Urban Europe and NSFC

Europe – China joint call on Sustainable Urbanisation in the Context of Economic Transformation and Climate Change: Sustainable and Liveable Cities and Urban Areas

Funded by
NCN (Poland), project UMO-2018/29 / Z / ST10 / 02986
NSFC (China), project 71961137011
FFG (Austria), project 870234

UNCNET

Urban nitrogen cycles: new economy thinking to master the challenges of climate change

D6/1: General guidance to quantify N in waste and wastewater

Due date of deliverable: **31/03/2020** Actual submission date: **30/03/2020**

Start Date of Project: **01/04/2019** Duration: **35 months**

Organisation name of co-chairs for this deliverable: **UZG**, **IIASA**

Authors: Monika Suchowska-Kisielewicz, Andrzej Jędrczak, Sylwia Myszograj, Ewelina Płuciennik-Koropczuk, Anita Jakubaszek

Dissemination Level		
PU	Public	☒
PP	Restricted to other programme participants (including funding agencies)	☐
RE	Restricted to a group specified by the consortium (including funding agencies)	☐
CO	Confidential, only for members of the consortium (including funding agencies)	☐

Executive Summary

The amount of waste and wastewater generation is closely linked to population and human activity, urbanization and affluence. Hence, emissions from waste and wastewater are a significant problem for cities, especially those that are characterized by low technological advancement of plants for their treatment.
This document provides general information on the method of calculating the amount of nitrogen present in waste and wastewater and the nitrogen emissions occurring at each stage of their treatment, taking into account various technology scenarios for their processing.

Introduction

Population increase and human activity have accelerated and increased the cycling of nitrogen (N) in the environment during the past hundred years. As a result, emissions of N have grown contributing to various environmental problems, such as eutrophication of surface waters, acidification (release of ammonia, NH_3, and nitrogen oxides, NO_X) and climate change (release of nitrous oxide, N_2O) (Sokka et al., 2004).
Nitrogen emissions to the environment in urban areas are linked to the human consumption system, where significant amounts of waste and wastewater are generated. Main source of N_2O emissions are wastewater treatment, sewage sludge incineration, municipal solid waste incineration, biomass combustion for energy production, incineration of waste-based fuels with high content of nitrogen, etc.
Quantification of their contribution to the anthropogenic N_2O emissions is still difficult because they remain uncharacterized (Svoboda et al., 2006).
It is estimated that i in countries developing N_2O emissions from waste and wastewater treatment plants are higher than in developed countries due to the slow development of municipal infrastructure in relation to the rate of urban development (UNFCCC/IPCC, 2004; US EPA, 2006).

Waste

The waste sector contributes <5% of global GHG Emissions.
Waste management covers a whole range of activities ranging from their generation to management through recovery of secondary raw materials to environmentally and humanally safe disposal. The issue of waste management due to its quantity, diverse composition and properties is highly complex and at the same time complicated. Figure 1 shows the material flow in the municipal solid waste management system.

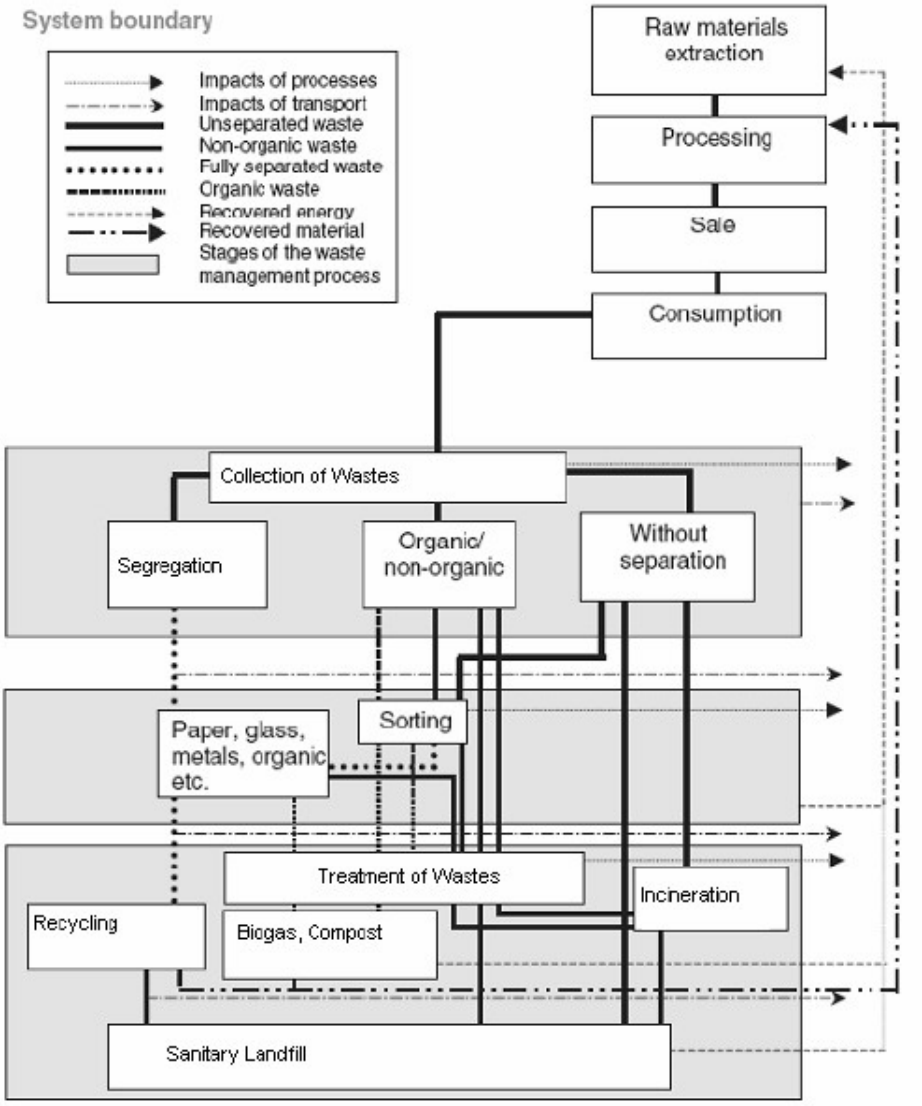


Fig. 1. Material flow in the municipal solid waste management system (Ramachandra, 2011)

The main waste flows are associated with urban, industry, and livestock production. The municipal waste fraction with the highest emissions from anthropogenic sources includes organic waste (Table 1).

Table 1. Nitrogen concentration (%) of different municipal solid waste components, (Sokka et al. 2004)

Waste faction	**N content (range)**
Organic waste	2 (1,3-2,7)
Paper and cardboard	0,15 (0-0,3)
Textile waste	3,7 (2,9-4,5)
Plastic	0,45 (0-0,9)

In the urban area, organic waste is directly produced in households mainly as kitchen and green waste and in sewage treatment plants as sewage sludge. Another stream

of organic waste produced in the vicinity of cities is waste from the food industry (Pardo et al. 2015). Organic waste is treated based on biological and thermal processes.

In European countries, the biological treatment of waste is divided into (Jędrczak et al. 2015):

- aerobic (composting) and anaerobic (methane fermentation) biological processes intended essentially for the treatment of clean, separately collected biodegradable waste, municipal and industrial origin,
- mechanical-biological treatment (MBP) processes intended mainly to treat mixed municipal waste (remaining after separate collection of fractions for recovery, including recycling) before final storage.

The end product of biological processes carried out in MBP is a stabilized, which, as a material with low potential for emissions, is discharged to landfills or used for land reclamation.
The product of composting and fermentation of clean waste that is selectively collected is a fertilizer that is used for agriculture or nature.
Places of nitrogen emission during waste processing are shown in Figure 2. Ammonia emissions are mainly observed in the composting process, while nitrous oxide is generated in most waste treatment processes. The amount of N_2O emissions varies greatly depending on the conditions and methods of waste treatment.
Waste combustion mainly produces NO_x emissions.
Both NO_x and NH_3 emissions from waste indirectly cause N_2O emissions. However, this figure is often insignificantly small.

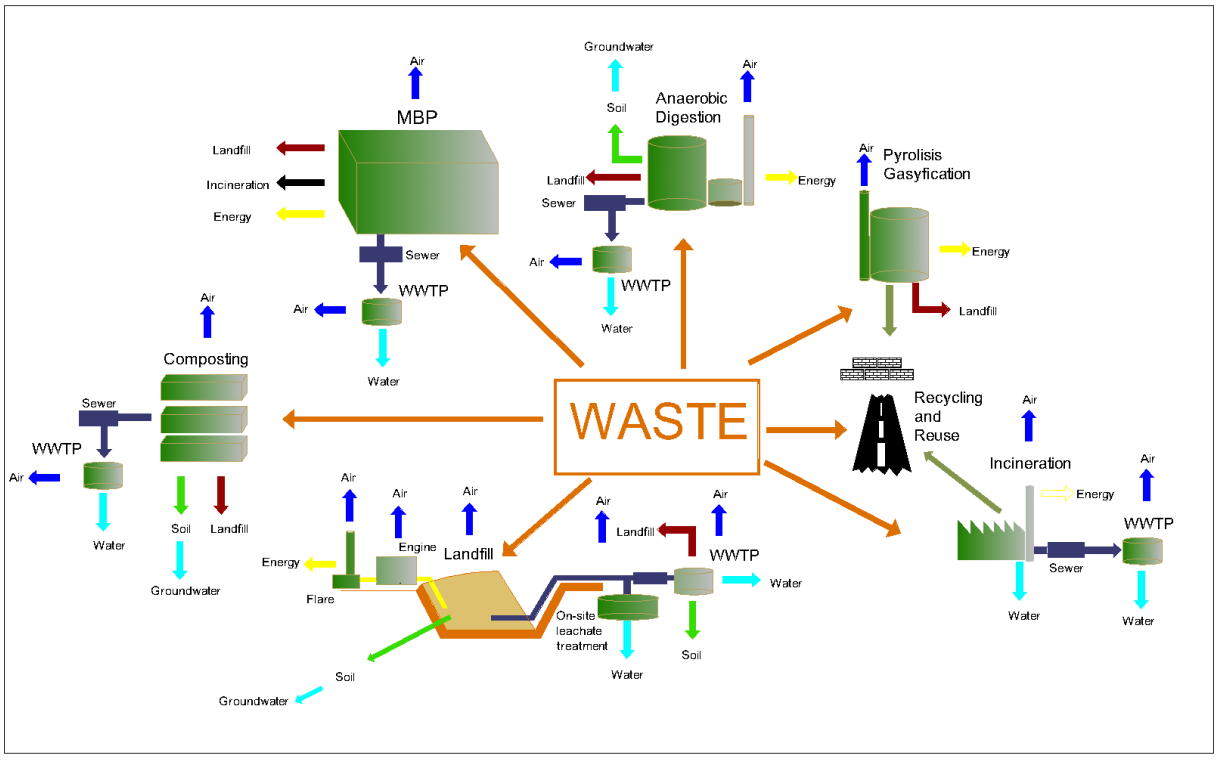


Fig. 2. Mass flow of waste in the processes of biological treatment

The starting point for estimating the emission of pollutants from biological and thermal processing of waste, including open combustion, is collecting data on waste generation sites, their quantity, composition and processing methods.
A more accurate approach to data collection is to consider waste streams during individual processing steps, taking into account changes in composition and other parameters that affect emissions.
An important element to consider in estimating emissions from waste is recycling that leads to changes in emissions in production processes and flows (IPCC 2006).
General guidelines for calculating the amount of nitrogen in waste and emissions are presented in chapter on “General guidance to quantify N in waste”.

Wastewater

In quantitative terms, nitrogen compounds, along with carbon compounds, are the most important component of municipal wastewater. Human faeces are the main source of nitrogen in household waste. It is estimated that every person excretes 10-14 g of nitrogen daily. In municipal wastewater, nitrogen occurs in four basic forms: organic nitrogen, ammoniacal nitrogen (both in ionized form (NH_4-N) and free ammonia (NH_3-N), nitrite (NO_2-N) and nitrate (NO_3-N). Due to the particle size, organic nitrogen in wastewater can be divided into dissolved, colloidal and suspension fractions (Czerwionka and Mąkinia, 2009).
In raw wastewater, nitrogen occurs as organic nitrogen, as urea or as a result of the beginning decomposition processes in the form of ammonia. The concentration of total nitrogen in domestic wastewater varies in the range of 15-80 g N/m^3, and a significant part of the nitrogen occurs in the form of ammonium nitrogen (10-15 g N-NH_4/m^3) or unstable organic compounds (proteins, urea), which, as a result of deamination or hydrolysis of urea, quickly turn into N-NH_4. The content of nitrogen bound in amino acids (products of protein degradation) usually does not exceed 5 g N/m^3, and the concentration of nitrogen in the form of urea can be 2-16 g N/m^3. Mineral forms, nitrites and nitrates together constitute less than 1% of total nitrogen in raw wastewater, which corresponds to concentrations generally less than 0.5 g N(NO_2 + NO_3)/m^3 (Sadecka, 2010; Miksch i Sikora, 2010).
Nitrogen compounds undergo a hydrolysis process, and then in a hydrolyzed form they can be a building block of cell mass (assimilation) or undergo oxidation processes (nitrification), and in anaerobic conditions denitrification (reduction). Such a mechanism is a reflection of the changes of nitrogen compounds occurring automatically in the environment and is used in wastewater treatment plants to eliminate these compounds. Characteristics of nitrogen compounds in raw wastewater are most often based on the analysis of general Kjeldahl nitrogen (TKN = organic nitrogen + ammonium nitrogen). The share of both forms depends on the time of wastewater retention in the sewage network, because this is where the hydrolysis of organic nitrogen to ammonium begins. Nitrate and nitrite nitrogen content is usually not included. For more accurate sewage characteristics, it is assumed that nitrogen in sewage occurs in the forms (Henze et al., 2000):

$$N_{TOT} = S_{N-NO_2^-} + S_{N-NO_3^-} + TKN = S_{N-NO_2^-} + S_{N-NO_3^-} + S_{N-NH_4^+} + S_{I,N} + X_{S,N} + X_{I,N} \ g/m^3 \ (1)$$

where:
S_{N-NO2-}, S_{N-NO3-} - nitrite and nitrate nitrogen concentration;
TKN - total Kjeldahl nitrogen;
S_{N-NH4+} - ammonium nitrogen concentration (ammonium ion and undissociated ammonia);
$S_{I,N}$ - concentration of dissolved organic nitrogen contained in non-biodegradable compounds;
$X_{I,N}$ - concentration of the bioavailable organic nitrogen contained in the total suspension;
$X_{S,N}$ - concentration of easily bioavailable organic nitrogen.

Nitrogen forms in treated wastewater have a different chemical structure than those found in raw wastewater (Pagilla et al. 2006). In treated wastewater dissolved organic nitrogen can constitute a significant fraction of total nitrogen (Czerwionka and Mąkinia 2009). Organic nitrogen dissolved in the effluent consists of both non-decomposable forms found in the inflowing wastewater, such as purines, pyridines and pyrimidines (APHA 1992), as well as products of the metabolism of activated sludge microorganisms.
Wastewater treatment plants (WWTP) that reduce nitrogen concentrations uses the natural nitrogen cycle implemented in a bacterial wastewater treatment process. Figure 3 illustrates the basic nitrogen cycle.

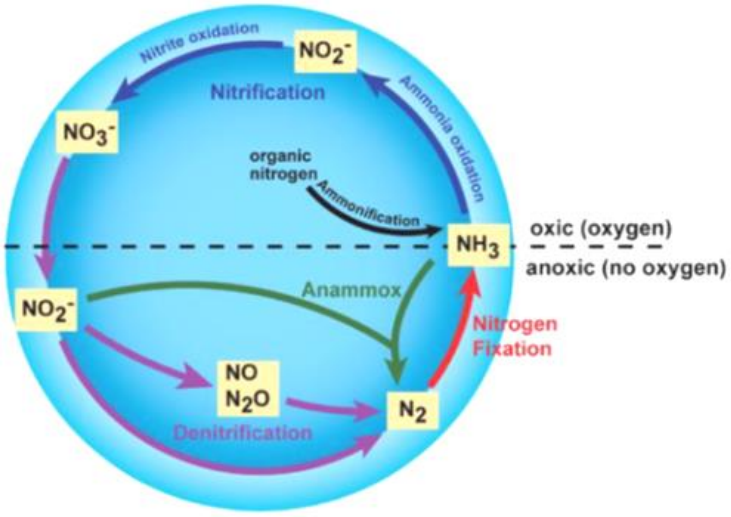


Fig. 3. Basic Nitrogen Cycle (Bernhard 2010)

In simplification during treatment processes, organic nitrogen is ammonified to ammonium nitrogen, which can be used to build a new cell mass or oxidized (in the nitrification process) successively to NO_2-N and NO_3-N. The nitrification process does not change the concentration of N_{tot} in the wastewater, but only changes its form. Denitrification, reduction of NO_3-N and NO_2-N to gaseous nitrogen, makes it possible to permanently reduce the total nitrogen concentration in wastewater.

Wastewater Treatment Plants (WWTPs) are identified as one of the four anthropogenic source of N_2O emissions, next to agriculture, industrial acid production, and combustion. Recent research and field surveys have revealed that emissions in sewer networks and from nitrification or nitrification-denitrification processes at WWTPs, previously judged to be a minor source, may in fact result in more substantial emissions (IPCC 2019). Data obtained from the operation of full-scale WWTPs show a wide range of values (0–14.6%) of the of the incoming nitrogen) for the fraction of nitrogen that is emitted as N_2O (Kampschreur et al. 2009, Ahn et al. 2010, Daelman 2014).
In accordance with the IPCC guidelines of 2019, in order to estimate N emissions from wastewater treatment plants, the following elements (Fig.4) should be taken into account: amounts of N in wastewater entering the treatment plant (TN_{DOM}), loss or removal of N in the treatment process (either through biological conversion or sludge removal) (N_{REM}), and N content in wastewater discharged into water systems ($N_{EFFLUENT,\ DOM}$) (IPCC 2019).

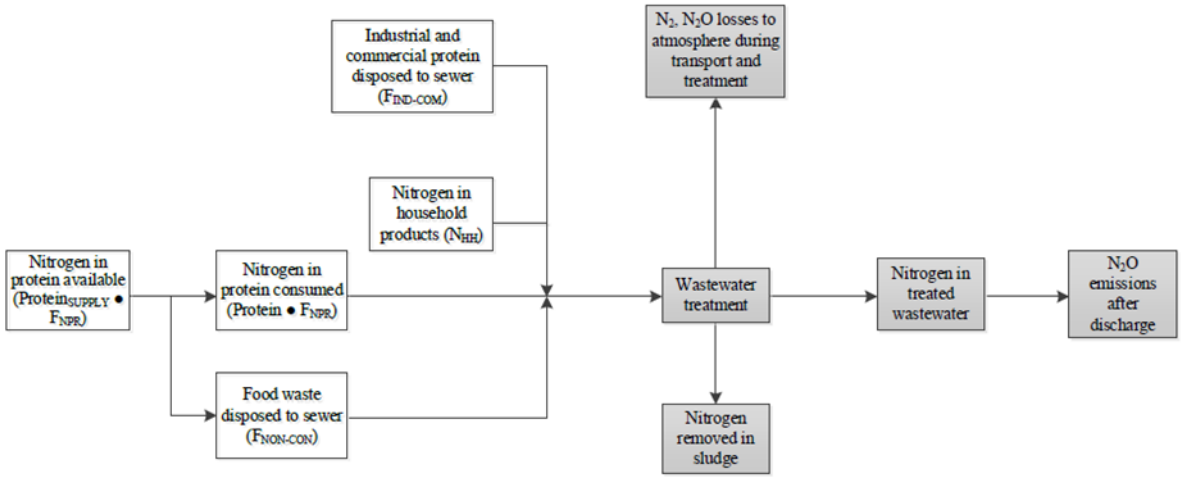


Fig. 4. Nitrogen in domestic wastewater treatment (IPCC 2019)

The removal of nitrogen from wastewater can potentially lead to the production and emission of nitrous oxide. The nitrous oxide (N_2O) emissions from wastewater treatment plants can occur as direct, and indirect emissions (IPCC 2006).
The direct emissions are the processes contributing to N_2O emission during biological nitrogen removal. In conventional activated sludge plants, nitrogen is removed via nitrification and subsequent denitrification. Nitrous oxide is not only produced biologically, but also chemically in a great number of chemical reactions involving nitroxyl (HNO), hydroxylamine (NH_2OH) and nitrite (NO_2^-)(Schreiber et al. 2012). Biological and chemical pathways of N_2O production in the nitrification and denitrification processes shows Figure 5.

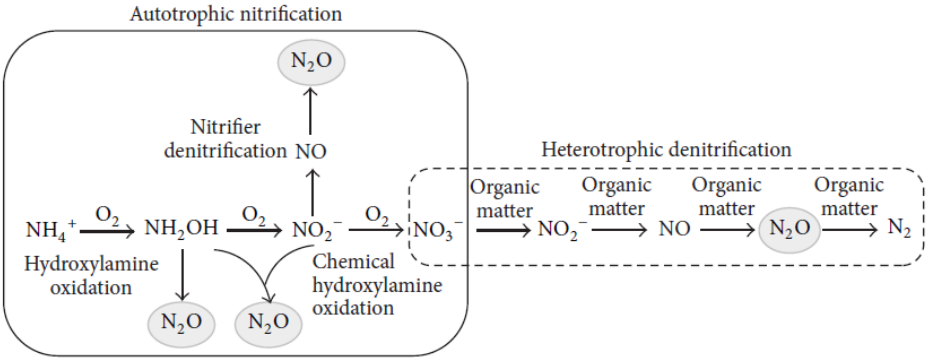


Fig. 5. Biological and chemical pathways of N_2O production in the nitrification and denitrification processes (Campos et al. 2016)

Nitrification consists of the oxidation of ammonium to nitrite via hydroxylamine by ammonia oxidizing bacteria and the oxidation of nitrite to nitrate by nitrite oxidizing bacteria. Denitrification, the reduction of nitrate to nitrogen gas via nitrite, nitric oxide and nitrous oxide, is usually performed by facultative aerobic heterotrophic bacteria, although some steps in this nitrogen reduction pathway are also performed by autotrophic nitrifying bacteria. Nitrite oxidizing bacteria have been observed to reduce nitrate to nitrite, while ammonia oxidizing bacteria use the same enzymes as the heterotrophs to reduce nitrite to nitric oxide and nitrous oxide (Kampschreur et al. 2009, Law et al.2012, Daelman 2014). Nitrous oxide can be an intermediate product of both processes, nitrification and denitrification, but has typically been associated with denitrification (Gupta D. et al.2012).

The most important operational parameters leading to N_2O emission in WWTPs are (Fig.6):

- low dissolved oxygen concentration in the nitrification and high in denitrification stages,
- increased nitrite concentrations in both nitrification and denitrification stages,
- low COD/N ratio in the denitrification stage (Kampschreur et al. 2009).

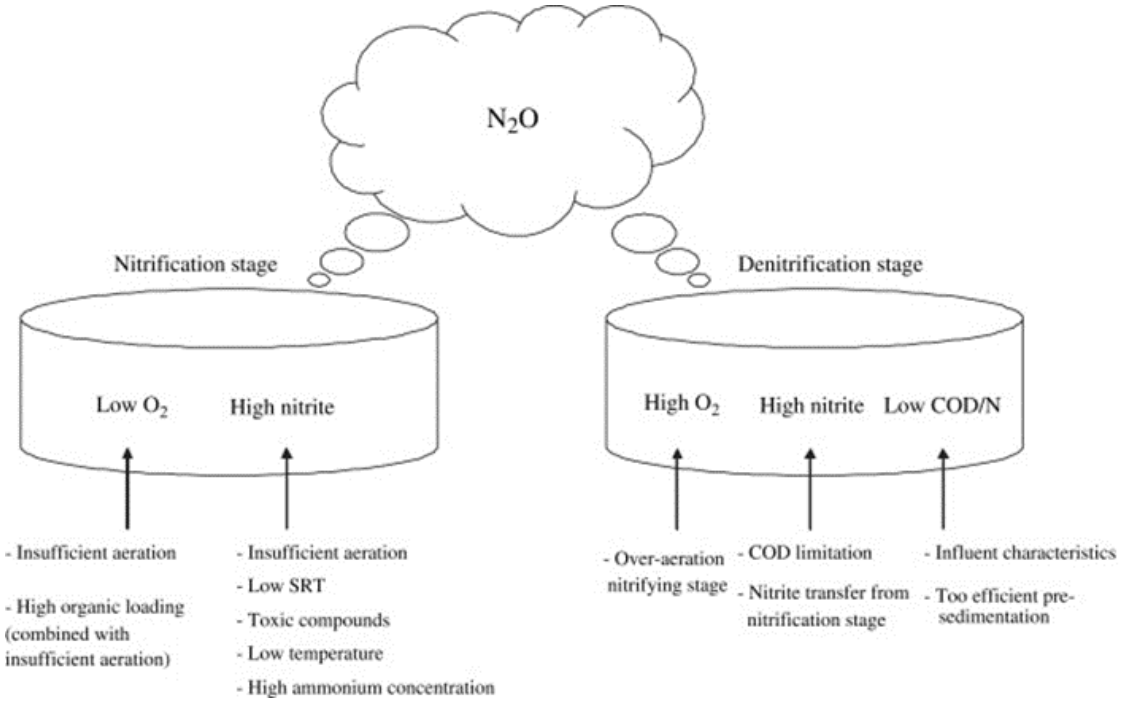


Fig. 6. Nitrous oxide emission during wastewater treatment (Kampschreur et al. 2009)

General guidance to quantify N in waste

Calculation of the nitrogen content in waste and the amount of nitrogen emissions requires determination of the mass of waste generated at the location in question, their morphological and chemical composition, the method of processing with determination of mass flows and the value of emission factors for individual stages of processing. Total N emissions should be determined taking into account the following 5 categories:

- Mass of waste generated and waste mass flow
- Emissions from waste treatment
- Emissions from waste landfilling
- Avoided emissions from material recovery from waste
- Avoided emissions from energy recovery from waste

The figure below shows how to calculate N emissions.

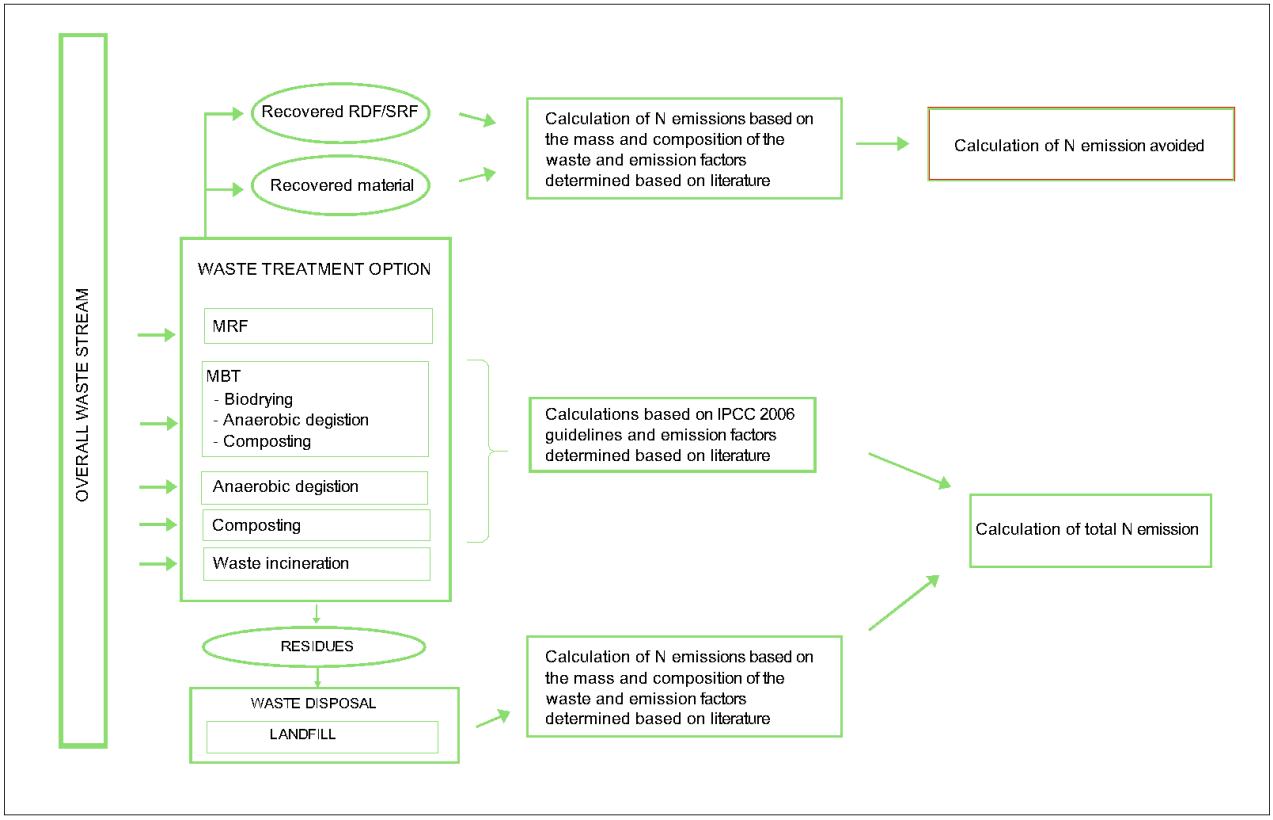


Fig.7. Workflow for calculating emissions of N (Teichmann et al., 2013)

MRF = Material Recovery Facility, MBT=Mechanical Biological Treatment Plant, SRF=solid recovered fuel, RDF=refuse derived fuel

N emissions from the waste management system should be calculated taking into account the following treatment scenarios:

- Material Recovery Facility (MRF)
- Anaerobic digestion
- Composting
- Mechanical-biological treatment (MBT)
- Waste incineration
- Landfilling

Specific emission factors taken from the literature are applied to calculate the N emissions that are characteristic for the individual processes that take place in these facilities.

Calculation of N emissions from biological waste treatment facilities

Direct nitrogen emissions from biological treatment facilities should be calculated by the equation (2) (ICCP, 2006):

$$\boldsymbol{N_2O\ Emission} = \sum_i (M_i \cdot EF_i) \cdot 10^{-3} \qquad (2)$$

M_i – mass of biologically processed waste, Mg/year

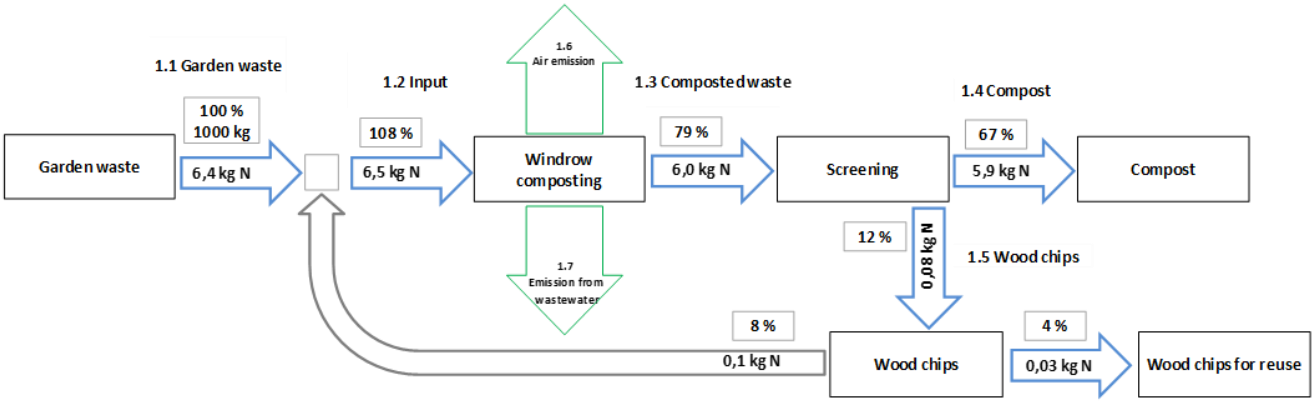
EF_i – coefficient of nitrogen emissions (N_2O, NH_3) from waste during treatment, gN_2O/kg waste

i – type of waste treatment: composting or fermentation

Unit mass balances of municipal waste and N for the biological waste treatment process

Below are presented the mass balances of waste and nitrogen calculated per 1000 kg of input waste treated in:
I. composting plants and digesters processing clean, separately collected biodegradable waste, municipal and industrial origin and
II. mechanical-biological treatment plant (MBT) installations processing mixed municipal waste - remaining after separate collection of fractions for recovery, including recycling).

Composting typical green waste in piles in open ground



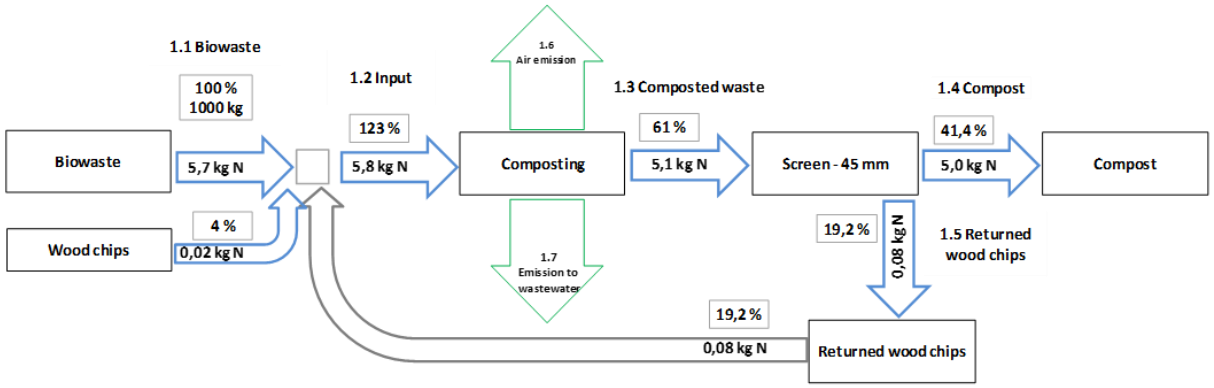
Scheme 1. Mass balances of waste and nitrogen calculated per 1000 kg

Mass balance in the waste treatment process includes:

Point	Waste stream	Description
1.1.	Garden waste	Mass of garden waste delivered to the installation - 100%. The balance was made for 1000 kg v/v of waste. Waste composition: Moisture (M) - 40%; dry organic matter (DOM) - 49.2% dry matter (DM); N - 1.1% DM (green waste contains 0.3-3.0% N in dry matter)
1.2.	Input	Waste composition: M – 39,26%; DOM – 51,69%DM; N – 0,99% DM
1.3.	Composted waste	The organic mass distribution of waste (green parts) was adopted at 55%, and the structural mass (brown parts) at 17.5%. Reduction of weight was adopted at 32%. Composted waste composition: M – 35,68%; DOM – 37,33% DM; N – 1,19% DM
1.4.	Compost	Separation on a sieve into factions: compost - constitutes 68% of the mass of waste Compost composition:

		M – 36,7%; DOM - 30% DM; N – 1,4% DM
1.5.	Wood chips	Wood chips - 12% of the mass of incoming waste: 2/3 of the mass is recycled, and 1/3 of the mass is wood for use. Wood chips composition: M – 30%; DOM - 95% DM; N – 0,09% DM (0,04-0,23 % N in dry mass)
1.6.	Air emission	0,45 kg N NH_3 emission - range: 25-354 gN/Mg of incoming waste (0.30 kgN/Mg was assumed) N_2O emission - range: 25-178 gN/Mg of incoming waste (0.15 kgN /Mg was assumed)
1.7.	Emission from wastewater	0.019 kgN During composting, 100-200 dm^3/Mg of sewage is generated in piles; 100 dm^3/Mg was taken NH_4-N concentration 0.10-252 mg/dm^3; 190 mg/dm^3 was taken

Composting bio-waste



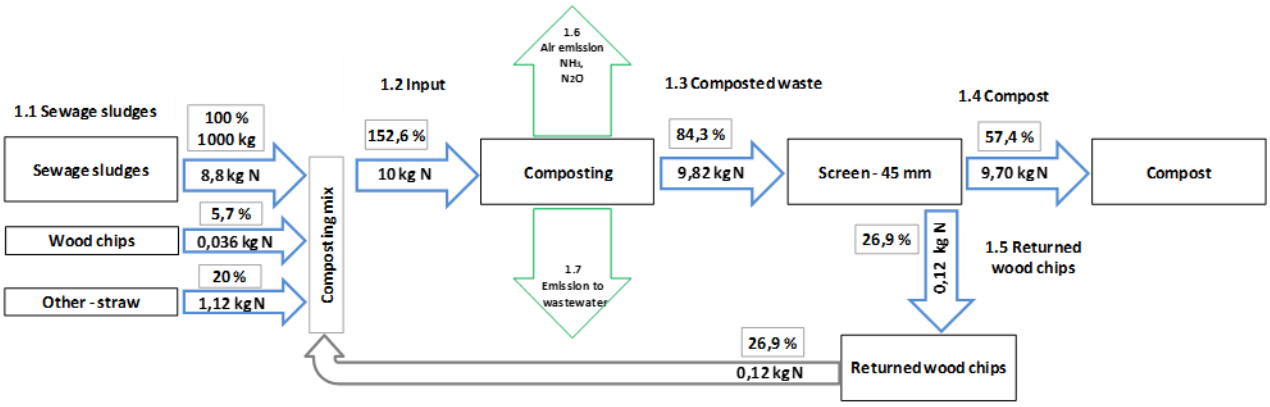
Scheme 2. Mass balances of waste and nitrogen calculated per 1000 kg

Mass balance in the waste treatment process includes:

Point	Waste stream	Description
1.1.	Biowaste	Mass of biowaste delivered to the installation - 100%. The balance was made for 1000 kg v/v of waste. Biowaste composition: Moisture (M) – 65.0%; dry organic matter (DOM) – 65.0% dry matter (DM); N - 1.6% DM (biowaste contains 0.5-2.7% N in dry matter)
	Raw wood chips	Raw wood chips composition: quantity – 4%; M – 30.0%; DOM – 95.0% DM; N – 0.09% DM
1.2.	Input	Composition: M – 60.0%; DOM – 70.2% DM; N – 0.17% DM
1.3.	Composted waste	The organic mass distribution of biowaste was assumed to be 55%, raw wood chips 10% and recycled wood chips 2%. Composition M - 40.0%; DOM - 59.6% DM; N - 1.39% DM
1.4.	Compost	Separation on a 45 mm sieve Compost - 41.4% of biowaste mass

		Composition: M – 40.0%; DOM – 50.2% DM; N – 2.0% DM
1.5.	Recycled wood chips	Recycled wood chips composition: quantity - 19.2%, determined from the water balance so that the moisture of the mixture (input) was 65% M – 40%; DMO – 80.0% DM; N – 0.08% DM
1.6.	Air emission	0,54 kg N NH_3 emission - range: 52-576 gN/Mg of incoming waste (0.50 kgN/Mg was assumed) N_2O emission - range: 0.06-0.6 gN/Mg of incoming waste (0.30 kgN /Mg was assumed)
1.7.	Emission from wastewater	0.019 kgN During composting, 100-200 dm^3/Mg of sewage is generated in piles; 150 dm^3/Mg was taken NH_4-N concentration 50-800 mg/dm^3; 500 mg/dm^3 was taken

Composting sewage sludge



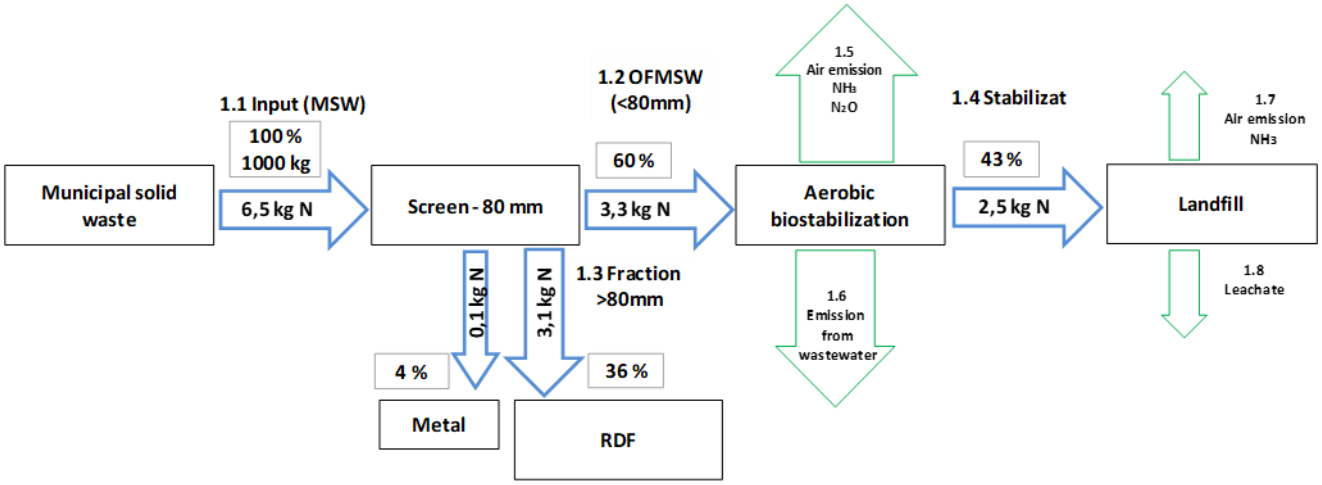
Scheme 3. Mass balances of waste and nitrogen calculated per 1000 kg

Mass balance in the waste treatment process includes:

Point	Waste stream	Description
1.1.	Sewage sludges	Mass of sewage sludge delivered to the installation - 100%. The balance was made for 1000 kg v/v of waste. Sewage sludge composition: Moisture (M) – 75%; dry organic matter (DOM) – 70% dry matter (DM); N – 3.5% DM (biowaste contains 0.1-9.5% N in dry matter)
	Wood Chips	Raw wood chips composition: quantity –5.7%; M – 30.0%; DOM – 95.0% DM; N – 0.09% DM (range: 0.04-0.23% N of dry mass)
	Other - straw	Straw composition: quantity –20%; M – 20.0%; DOM – 90.0% DM; N – 0.79% DM (range: 0.3-1.1% N of dry mass)
1.2.	Input	Composition: M – 60%; DOM – 79,5% DM; N – 1,64% DM
1.3.	Composted waste	The organic mass distribution of biowaste was assumed to be 55%, raw wood chips 10% and recycled wood chips 2%. Composition

		M - 40.0%; DOM - 75.2% DM; N – 1.94% DM
1.6.	Compost	Separation on a 45 mm sieve Compost – 57.4% of sewage sludge mass Composition: M – 40.0%; DOM – 73.0% DM; N – 2.82% DM
1.5.	Returned wood chips	Recycled wood chips composition: quantity – 26.9%, determined from the water balance so that the moisture of the mixture (input) was 75% M – 40%; DMO – 80.0% DM; N – 0.076% DM
1.6.	Air emission	0,54 kg N NH_3 emission - range: 52-576 gN/Mg of incoming waste (0.50 kgN/Mg was assumed) N_2O emission - range: 0.06-0.6 gN/Mg of incoming waste (0.30 kgN /Mg was assumed)
1.7.	Emission from wastewater	0.019 kgN During composting, 100-200 dm^3/Mg of sewage is generated in piles; 150 dm^3/Mg was taken NH_4-N concentration 50-800 mg/dm^3; 130 mg/dm^3 was taken

MBT - Biostabilization



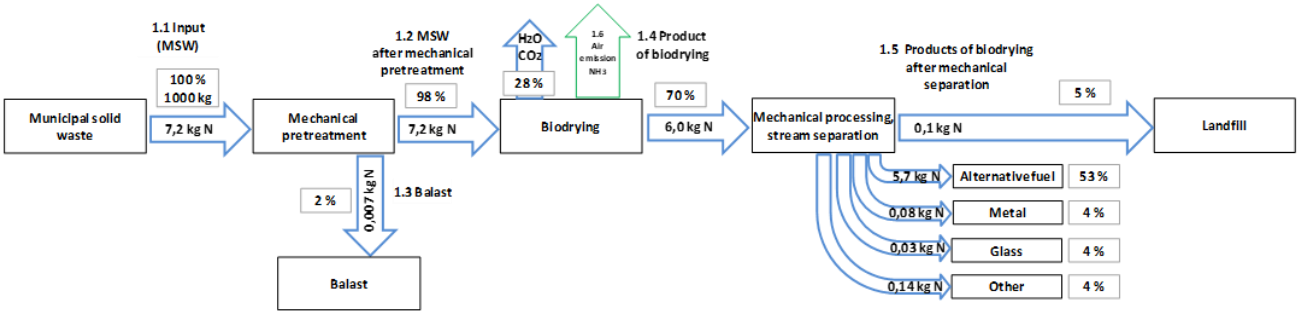
Scheme 4. Mass balances of waste and nitrogen calculated per 1000 kg

Mass balance in the waste treatment process includes:

Point	Waste stream	Description
1.1.	Input (MSW)	Mass of waste delivered to the MBT installation - 100%. The balance was made for 1000 kg v/v of waste. Waste composition: Moisture (M) – 35%; dry organic matter (DOM) – 38% dry matter (DM); N – 1.0% DM (household waste contains 0.8-1.1% N in dry matter)
1.2.	OFMSW (fraction<80mm)	Separation on a sieve 80 mm into : under the sieve fraction (OFMSW- organic fraction of municipal solid waste) - it constitutes 60% of the mass of incoming waste (range 50.8-71.8%). Composition:

		quantity – 60%; M – 45%; DOM – 43,3% DM; N – 1,0% DM
1.3.	Frakcja >80mm	Over the sieve fraction: Composition: - RDF (high calorie fraction) - it constitutes 36% of the mass of incoming waste, M – 22%, DOM – 36% DM, N – 1,11% DM Metal: quantity – 4%; M – 5%; DOM – 10% DM; N – 0,22% DM
1.4.	Stabilized	The reduction of organic mass in the biostabilization process was 50%. Composition: quantity – 43%; M – 40%; DOM – 28% DM; N – 0,98% DM
1.5.	Air emission	NH_3 emission - 0.202 kgN (range: 20 - 40 mg/m^3; 30 mg/m^3 was assumed). The air demand in the biostabilization process was assumed -10 m^3/ Mg * h) and the duration of the process - 10 weeks (8-12 weeks) N_2O emission – 0.403 kgN (range: 11 - 110 mg/m^3;assumed 60 mg/m^3)
1.6.	Emission from wastewater	0.16 kgN/kgN Calculated on the basis of the amount of wastewater generated in the biostabilization process (range 260-470 dm^3/Mg; assumed 300 dm^3/Mg) and total nitrogen concentration in wastewater (range 70-8449 mgN/dm^3; assumed 530 mgN/dm^3).
1.7.	Air emission from landfil	Ammonia emission assumed: 0.008 kgN/Mg of waste Ammonia emission from Mg of waste delivered to the MBT installation - 0.0036 kgN/Mg
1.8.	Leachate	Emissions from waste after MBP Total nitrogen emission in the leachate: 0.6-2.4kg/Mg DM (1.5 kg/Mg DM was taken) Total nitrogen emission from Mg of waste delivered to the MBT installation - 0.4 kgN/Mg
		Emission from unprocessed waste delivered to the landfill: Total nitrogen emission in the leachate: 2.4-4.6 kg/Mg DM (3.5 kg/Mg DM was taken)

MBT - Biodrying

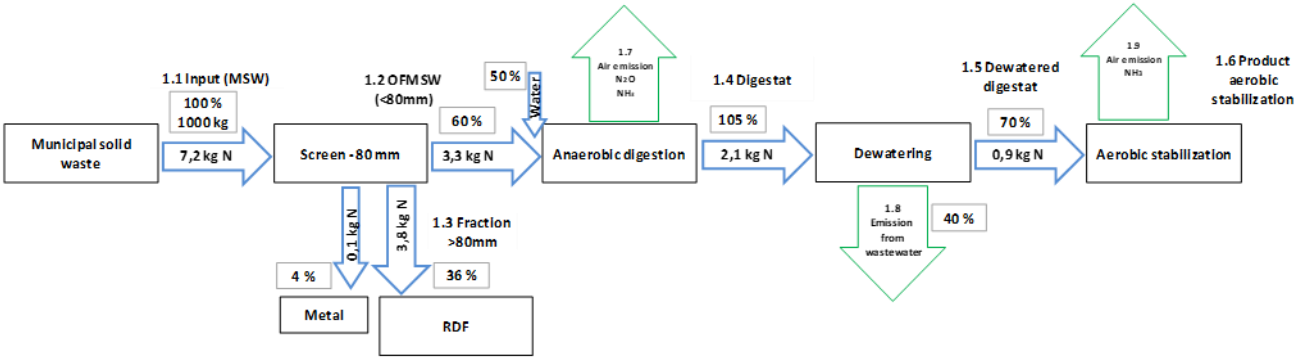


Scheme 5. Mass balances of waste and nitrogen calculated per 1000 kg

Mass balance in the waste treatment process includes:

Point	Waste stream	Description
1.1.	Input (MSW)	Mass of waste delivered to the MBT installation - 100%. The balance was made for 1000 kg v/v of waste. Waste composition: Moisture (M) – 35%; dry organic matter (DOM) – 37% dry matter (DM); N – 1.1% DM (household waste contains 0.8-1.1% N in dry matter)
1.2.	MSW after mechanical pretreatment	Composition: quantity – 98%; M – 45%; DOM – 43,3% DM; N – 1,0% DM
1.3.	Balast	Composition: quantity – 2%; M – 10%; DOM – 50% DM; N – 0,04% DM
1.4.	Product of biodrying	The organic mass distribution of waste was assumed to be 15% Composition: quantity – 70%; M – 15%; DOM – 33% DM; N – 1% DM
1.5.	Product of biodrying after mechanical separation	Waste for landfilling: quantity – 5%; M – 5%; DOM – 5% DM; N – 0,21% DM Alternative fuel: quantity – 53%; M – 17%; DOM – 41,5% DM; N – 1,3% DM Metal: quantity – 4%; M – 5%; DOM – 10% DM; N – 0,22% DM Glass: quantity – 4%; M – 3%; DOM – 3% DM; N – 0,07% DM Other: quantity – 4%; M – 20%; DOM – 20% DM; N – 0,44% DM
1.6.	Air emission	0,45 kgN Oxidation of 1 kg of organic substances leads to the formation of approx. 0.615 kg of water and 0.013 kg of N-NH_3

MBT - Fermentation



Scheme 6. Mass balances of waste and nitrogen calculated per 1000 kg

Point	Waste stream	Description
1.1.	Input (MSW)	Mass of waste delivered to the MBT installation - 100%. The balance was made for 1000 kg v/v of waste. Waste composition: Moisture (M) – 35%; dry organic matter (DOM) – 37% dry matter (DM); N – 1.1% DM (household waste contains 0.8-1.1% N in dry matter)
1.2.	OFMSW (fraction<80mm)	Separation on a sieve 80 mm into : under the sieve fraction (OFMSW- organic fraction of municipal solid waste) - it constitutes 60% of the mass of incoming waste (range 50.8-71.8%). Composition: quantity – 60%; M – 45%; DOM – 45% DM; N – 1,0% DM moisture of the fermentation charge – 70%
1.3.	Frakctuin >80mm	Over the sieve fraction: RDF: quantity – 36%; M – 22%; DOM – 31% DM; N – 1,34% DM Metale: quantity – 4%; M – 5%; DOM – 10% DM; N – 0,22% DM
1.4.	Digestat	The organic mass distribution was 35%. Composition: quantity – 105%; M – 73,5%; DOM – 35% DM; N – 1,0% DM
1.5.	Dewatered digestat	Composition: quantity – 70%; M – 60%; DOM – 33,8% DM; N – 0,32% DM
1.6.	The product after aerobic stabilization	The organic mass distribution was 19,6%. Composition: quantity – 39%; M – 35%; DOM – 29,1% DM; N – 0,33% DM
1.7.	Air emission NH_3	NH_3 emission - 0.002 kgN NH_3 emission from waste fermentation: 0.46-83 mg/Nm^3 NH_3 emission in biogas from waste fermentation: 1.8 g/Mg, N_2O emissions in biogas after fermentation are negligible.
1.8.	Emission from wastewater	1.2 kgN In the process of dewatering the digested waste, sewage is generated in an amount of 0.10 to 0.83 m^3/Mg of charge. Ammonium nitrogen concentration in the wastewater (range: 2-4 mgN/dm^3; assumed: 3 mgN/dm^3).
1.9.	Air emission NH_3	0.016 kgN Ammonia emission rate to air after fermentation and aerobic stabilization: 41 gN/Mg

General guidance to quantify N in wastewater

According to IPCC (2019) the emissions from domestic wastewater treatment plants may be calculated using eq. 3.

$$N_2O\ Plants_{DOM} = [\sum_{i,j}(U_i \cdot T_{ij} EF_j)] \cdot TN_{DOM} \cdot \frac{44}{28} \quad (3)$$

Where:
N_2O $Plants_{DOM}$ = N_2O emissions from domestic wastewater treatment plants in inventory year, kg N_2O/year
TN_{DOM} = total nitrogen in domestic wastewater in inventory year, kg N/year.
U_i = fraction of population in income group in inventory year.
T_{ij} = degree of utilisation of treatment/discharge pathway or system *j*, for each income group fraction *i* in inventory year.
i = income group: rural, urban high income and urban low income
j = each treatment/discharge pathway or system
EF_j = emission factor for treatment/discharge pathway or system j, kg N_2O-N/kg N
The factor 44/28 is for the conversion of kg N_2O-N into kg N_2O.
The detailed data needed for estimating the $N_2OPlants_{DOM}$ emissions are included in IPCC guidelines of 2019.

The indirect emissions is emissions from effluent from centralised treatment systems that has been discharged into aquatic environments. In addition to in-plant emissions from wastewater treatment (direct emissions), N_2O is emitted when the nitrogen that is released in wastewater treatment plant effluent is transformed through natural processes. This effluent-derived N_2O is considered to be the larger source of N_2O emissions associated with wastewater treatment (IPCC 2006; Kampschreur et al. 2009; U.S. EPA 2014). River conditions are favorable for N_2O production (Cole and Caraco 2001), and numerous studies have demonstrated that rivers dominated by wastewater effluent have higher N_2O saturation values (Beaulieu et al. 2010, Liu et al. 2015, Yu et al. 2013, Schreiber et al.2012). That emissions are dependent on the nutrient-impacted status and oxygenation level of the aquatic environment receiving the wastewater discharge. In the case of discharge to nutrient-impacted waters such as eutrophic lakes, estuaries and rivers, or locations where stagnant conditions occur, emissions can be significantly higher (IPCC 2019).

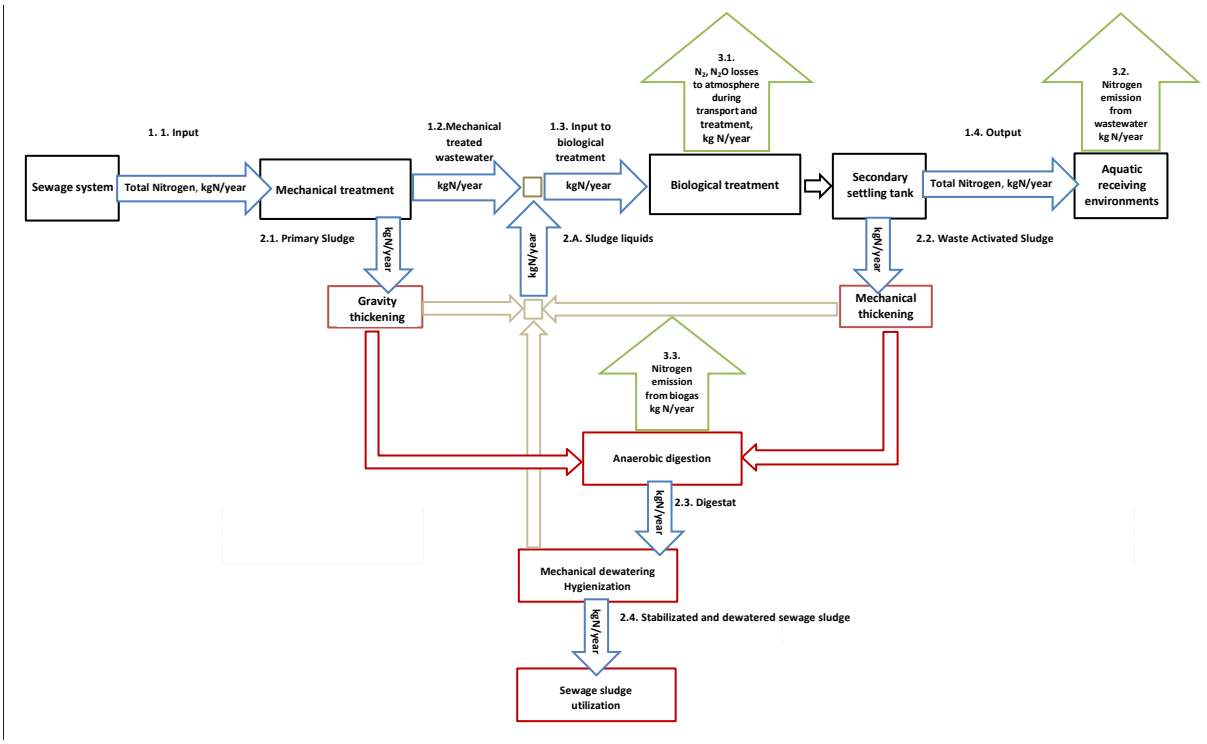
N_2O emissions from wastewater effluent can be calculated using eq.4 (IPCC 2019).

$$N_2O_{EFFLUENT,\ DOM} = N_{EFFLUENT,\ DOM} \cdot EF_{EFFLUENT} \cdot \frac{44}{28} \quad (4)$$

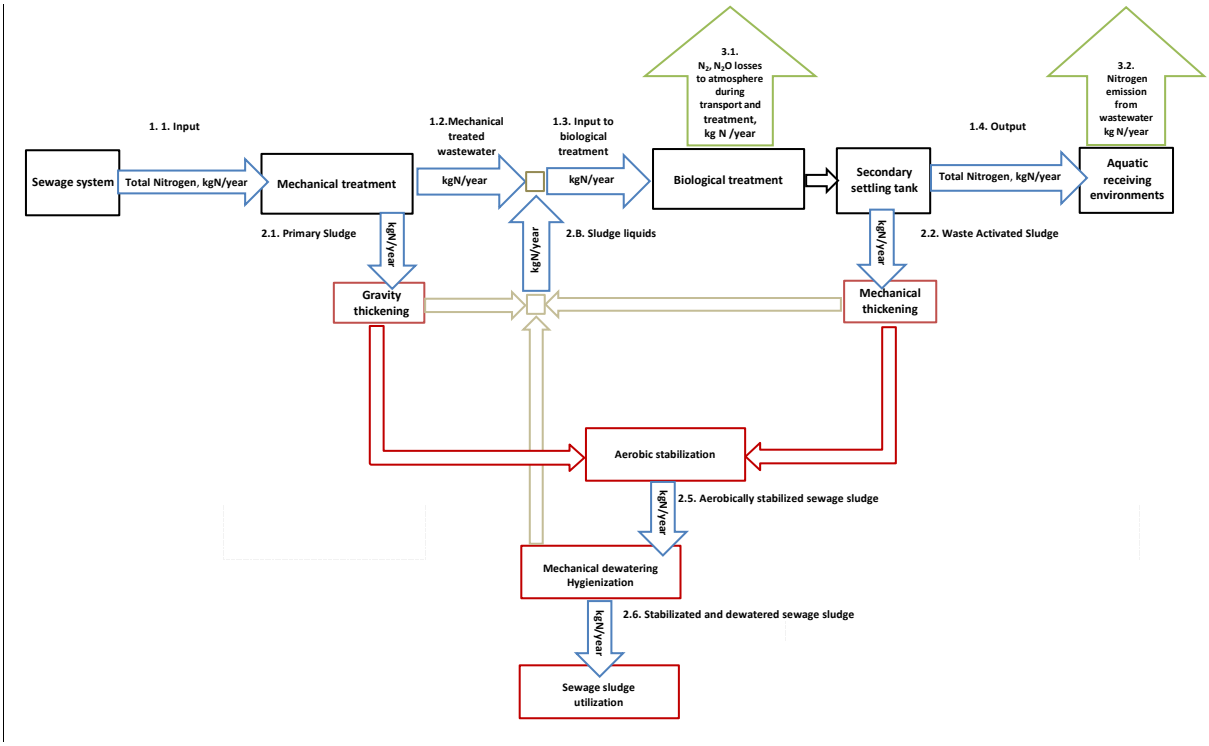
Where:
$N_2O_{EFFLUENT,DOM}$ = N_2O emissions from domestic wastewater effluent in inventory year, kg N_2O/year
$N_{EFFLUENT,DOM}$ = nitrogen in the effluent discharged to aquatic environments, kg N/year
$EF_{EFFLUENT}$ = emission factor for N_2O emissions from wastewater discharged to aquatic systems, kg N_2O-N/kg N
The factor 44/28 is the conversion of kg N_2O-N into kg N_2O.

The detailed data needed for estimating the $N_2O_{EFFLUENT,DOM}$ emissions are included in IPCC guidelines of 2019.

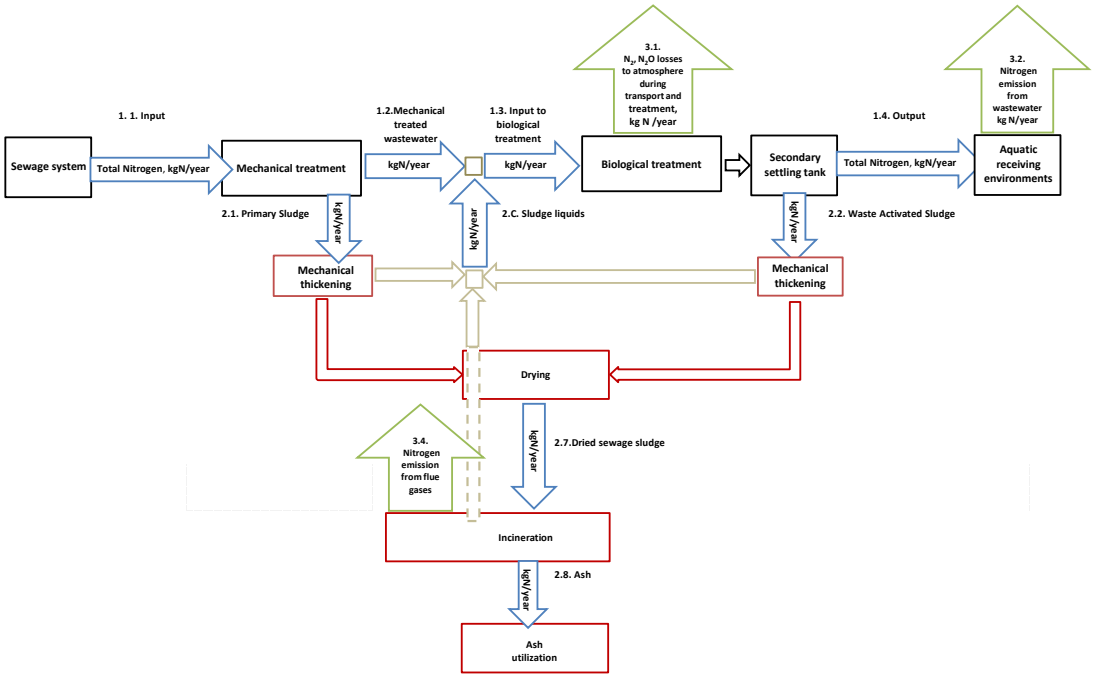
Data obtained from the operation of full-scale WWTPs show a wide range of values of the N_2O emission factors = 0.0006 - 0.045 (kgN_2O-N/kgN) (IPCC 2019).
Other potential sources of N_2O emissions connected with wastewater treatment are sewers networks and decentralised treatment systems of domestic wastewater (onsite sanitation).
Open sewers are not a source of N_2O. Closed and underground are likely source of N_2O. However, insufficient data exist to quantify emission factors that address the variation in sewer type and operational conditions.
A septic system usually composed of a septic tank, is generally buried in the ground, and a soil dispersal system. Septic tanks, as opposed to soil dispersal, are not the source of N_2O. Gases produced in the effluent dispersal system mainly N_2O, and CO_2 are released through the soil. Latrines are not the source of N_2O (IPCC 2019).



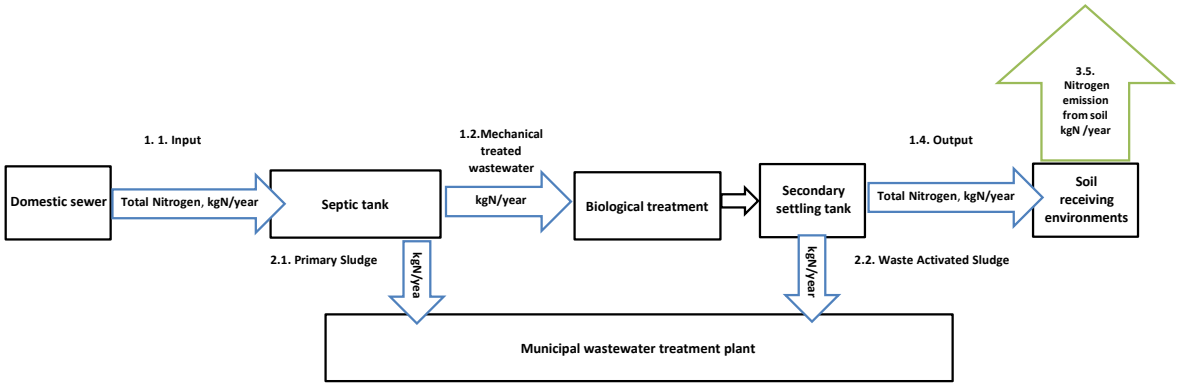
Scheme 7. Mechanical-biological wastewater treatment and sewage sludge management with anaerobic digestion



Scheme 8. Mechanical-biological wastewater treatment and sewage sludge management with aerobic stabilization



Scheme 9. Mechanical-biological wastewater treatment and sewage sludge management with thermal stabilization



Scheme 10. Domestic wastewater treatment plant

The mass balance of nitrogen flow during wastewater treatment

Point		Necessary parameters to description
1.1.	Input (raw wastewater)	Population, PE Load per capita, 2-15 gN/PE·day
1.2.	Mechanical treated wastewater	Population, PE Load per capita, 10 gN/PE·day
1.3.	Input to biological treatment	Increase in nitrogen load due to the liquid sludge aerobic stabilization + (5-10)% anaerobic stabilization + 15% thermal pretreatment +(15-20%)
1.4.	Output (treated wastewater)	Nitrogen concentration: 10 or 15 g/m^3 (depends on PE); Poland, Austria 15 or 20 g/m^3 (depends on PE); China Population, PE Amount of wastewater (water consumption) 100-150 L/PE·day

Mass balance of nitrogen flow during sewage sludge treatment

Point		Necessary parameters to description
2.1.	Primary sludge	Population, PE Amount of sludge per capita 28g/PE·day Nitrogen concentration 1.5-4.0 (2.5) %DM
2.2.	Waste activated sludge	Population, PE Amount of sludge per capita 32g/PE·day Nitrogen concentration 2.4-7.0 (5.0)%DM
2.3.	Digestat	Population, PE Amount of sludge per capita 39g/PE·day Nitrogen concentration 2.6 -9 (5.0) %DM Moisture, 97%
2.4.	Stabilizated and dewatered sludge	Moisture, % Nitrogen concentration 2 -7 (5.0) %DM
2.5.	Aerobically stabilizated sludge	Population, PE Amount of sludge per capita 49g/PE·day Nitrogen concentration 2.6 -12 (5.0) %DM Moisture, 99%
2.6.	Stabilizated and dewatered sludge	Moisture, % Nitrogen concentration 2 -12 (5.0) %DM
2.7.	Dried sludge	Moisture, % Nitrogen concentration 2 -12 (5.0) %DM
2.8.	Ash	Nitrogen is not significant
2 A	Sewage liquids	Increase in nitrogen load due to the liquid sludge anaerobic stabilization + 15%
B	Sewage liquids	Increase in nitrogen load due to the liquid sludge aerobic stabilization + (5-10)%
C	Sewage liquids	Increase in nitrogen load due to the liquid sludge thermal pretreatment +(15-20)%

The balance of nitrogen emissions in the wastewater treatment plant

	Point	Necessary parameters to description
3.1.	N_2, N_2O losses to atmosphere during transport and treatment	Centralised, advanced plants with nutrient removal (nitrification and denitrification) 0.00016 – 0.045 kg N_2O-N/kg N Anaerobic treatment N_2O is not significant 0.0-0,001 kg N_2O-N/kg N
3.2.	Nitrogen emission from wastewater and aquatic receiving environments	The assumption is that N_2O production in rivers and estuaries is directly related to nitrification and denitrification and, thus, to the nitrogen that is discharged into the river. 3.2 -7.0 g N_2O per person per year from treated wastewater For aquatic receiving environments it can be from 90 to 32,600 µg N_2O as N/m^2·day; area of rivers should be available from national statistics;
3.3.	Nitrogen emission from biogas	N_2O is not significant
3.4.	Nitrogen emission from flue gases	N_2O content in flue gases 100-300 mg N_2O/m^3 incineration of semi-dried sludge 300-400 mg N_2O/m^3 incineration of sludge in the form of pellets Amount of flue gases m^3/year
3.5.	Nitrogen emission from soil	0,0045 kg N_2O-N/kg N (range 0-0.001 kg N_2O-N/kg N)

Calculation of N emissions from waste incineration plants

Nitrogen emissions from waste incineration plants should be calculated on the basis of equation (5) (ICCP, 2006):

$$N_2O\ Emission = \sum_i (IW_i \cdot EF_i) \cdot 10^{-3} \quad (5)$$

IW_i – amount of waste burned (i type of technology), Gg/year

EF_i – emission factor of waste incineration, gN_2O/kg incinerated waste for and type of technology

i – combustion technology

Indirect N_2O emissions from NO_x and NH_3 deposition in the atmosphere should be calculated according to the equation (6):

$$N_2O_{(i)} = \left[\left(NO_X - N_{(i)}\right) + \left(NH_3 - N_{(i)}\right)\right] EF_4 \cdot 44/28 \quad (6)$$

NO_x-$N_{(i)}$ – nitrogen content in the NO_x emitted from the source 'i', NO_x is expressed as NO_2 equivalent (Gg NO_x-N or Gg NO_2·14/46),

NH-$N_{(i)}$ – nitrogen content of NH_3 emitted from the source "i" (Gg NO_x-N lub Gg NO_2·14/17)

EF – N_2O emission factor from deposition N (GgN_2O-N/GgNH_3-N lub NO_2-N_x)

Literature

1. Ahn J., Pagilla K., Chandran K. (2010): Spatial and Temporal Variability in 1. Atmospheric Nitrous Oxide Generation and Emission from Full- Scale Biological Nitrogen Removal and Non- BNR Processes. Water Environ Res. 82 (12), 2362-2372.
2. APHA (1992). Standard Methods for the Examination of Water and Wastewater, 18th ed. American Public Health Association, Washington, DC.
3. Beaulieu, J. J., Shuster, W. D., and Rebholz, J. A. (2010): Nitrous oxide emissions from a large, impounded river: The Ohio river. Environ. Sci. Technol., 44(19), 7527–7533.
4. Bernhard, A. (2010) The Nitrogen Cycle: Processes, Players, and Human Impact. Nature Education Knowledge 3(10):25.
5. Campos, J. L., Valenzuela-Heredia D., Pedrouso A., Val del Río A., Belmonte M. and Mosquera-Corral A. (2016): Greenhouse Gases Emissions from Wastewater Treatment Plants: Minimization, Treatment, and Prevention, Hindawi Publishing Corporation, Journal of Chemistry Volume 2016, Article ID 3796352, http://dx.doi.org/10.1155/2016/3796352.
6. Cole, J. J., and Caraco, N. F. (2001): Emissions of nitrous oxide (N2O) from a tidal, freshwater river, the Hudson River, New York. Environ. Sci. Technol., 35(6), 991–996.
7. Czerwionka, K. i Mąkinia, J. (2009). Charakterystyka i pochodzenie rozpuszczonego i koloidalnego azotu organicznego w odpływach z komunalnych oczyszczalni ścieków. Monografie 3 Ogólnopolski Kongres Inżynierii Środowiska. 29.
8. Daelman, M.R.J. (2014): Emissions of methane and nitrous oxide from full-scale municipal wastewater treatment plants. Doctoral thesis. Printing: Ipskamp Drukkers, Enschede. ISBN: 978-94-6259-362-6.
9. Gupta D., Singh S. K. (2012) Greenhouse Gas Emissions from Wastewater Treatment Plants: A Case Study of Noida Journal of Water Sustainability, 2(2), 131–139.
10. Henze M., Gujer W., Mino T. and van Loosdrecht M.C.M. (2000): Activated Sludge Models ASM1, ASM2, ASM2d and ASM3. Scientific and Technical Report No. 9., TWA Publishing, London, UK, 16-22.

11. IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds), IPCC, Hayama, Japan.
12. IPCC (2019): Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Edited by Buendia E.C., Tanabe K., Kranjc A., Jamsranjav B., Fukuda M., Ngarize S., Osako A., Pyrozhenko Y., Shermanau P. and Federici S. IPCC, Switzerland.
13. Jędrczak, A., (2008), Biological Waste Treatment; Polish Scientific Publishers PWN: Warsaw, Poland
14. Kampschreur, M. J., Temmink, H., Kleerebezem, R., Jetten, M. S. M., and van Loosdrecht, M. C. M. (2009) Nitrous oxide emission during wastewater treatment. Water Res., 43(17), 4093–4103.
15. Law Y., Ye L., Pan Y. and Yuan Z. (2012): Nitrous oxide emissions from wastewater treatment processes. Phil. Trans. R. Soc. B (2012) 367, 1265–1277.
16. Liu, X. L., Bai, L., Wang, Z. L., Li, J., Yue, F. J., and Li, S. L. (2015):Nitrous oxide emissions from river network with variable nitrogen loading in Tianjin, China." J. Geochem. Explorat., 157, 153–161.
17. Miksch, K. i Sikora, J. (2010): Biotechnologia ścieków. PWN. Warszawa.
18. Pagilla, K.R., Urgun-Demirtas, M. i Ramanir, R. (2006): Low effluent nutrient treatment technologies for wastewater treatment. Water Sci. Technol., 53(3), 165-172.
19. Sadecka Z. (2010): Podstawy biologicznego oczyszczania ścieków. Wydawnictwo Seidel – Przywecki Sp.z.o.o.
20. Schreiber, F., Wunderlin, P., Udert, K.M. and Wells, G.F. (2012) Nitric oxide and nitrous oxide turnover in natural and engineered microbial communities: biological pathways, chemical reactions and novel technologies. Frontiers in microbiology 3.
21. Sokka, L., Antikainen, R. and Kauppi, P.E. (2004). Flows of nitrogen and phosphorus in municipal waste: a substance flow analysis in Finland. Progress in Industrial Ecology 1(1/2/3): 165-186
22. Svoboda, K., Baxter, D., and Martinec, J., 2006, Nitrous Oxide Emissions from Waste Incineration Institute of Chemistry, Slovak Academy of Sciences
23. U.S. EPA. (2014): Inventory of U.S. greenhouse gas emissions and sinks. Washington, DC.
24. Yu Z., Deng H., Wang D., Ye M., Tan Y., Li Y., Chen Z. and Xu S. (2013): Nitrous oxide emissions in the Shanghai river network: Implications for the effects of urban sewage and IPCC methodology. Global Change Biol., 19(10), 2999–3010.
25. Pardo, G., Moral, R., Aguilera, E., Del Prada, A., (2015): Gaseous emissions from management of solid waste: a systematic review, Global Change Biology 21, 1313–1327

26. Ramachandra, T. V., (2011): Integrated Management of Municipal Solid Waste, Environmental Security : Human & Animal Health, Editor Sudhi Ranjan Garg

27. Teichmann, D., Schempp, C., (2013): Calculation of GHG Emissions of Waste Management Projects