduction in total emitted CO_2.

Fig. 5 shows the global trends projected for N_2O emitted from domestic (treated and untreated) wastewater and sludge managed in the MR. The strategies involved in Scenarios S2 and S3 would generate a lower level of emissions than that projected for S1. This would be associated to biogas reuse and to the higher percentage of treated wastewater in treatment plants. The model for wastewater used in this study considered four factors in a linear relationship: population connected to treatment plant, the associated per capita load, the fraction of easily degraded BOD and the emission factor for removed gN_2O/gBOD. Also, emissions would be lower applying the management strategy included in Scenario S4. The fraction of easily degraded BOD ranged from 0 for the aerobic treatment to 1 for the anaerobic treatment. Then, the factor bearing on the emission is the emission factor for removed gN_2O/gBOD, where the removed gBOD depends on design parameters. So, as could be expected, N_2O emissions (expressed in CO_2-equiv. units) would be higher if the management strategy applied considered a higher percentage of anaerobic wastewater treatment.

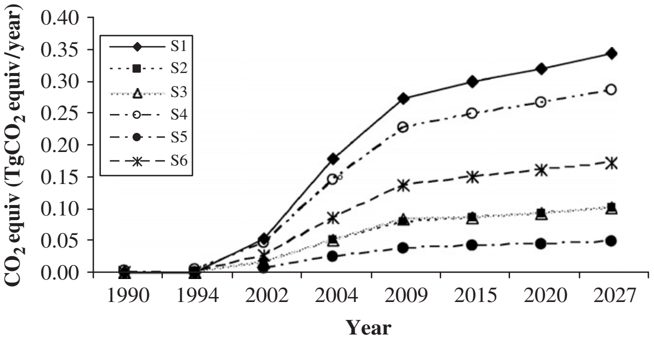

Fig. 4. Total carbon dioxide emitted, as CO_2-equiv. units, from domestic wastewater and sludge treated in the Metropolitan Region, for the different management scenarios (S1–S6) for the period 1990–2027.

Fig. 6 shows the total (Gran Stgo) and the individual relative contribution of each treatment plant in Santiago to the MR GWP.

In general terms, wastewater managed in the El Trebal plant would produce 19 Tg CO_2-equiv. units/year during 2027, whereas wastewater treated in the La Farfana and Los Nogales plants would contribute 26.1 and 16.9 Tg CO_2 equiv. units/year, respectively. Since the first year of analysis (7.3 Tg/year), the trend has been for these plants to increase their emissions, reaching 17.1, 34.4 and 48.5 Tg CO_2 equiv. units/year for the years 2002, 2004 and 2009, respectively. For the year 2027, a GWP of about 62 Tg CO_2 equiv./year would be expected.

The GWP of domestic wastewater managed in surrounding town wastewater treatment plants would increase from the GWP of 0.3 Tg CO_2 equiv./year in 1990 to 3.6 Tg CO_2 equiv./year in 2027.

Fig. 7 shows that the relative contribution of each gas determines the behavior of the regional GWP during the analyzed period. In this way, the behavior of the MR GWP is determined from N_2O–CO_2-equiv. unit emissions since 2002. N_2O emissions came from the sludge disposed of on the soil and not from wastewater treatment. The calculation was based on the amount of sludge produced and the nitrogen content determined analytically (15.7–28.4 gN/kg sludge). So, N_2O generation is likely to occur under propitious conditions since the handling of this sludge in the drying fields (solar energy) and at the monolandfill site contemplated turning it for ventilation (mix and make turn). Also, in this study, the emissions derived from sludge

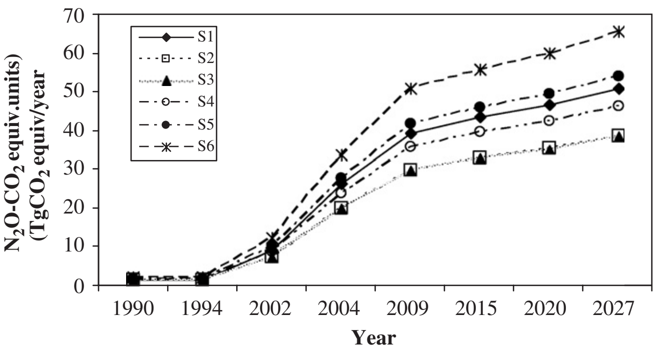

Fig. 5. Total nitrous oxide emitted, as CO_2-equiv. units, from domestic wastewater and sludge managed in the Metropolitan Region, for the different management scenarios (S1–S6) for the period 1990–2027.

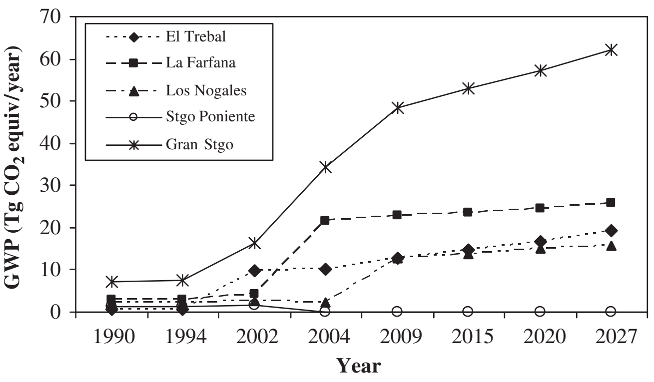

Fig. 6. Total (Gran Stgo) and individual contribution to the global warming potential of each domestic wastewater treatment plant in Santiago, for the period 1990–2027.

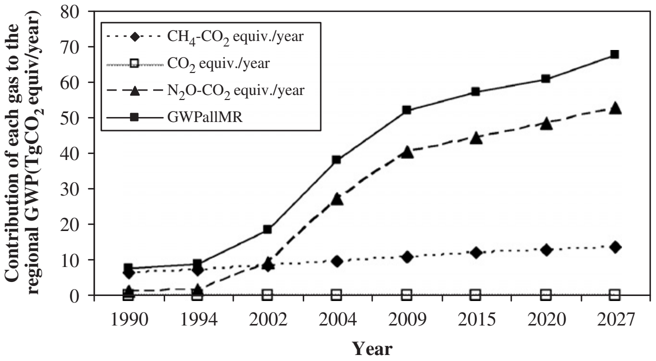

Fig. 7. Contribution of each greenhouse gas to the global warming potential for the Metropolitan Region, for the period 1990–2027.

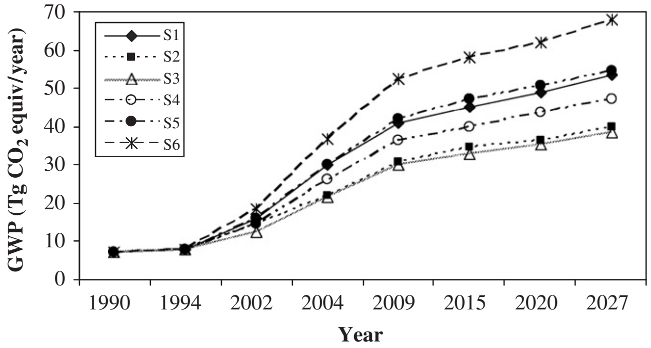

Fig. 8. Global warming potential for domestic wastewater and sludge managed in the Metropolitan Region, for the different management scenarios (S1–S6) for the period 1990–2027.

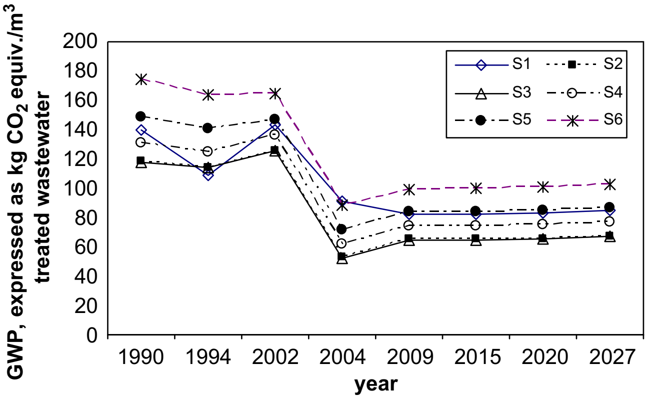

Fig. 9. Global warming potential produced by cubic meter of treated wastewater in the Metropolitan Region, for the different management scenarios, (S1–S6) for the period 1990–2027.

transport were not considered since they were arranged within the facility.

Fig. 8 shows the incidence of the management strategies available for wastewater and sludge treatment on the regional GWP and Fig. 9 shows the GWP produced by cubic meter of treated wastewater in the MR, for different scenarios, from 1990 to 2027.

The GWP trend in the MR will depend on the technology used for wastewater and sludge treatment as well as on the percentage of biogas used. Scenarios S2 and S3, corresponding to 50% and 75% reuse of generated biogas, respectively, will generate lower GHG emissions (CO_2-equiv. units). The worst scenarios correspond to the use of anaerobic systems, as in the case of Scenarios S5 and S6. Those scenarios considered lagoons. Calculations were made considering two kinds of factors: population increase and efficiency of organic loading removed. In the case of wastewater, the numbers used were 0.8 for the anaerobic process and 0.6 for the aerobic process.

4. Discussion

The results obtained in this study show that:

- CH_4 emissions would be related to the treatment technology used for wastewater cleaning (2.34%), especially for sludge digestion (97.6%). Untreated wastewater would also generate important quantities of CH_4 at the beginning of the period. The management strategies considered permit minimizing the environmental impact of CH_4 emissions making it possible to establish mitigation measures through the use of the generated biogas throughout the analyzed period.
- As the biogenic contribution of CO_2 is not considered in the inventories, the potential reduction of these emissions would be related to the potential for using the generated biogas (with 25% CO_2 content). However, the effectiveness of this strategy will depend on the type of energy used in the operation of the wastewater and sludge treatment system. Potential CO_2 emissions from wastewater would only represent 0.1% of the total, while 99% would come from anaerobic sludge treatment.
- At the beginning of the period, only 2% of wastewater was treated in a treatment plant. As of the year 2009, the percentage would increase to 100%. Therefore, N_2O contributions would increase over the years and depend on the water volume to be treated, protein ingestion [g/hab/d] and the nitrogen content in the protein [kgN/kg consumed protein]. Therefore, at the beginning of the analysis, the main contributions were made by surface runoff of untreated waters (using an indirect generation factor of 0.01 [kg N_2O-N/kg of wastewater N] given by IPCC (1997a, b, c) and Doorn and Liles (1999), whereas, from 2009, N_2O would come from the waters being treated using a direct generation factor of 0.025 [kg N_2O-N/kg of present N] in treated wastewater, given by IPCC (1997, 2000). The emissions coming from the N_2O generated by the sludge treated and disposed of on the surface of the soil would directly depend on the volume of sludge produced and on the choices for final disposal. In spite of the low emission levels that would be recorded, N_2O would contribute to more than 90% of total GWP due to its high calorific power.

- Even after establishing management actions, the projections indicate that the emission reduction obtained in the different scenarios would not reach the level estimated for 1994.
- It would be convenient to establish a system for monitoring GHG under field conditions in one of the Santiago wastewater treatment plants, especially in relation to N_2O (in the different treatment units of each facility, clarified flows and during sludge management), due to their contribution to the total GWP at the regional level.

5. Conclusions

The GWP attributable to the treatment of wastewater would be determined by N_2O–CO_2-equiv. emissions from the year 2002. This is of extreme importance because it demonstrates that, even though N_2O emissions are smaller than the rest of the GHG, they have a determining role in the atmospheric balance due to their high calorific power (310 times greater that CO_2).

An emissions projection indicates that if no GHG minimization strategy is applied, the sanitation action, very positive from the point of view of wastewater cleaning, could possibly decrease the air quality, due to increasing GHG emissions in a region that is currently facing many environmental problems. In this sense, the impact of N_2O is closely related to the way in which sludge is disposed of or used, not a minor issue considering the volume of sludge that is being managed.

The results show that sanitation company executives and government authorities should also consider GHG emissions from final sludge management in treatment plants and at monolandfill sites.

The possibility of designing a permanent system for updating and enriching the inventories generated in this work would enable the creation of a national database in this area.

Despite the fact that the contribution of the GHG produced by wastewater management only reaches about 0.18% in relation to other anthropogenic sources, the management of this type of information could enable the sanitation company to control their environmental management, thus contributing to the accomplishment of GHG emission reduction objectives at the n ational level.

From a national point of view, MR GHG emissions correspond to 50% of total national GHG emissions. Estimations for 2027 represent an increment of 30 (optimistic scenarios S2 and S3) and 58 (pessimistic scenario S6) Tg CO_2-equiv. units over the 10 Tg CO_2-equivalent estimated for the baseline year (1994).

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