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Measurement methodology for greenhouse gas emissions from storage of forest chips – a review

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Abstract

Research on greenhouse gas emission related to solid biofuels has focused mainly on the emissions from end use and the production chain. GHG emissions from the storage of forest chips have not received much attention in recent literature. In order for EU emission reduction targets to be fully understood, emissions from solid biofuel storage needs to be better described. Usually

emissions from chip piles have been modelled using studies from organic waste composting but these two materials can differ appreciably; for example the C/N-ratio and moisture content.

Herein, previous studies on greenhouse gas emissions from forest chips piles during storage are reviewed. The objective is to report on the methodology for measuring GHG emissions from organic waste composting in order to understand the suitability of applying the same methods for measuring emissions from woody biomass piles.

Keywords: greenhouse gas emissions, forest chips, storage, wood chips, composting, measurement methodology

1. Introduction

In the forest sector, the term *forest chips* means chipped material produced from woody biomass that is not otherwise suitable for use by sawmills or the pulp and paper industry. Such woody biomass includes logging residues (tree branches, crown wood, tree stumps) and under-sized trees. Nowadays the use of forest chips is a growing trend in energy production in order to offset fossil fuel use and reduce net greenhouse gas emissions. For instance in Finland energy production from forest chips accounts for some ten per cent of all woody fuels with good potential for increasing utilisation in energy production [1, 2]. EU targets for reducing greenhouse gas emissions and increasing inland sources of energy by 2020 has increased interest in renewable fuels. Therefore, it is expected that the use of forest chips will increase in future [2, 3].

Typically forest residues and under-sized trees are harvested from the logging area and can be chipped or crushed for energy production either on site, at the road side, at satellite storage

terminals or at power plants. Fluctuating energy demand through the seasons increases the need for storage of chips [1, 2]. For this reason, the storage of forest chips in piles is commonplace in Finland. The duration of storage can vary from just a few weeks up to a year depending on energy demands. For the purpose of analysis, it has been estimated that on average forest chips are stored for a six month period in Finland [4]. This estimate considered both energy demand and the production season for forest chips.

Forest chip piles are exposed to outdoor weather conditions (fluctuating temperature and moisture) during storage. As a result, microbial activities in the pile are stimulated and the material begins to undergo biological degradation. Decomposition is either aerobic or anaerobic or a combination of these [4-7]. Forest chips properties undergo changes during decomposition. The heating value of the chips decreases and there is a (dry) mass loss from the pile [7-9]. These property changes as they relate to energy production have been widely investigated [7, 10, 11], but greenhouse gas (GHG) emissions, due to the storage phase, have received less attention in literature. Work by Wihersaari, however has been among the most recent [9].

The GHG emissions from decomposition of forest chips include methane (CH_4), carbon dioxide (CO_2) and dinitrogen oxide (N_2O) not unlike organic waste composting [9]. The concentrations of greenhouse gases depend on duration of storage, local climate and forest chips properties; such as particle size, moisture and nitrogen content for instance [4, 7]. These properties are seen to increase or decrease emissions from microbial activities in the storage pile [7, 9, 12, 13].

According to literature the drying of forest chips to a level below 20% moisture content can slow down the decomposition process [9, 14]. However, such low moisture content is challenging to achieve in practice by natural drying alone, especially in Nordic countries.

In this paper, previous studies on greenhouse gas emissions from forest chips piles during storage and their measurement methodology are reviewed. The objective here is to report the methodology for measuring GHG emissions from past studies. However, there is a lack of experimental studies reporting GHG emissions from forest chips storage piles. Most experimental GHG studies from literature deal with emissions from soils, agriculture and solid biowaste treatment. In these studies the environment is similar to that in forest chips piles. Therefore, these methods may be applied to the measurement of GHG emission from forest chips piles during storage.

The greenhouse gases reviewed herein, are carbon dioxide (CO₂), methane (CH₄) and dinitrogen oxide (N₂O). According to the IPCC, halogenated hydrocarbons and the aforementioned compounds are the most important greenhouse gases [15, 16].

2. Formation of greenhouse gas emissions from woody biomass

The formation of greenhouse gases (CO₂, CH₄ and N₂O) during the storage of forest chips is depended on the decomposition processes in the piles [4, 9]. Processes can vary widely and even within a single pile homogeneity cannot be assumed. It is known that the decomposition of a biodegradable material begins as a consequence of microbial activities, which can change the temperature of the material [6, 7, 17-19].

The composting process can be described using three different temperature phases: the warm-up phase (mesophilic), a hot phase (thermophilic) and a cooling phase (maturation) as depicted in Figure 1. During the mesophilic phase the temperature increases, but remains below 40°C. In the thermophilic phase, microbe activity and the decomposition of biomass increases rapidly and the temperature can rise to 65 °C. This phase is the shortest. When the maximum microbial activity is

achieved, the temperature of the biodegradable material decreases and the maturation of the compost begins. The decomposition rate and sensitivity of microbe activity depend on particle size and density [7, 18, 20-23]. The bigger the forest chip size and the more compact the pile then the more susceptible it is to composting. It has been stated that the decomposition of biodegradable material, which includes a lot of lignin, requires longer times than for instance food waste in a biowaste composter [24].

<< Figure 1. The three different temperature phases of the composting process over time: the warming phase, hot phase and cooling phase. >>

Forest chip piles can be covered or uncovered during storage. Investigations of the effect of coverage have been for the most part inconclusive [21, 25, 26]. However, Hansen et al. have found from studying composting of solid digested manure that the covered pile released less GHG emissions than an uncovered one [27]. The temperature within the pile was also found to be lower and material losses less in the covered pile.

2.1 Carbon dioxide (CO₂) formation

Emissions of CO₂ during storage result from decomposition of forest chips as a product of microbial activities under aerobic and nonaerobic conditions. Especially during the thermophilic phase, when temperature is high, the amount of CO₂ emissions is also high [4, 6, 9]. According to Jirjis, a large pile and small particle size cause rapid temperature increase in willow wood piles [18]. At the same time the growth of microbes increases, which means higher CO₂ emissions. The magnitude of CO₂ emissions in the composting process has been linked to the nutrient contents of the biodegradable material [6, 28, 29]. According to He, high concentration of nutrient containing green materials as needles and leaves, that are mixed into wood chips pile, increase microbe

activities. This can lead to higher amount of CO₂ emissions [6]. As a nutrient for micro-organisms nitrogen is an important element and low concentrations in a material may restrict the composting process. [28, 29]

In studies of biowaste composting, the waste is often composted with support material such as forest chips, so that it is not overly compacted and air can circulate inside the pile [30, 31, 32]. In addition biowaste composting is turned [24, 30] and aerated [33] in order to ensure a good air current the different parts of compost. These methods ensure that anaerobic areas are not long-lived in the pile. However, in studying GHG emissions during composting of dairy manure, that CO₂ emissions increased substantially by pile mixing [34]. Because four weeks is a typical timespan for microbe activity to calm down, mixing is recommended after this, or not at all, in order to minimise GHG emissions.

2.2 Methane (CH₄) formation

Methane is formed during anaerobic decomposition during the composting. The rate of formation is highest during the thermophilic phase. Usually anaerobic conditions are present in the middle of the pile [4, 9, 24]. The formation is faster at the beginning of composting, when microbial activities are strong [34]. In some cases the nitrogen-containing material, which including ammonium nitrogen (NH₄⁺) or nitrate (NO₃⁻), have been noted to increased CH₄ emissions, because these compounds inhibit the oxidation of CH₄ [35-38]. However Jang et al. have found that the amount of emissions are dependent on the different types and process mechanisms of methanotrophic bacteria.[38]

According to the composting study by Amlinger's et al. strong methane peak was observed from the biodegradable material during the thermophilic phase [24]. On the other hand, similar

behaviour was not observed from garden waste, which contained a lot of lignin. In this case more air could get into the compost and anaerobic conditions cannot occur, because compost is loosely packed [24, 33].

Some studies indicate that the formation of CH_4 emissions from mixed piles is more pronounced than from non-mixed piles [28, 34, 39]. Generally it is understood that formation of CH_4 occurs in anaerobic conditions in the middle of the pile and that mixing is supposed to decrease anaerobic conditions. In spite of this, the three authors above have all conjectured that the released CH_4 gas is oxidized to CO_2 by methanotrophic bacteria during CH_4 gas transfer from the centre to the outer surface of the pile. Most likely, the mixing disturbs the balance of bacteria in the pile, when CH_4 gas does not have time to oxidize.

2.3 Dinitrogen oxide (N_2O) formation

Dinitrogen oxide can be formed in two ways: by either nitrification during aerobic decomposition from incomplete oxidation of ammonium or denitrification during anaerobic decomposition from incomplete denitrification [4, 9, 40]. N_2O -forming microbes are sensitive to high temperature, thus very little N_2O emissions are generated above 40 °C. Therefore N_2O emissions from forest chip piles are to be expected at the beginning and end of the storage phase, when the temperature of the pile is low [4, 9, 24]. During the mesophilic phase N_2O emissions from composting material are high [24]. It is also known, that the formation of N_2O emissions increase with nitrogen content of the biodegradable material or/and soil [24, 38, 40-42]. Although with woody biomass emissions are lower than from other biodegradable material, decomposition takes longer. This is taken into account, when N_2O emissions are measured from piles of forest chips, in order that measurements are continued at sufficiently long periods of time [24].

It has been shown that soil freezing and melting affect the production of N_2O emissions in winter [41, 43, 44]. When the temperature falls below zero degrees Celsius, production of N_2O is increased depending on both soil type and moisture [41, 44]. In winter conditions, the oxygen supply to the soil is reduced and at the same time denitrification is accelerated, which increased N_2O emissions [43]. Usually, snow cover prevents the release of gases from the soil during the winter, but in spring, with snow melt, research has shown higher N_2O concentrations [41]. Snow melt provides more moisture to the soil for the denitrification process and, hence, the formation of N_2O emissions are possible via this pathway [44].

3. Measurement methods of emissions from woody biomass

Most of the analytical methods for GHG emissions are used in soil and agriculture emission research, but also composting studies of solid sludge from waste treatment processes use the same methods. In the next sections three established measurement methods are described: the closed chamber, gradient and integrated horizontal flux (IHF), which are often used to detect CO_2 , CH_4 and N_2O emissions. Also some other methods, such as He's [6] laboratory tests are used, but this paper focuses only on the methods, which may be used with forest chip pile studies.

3.1 Closed chamber method

The closed chamber method is based on a closed static chamber, which allows sunlight to pass through (light chamber) or not (dark chamber), see Figure 2. Typically, the chamber bottom (collar) is placed on the ground or other researched material onto the desired depth before measurements. The collar includes an opening, through which gases can pass into the chamber. The chambers can be used many and these can be placed at different locations in the composting

pile or other research area. After installation the research environment is allowed to stabilize in order that measurements do not show errors, which for instance follow from soil breakage during collar installation [41, 42, 45-49, 50].

For instance Maljanen et al. have collected samples from 3–25 minutes after the chamber is closed [41]. After that the chamber is put on the collar, closed the chamber lid and ensured that the chamber is sealing well either by the water groove from the collar. The purpose is to provide a sealed chamber in order to the formation of gases inner the chamber can be measured. The chamber is equipped a tube and a valve, through which gas samples can be drawn into a syringe and injected to vacuum vial [41, 42, 45-47].

<< Figure 2. Example of the apparatus for closed chamber emission measurements. >>

In differences studies the chamber and collar materials may be composed of galvanized iron [51], stainless steel [52, 53], aluminium [41, 45] and PVC [42, 45, 47, 53]. According to studies, the chamber width and high varies. The width has been between 0,10–0,8 m and high over 10 cm to even 80 cm depending on measurement environment. Sample sizes also varied between 7–40 mL as well as the sampling intervals [41, 42, 45, 47-49, 51-53]. According to studies, the sampling intervals varied depending on gas sampling methods from seconds to few minutes [53], 5, 10, 15 and 20 minutes after the chamber was closed [41], 2–4 weeks during the year [51] or once a week for about a year [45]. Sometimes the air inside the chamber is mixed by use of a fan [41, 51, 53].

Usually collected gas samples by closed chamber method can be analysed by gas chromatography. In addition to this the identification of N_2O gas requires an electron capture detector and respectively CH_4 gas requires a flame ionization detector in connection with the gas chromatography [41, 42, 45-47, 51, 54]. Also [52, 53] the automatic chamber method has been

used in measurements. For instance Laville et al. measured N_2O concentrations using infra-red absorption spectrometry [52].

The disadvantage of the closed chamber method is making measurements in winter, because snow cover may produce errors in the results. This problem is especially observed in measurements of N_2O emissions. Installation of the chamber within freezing soils or other material is also difficult. Disturbance of the material during installation will have an effect on emissions. Due to this the measurements should be started only after the study environment has stabilized [46]. Also mixing of air inside the chamber varies significantly causing of errors to measurement results. On the other hand mixing is necessary that gases are not separated inside of chamber [53]. Convection, which due to recycled air through composting pile, cannot be detected by chamber method so it should be considered in experimental error assessment [48, 49]. Sommer et al. detected during the composting measurements from manure piles that CO_2 and CH_4 emissions were generated more on the top of pile whereas N_2O emissions on the side [48, 49].

3.2 Gradient method

In the gradient method gas samples are collected by tubes, which are perforated. The tubes are closed at each end and are equipped with a valve, through which gas samples can be taken. The tubes are placed horizontally within the material being studied. It is important to discard the first samples before collected those to be analyzed. This ensures a clean sample. The samples can be analyzed in the same way as in the chamber method [46, 55, 56]. Figure 3 shows the equipment, as an example, which Maljanen et al. have utilised in the N_2O emissions studies using the gradient method [46].

<< Figure 3. The measurement set-up for the gradient method of measurement according to Maljanen et al. [46]. >>

Maljanen et al. have investigated the gradient method and its suitability for the measurement of N₂O emissions. They took samples every two weeks throughout the growing season. The samples were analyzed during 24 hours. [46] The gradient method has the advantage that it can also be used in winter. The gradient method is based on Fick's diffusion law. [46, 56] According this law can be calculated for instance flow of N₂O gas between snow and atmosphere (equation 1 [46]).

$$J_{\text{gas}} = D_{\text{gas}} \frac{d_{\text{gas}}}{dz} f, \quad (1)$$

In which J_{gas} is flow of gas diffusion ($\text{g cm}^{-2} \text{s}^{-1}$), D_{gas} is diffusion coefficient in the air ($0,139 \text{ cm}^2 \text{s}^{-1}$), (d_{gas}/dz) is vertical gradient of N₂O gas ($\text{g cm}^{-3} \text{cm}^{-1}$) within the surface to a 20 cm depth and f is air in the pore space of snow ($\text{cm}^3 \text{cm}^{-3}$). When Fick's law is applied to soil studies, the resistance to diffusion, which originates from the soil porosity, is taken into account in calculation. [46, 56]

The gradient method is a fast way to measure GHG emissions. This method does not disturb the soil, damage plants or other components of the study area in the same way as the chamber method. [46, 55] Problems can occur from moisture, which affect the porosity and the flow of gas from the measurement area. Furthermore, it is recommended that the measurement area, where installation is done, be homogenous in composition [46, 56].

3.3 Integrated horizontal flux (IHF) method

GHG emissions can also be calculated by the integrated horizontal flux (IHF) method which uses air flow from research area [48, 49, 57]. Usually one or more masts, which houses anemometers, sample shuttles and air intakes, are used this method. The basic idea for IHF-method is the released gas emissions as CH₄, CO₂ and N₂O can be detected from the surface of the pile and surrounding air space. The taken gas samples can be analysed by chromatography, which would require the inclusion of an electron capture detector, to identification of N₂O or gas chromatography for CH₄ detection. The gas samples can be collected using vacuum vial by syringe or analysed directly to the measuring point (on-line). This method is suitable, where the gas measurements are made at spatially inhomogeneous locations and in rough research environments as for instance with forest chip piles.

Sommer et al. have used the IHF-method to measure the GHG emissions from the manure composting piles [48, 49]. They developed the experimental arrangement, depicted in Figure 4, in which included gas collectors (shuttles), the passive flow meters (air intake) and anemometers.

<< Figure 4. The schematic arrangements of measurement apparatus for IHF-method according to Sommer et al. [48, 49]. >>

The installed apparatus included two masts at a constant distance from each other, which were connected together. The masts circulated around the stockpile of 360°. The wind vane ensures that the sampling locations were up and down stream of the wind. This ensured that the meters detected gas emissions and gas background level from the entire measuring area. Some meters were set to measure the values on either side of downwind or upwind. The meters were set to difference heights in order that the formed gas emissions were detectable from difference sides of the pile. [48, 49]

The average flow density of gas on the pile surface was determined by the difference between horizontal flows of down- and upwind. (eq. 2 and 3 [48, 49])

$$Q = \frac{1}{X} \int_{z_o}^{z_p} F_x dz, \quad (2)$$

$$F_x = \bar{u} \bar{C}_{dw} - \bar{u} \bar{C}_{uw}, \quad (3)$$

where Q is emission flux ($\mu\text{g m}^{-2} \text{s}^{-1}$), F_x is the horizontal net gas flow ($\mu\text{g m}^{-2} \text{s}^{-1}$), X is the distance (m) travelled by the wind across the pile, u is horizontal mean wind speed (m s^{-1}), C_{dw} is average downwind concentration ($\mu\text{g m}^{-3}$), C_{uw} is upwind concentration ($\mu\text{g m}^{-3}$), z_o is the high above the soil surface (m) and z_p is high of integrated limit, which the gas concentration is at the background level.

According to Sommer et al. the measured results varied with respect to time. As a result in the stockpile investigations an on-line analyser is recommended for GHG emission measurements [48, 49]. When using IHF-method the GHG emissions can be measured at different heights from the pile, but also from the pile as a whole [48, 49, 57].

4. Applicability of reviewed methods for research of wood chips piles

The results from this review have been classified and presented in the contents of the following three tables. Table 1 describes the formation pathways of the three greenhouse gases discussed above and their characteristics with regards to composting phases.

<< Table 1. Here >>

Table 2 contains the measurement methods along with the advantages and disadvantages associated with each method.

<< Table 2. Here >>

Based on the information in Table 2, the methodology requires two or more methods in order that the GHG emissions from within the forest chip pile and on the exterior can be measured extensively.

Table 3 contains collected examples of GHG emission data from different composting studies. The emissions have been measured using the chamber or gradient method. Measurement data units from differences research results are given as they appear in the references. The IHF method did not provided high-quality data from composting research, only N₂O emissions from soil research was available in the literature.

<< Table 3. Here >>

Using emission data from composting piles some guidelines for amount of GHG emissions released from wood chips piles during storage can perhaps be given. In some cases the research environment is identical to that of composting sites; for instance location, size and shape of piles. The only difference is the material. The question is: Can GHG emissions from wood chips piles be comparable to those of composting piles? Unfortunately at present similar GHG emissions data from wood chips piles have not been studied.

5. Discussion

The most important GHG emissions from composting piles of forest chips are CO₂, CH₄ and N₂O, which are detected. Typically CH₄ and N₂O emissions are formed in anaerobic conditions, which are depended on the moisture content of the pile, whereas CO₂ emissions are formatted in aerobic conditions by microbial activities. In some cases the natural microbial activity is disturbed during stockpile mixing and as a result GHG emissions, especially CH₄, from the pile are increased. Also the soil beneath forest chips piles are affected by the pile and produce N₂O and CH₄ emissions. This has to be taken into account when measuring the GHG emissions from a forest chip pile, especially if the storage area in use is a field, forest or a sand field.

Based on this review the modelling of emissions during storage of forest chips can be validated by use of three different measurement methods: the closed chamber method, the gradient method and integrated horizontal flux (IHF) -method. These methods are usually used in soil and composting research. On the basis of soil and composting studies it can be noted that the measurement methods are in theory suitable for forest chips piles. In practice however these experimental methods need to be verified to determine their suitability. It remains to be determined exactly which differences, if any, stem from environmental factors.

Generally the research environment is planned carefully when making measurements in order that GHG emissions from the different sides of the pile can be detected by the all methods. CH₄ and N₂O emissions are observed to form on the top of the pile by chamber method during composting studies. Respectively, N₂O emissions are released on the side of pile. Both the chamber and gradient methods can be easily applied to measure GHG emissions from forest chips pile, although the suitable of the chamber method for heating composting pile has been scrutinized.

The problem with the IHF-method is the complicated experimental arrangements. In particular, if experimental area is located for instance in far away industrial area, where it is difficult to transport and install the needed equipment. On the other hand, this will not be a problem at a wood chip terminal.

Usually the taken gas samplers are analysed by gas chromatography regardless of measurement methods. In addition, the identification of N_2O needs at least an electron capture detector and CH_4 requires a flame ionization detector, which are in connection with gas chromatography.

Nowadays online measuring instruments, which are facilitated and speed up to measure GHG emissions, are also popular to use.

In this review the focus is on measuring the GHG emissions from wood chips piles. However, the methods described here (or in fact their combinations) can also be used for measuring other gaseous emissions. For instance, when studying the role of gaseous emissions in the self-ignition phenomenon of large storage piles containing material of wood chips piles.

Finally, there has been limited research dealing with the storage of forest chips. Although there is awareness about the existence of GHG emission of forest biomass from a variety of bioenergy and forestry sector publications [11, 14, 58] but no literature on GHG emissions modelling of forest chips has been published since Wihersaari [9].

Present research has focused on the properties of forest chips and other processing emissions from production the production chain. Usually the GHG emissions from the storage of forest chips have been modelled from studies of organic waste composting. The properties of the two materials, however, differ with regards to moisture and C/N-ratio. This makes comparison

difficult. Further studies on GHG emission during storage are required in order that EU reduction targets can be better understood in future.

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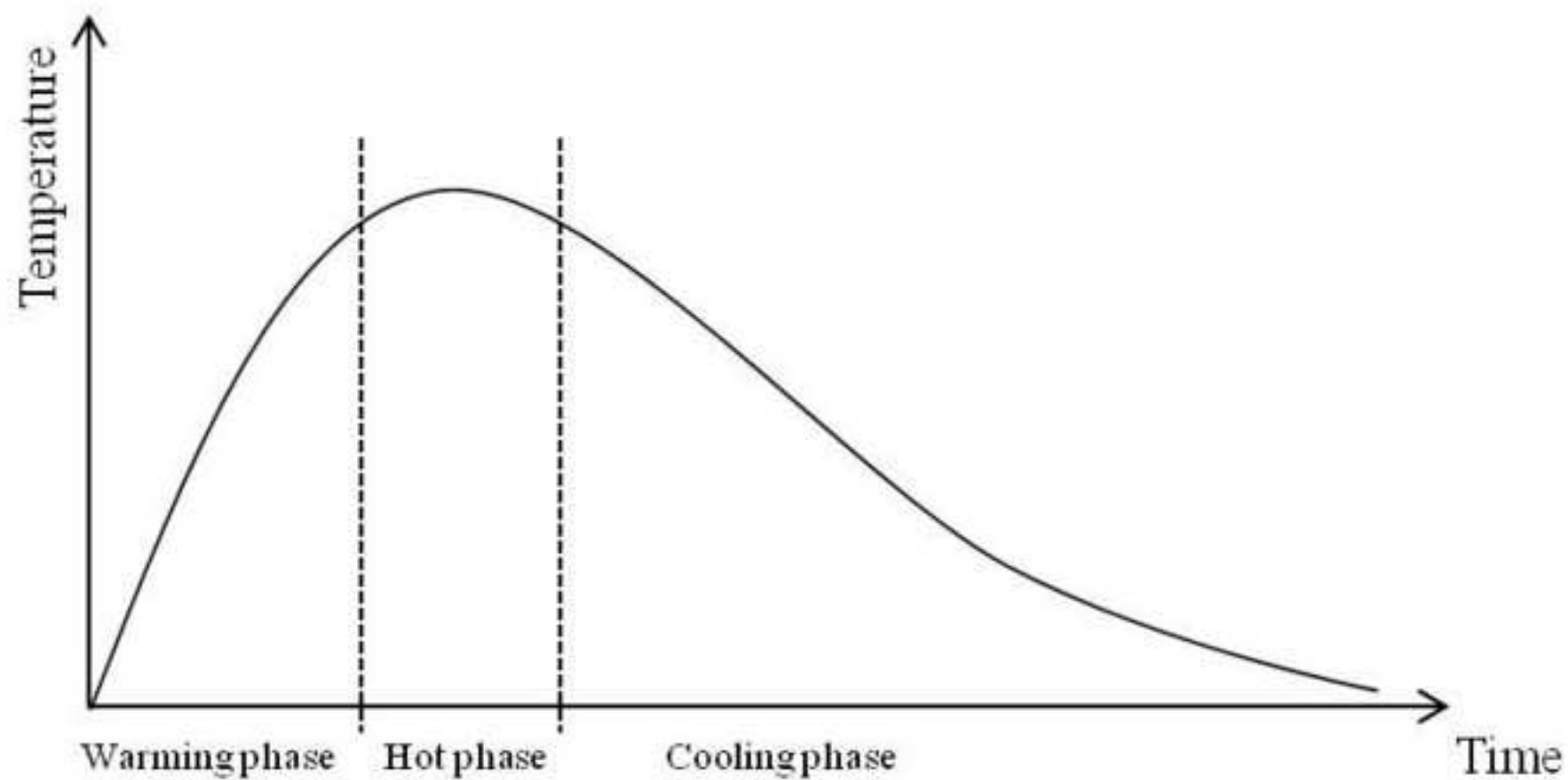


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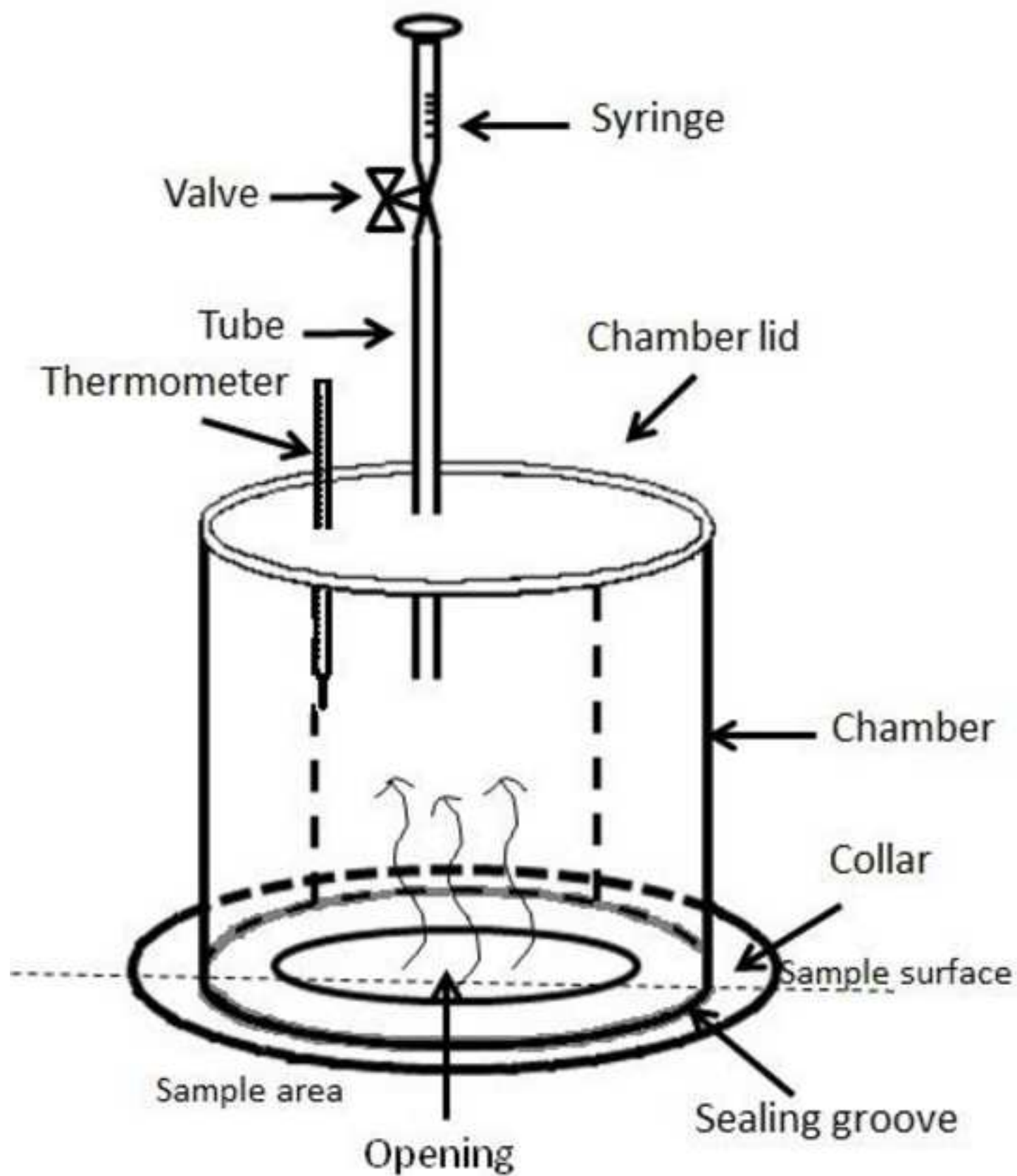


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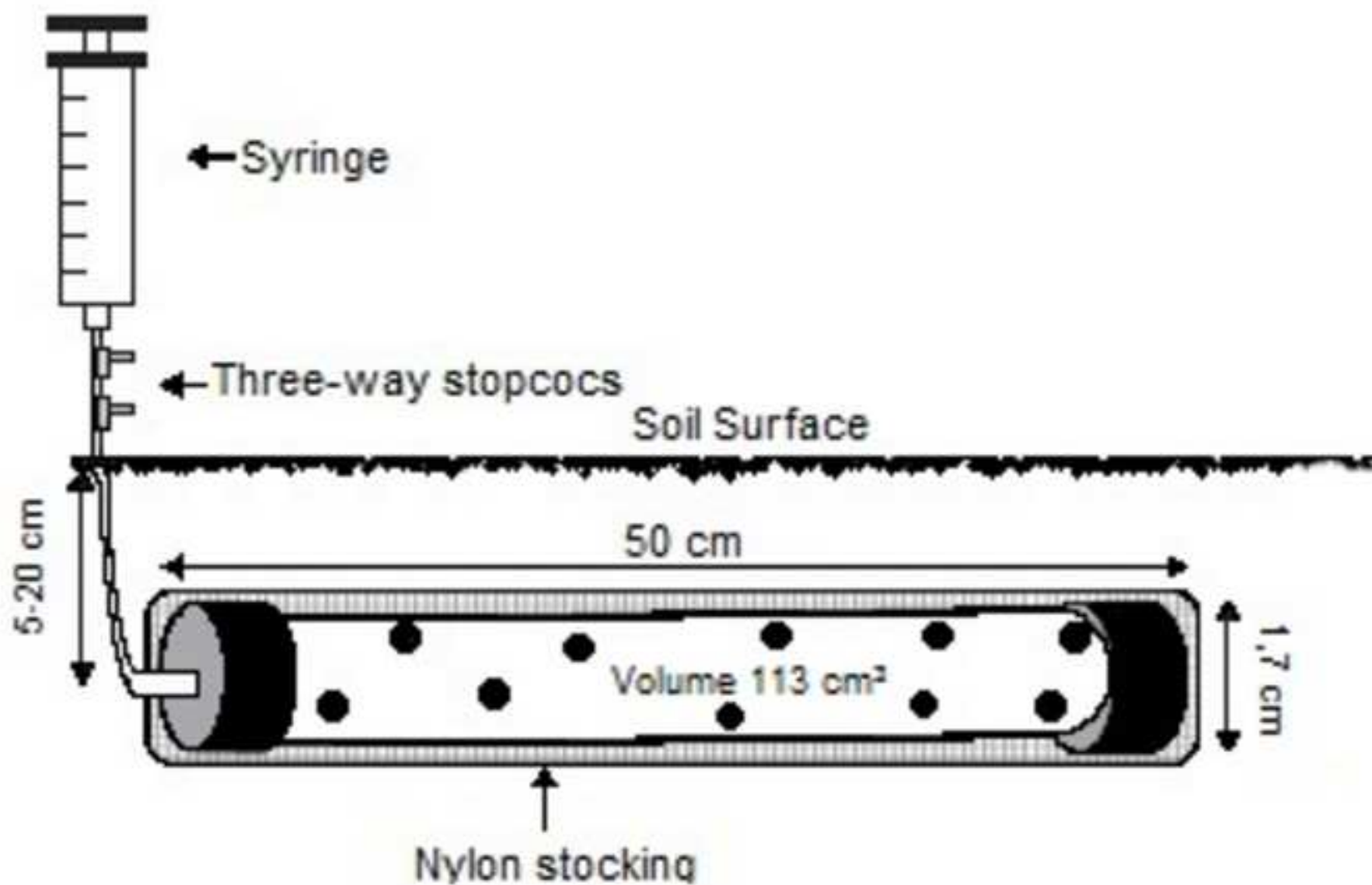


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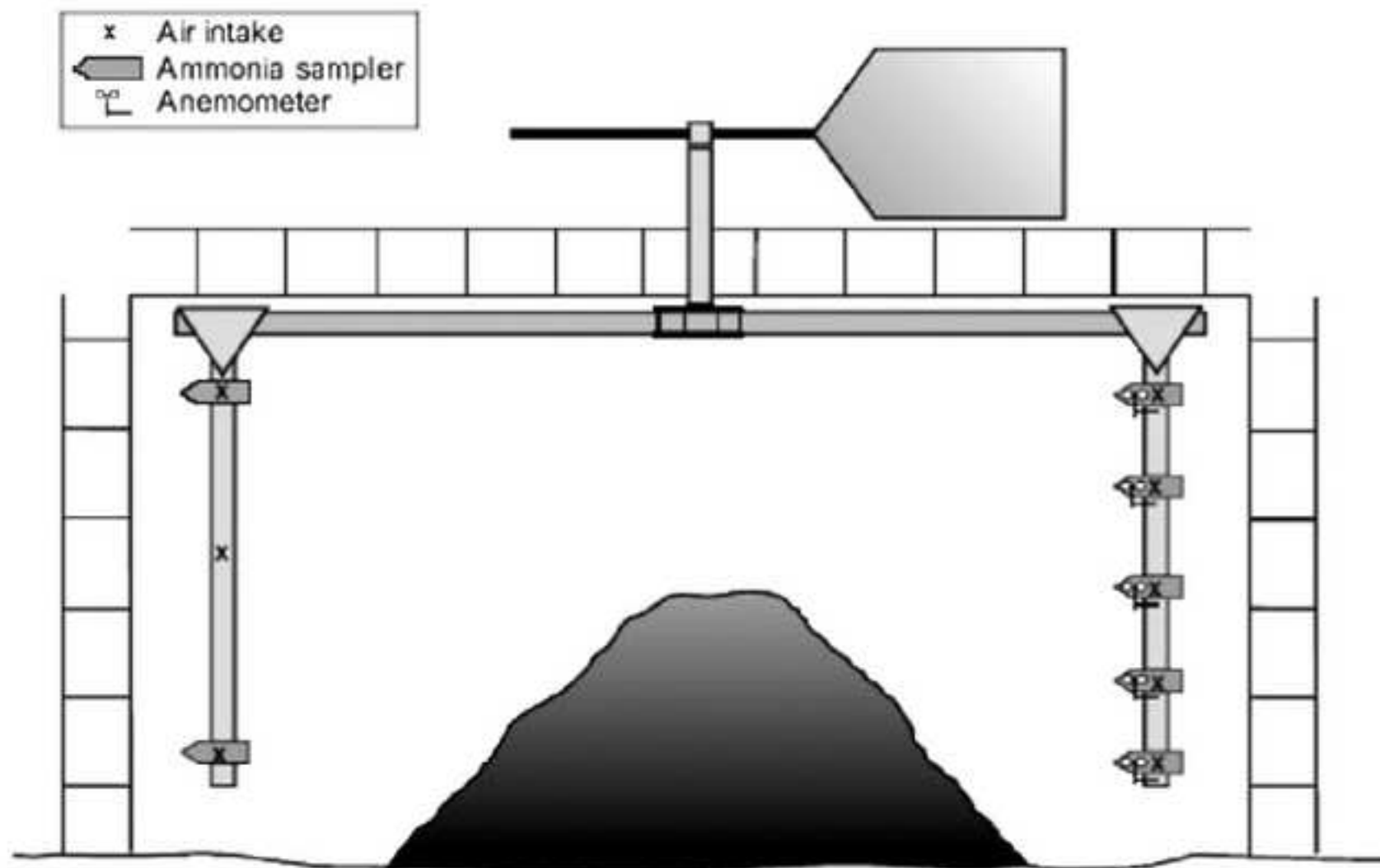


Table 1

GHG	Conditions	Temperature phase, where released GHG is the highest	Potential pathway of formation in pile	GHG emission factor [16]
Carbon dioxide (CO ₂)	Aerobic	Thermophilic	Decomposition by microbial activities The concentration is dependent on the nitrogen content of the biodegradable material. Pile mixing increases the concentration of released gas	1 (g CO ₂ eq/g CO ₂)
Methane (CH ₄)	Anaerobic	Thermophilic	Decomposition by microbial activities in the middle of the pile. Pile mixing disturbs function of methanotropic bacteria, increases concentration of released gas.	23 (g CO ₂ eq/g CH ₄)
Dinitrogen oxide (N ₂ O)	Anaerobic and aerobic	Mesophilic and maturation	Denitrification by N ₂ O-forming microbes Gas emission from sides of pile, where temperature is lower.	296 (g CO ₂ eq/g N ₂ O)

Table 1. Specific greenhouse gases present in emissions from storage of forest chips and their characteristics.

Table 2

Emission measurement method	Advantage	Disadvantage
Closed chamber	Easy and fast method Can be placed at different locations Many samples possible Can be connect to on-line gas analyser	External pile measurements only Difficult to install on sloping surface Difficult to install on frozen piles Requires disturbance of pile Snow cover can produce errors in the result Provides no information about convection inside pile Air mixing are needed before sampling
Gradient	Easy and fast method Can be placed at different locations Many samples possible Can be placed inside the pile Can be connect to on-line gas analyser Installation does not give errors for measurement results	Moisture can cause problems by disturbing pile porosity and gas flow Material should be homogenous in composition
Integrated horizontal flux	Is suitable spatially in homogenous locations and on sloping surfaces Can be connect to on-line gas analyser Emissions can be measure at different location on pile	Cannot detected the formation GHG emissions inside forest chips pile Measurement results may varies a lot without on-line systems Requires longer installation times

Table 2. The advantages and disadvantages of discussed greenhouse gas emission measurement methods

Table 3

<i>Substrate</i>	<i>Analyses method</i>	<i>GHG results</i> [kg t ⁻¹]			<i>Additional information</i>
		CO ₂	CH ₄	N ₂ O	
a) Anaerobically digested pig solid slurry heap[27]	Gradient	30,0	1,6	0,65	uncover heap, initial ww ¹ , cumulative
		2,2	0,2	0,005	cover heap, initial ww ¹ , cumulative
b) Solid dairy manure composting pile[34]	Chamber/ online	586 ± 24	21 ± 1,5	0,011 ± 0,0052	In start, degraded VS ²
		336 ± 4	1,6 ± 0,1	0,019 ± 0,001	mixed, sampled during days 11-23, degraded VS ²
		331 ± 23	0,3 ± 0,04	0,023 ± 0,005	non-mixed, sampled during days 11-23, degraded VS ²
		600 ± 88	0,1 ± 0,1	0,874 ± 0,151	mixed, in the end, degraded VS ²
		404 ± 11	0,9 ± 0,3	0,06 ± 0,007	non-mixed, in the end, degraded VS ²
c) Home composting unit[39]	Chamber/ online	252	4,2	0,45	mixed, every week
		177	0,4	0,30	non-mixed

¹ww, wet weight ²VS, Volatile Solids
a) heap size: ~6500 kg, h=1,5 m, d=4,8m; storage time: 4 months
b) pile size: 1200 kg, h =1,2 m, d=1,4m; storage time: 80 days
c) unit size: 0,32 m³, h=95 cm, d=48cm / 105 cm; storage time: (three phases) 2 months, 1 year and 3 months

Table 3. GHG emissions data from different composting studies, in which chamber and gradient measurement methods are used.