



## Research Paper

# Extensive study on biogas trace compounds from agricultural and municipal biomass residues for downstream catalytic conversion

Selina Nieß<sup>a,\*</sup>, Mathias Stur<sup>a</sup>, Ute Mikow<sup>b</sup>, Marcel Pohl<sup>a</sup>, Marco Klemm<sup>a,c</sup>

<sup>a</sup> DBFZ - Deutsches Biomasseforschungszentrum gGmbH (German Biomass Research Center), Torgauer Straße 116, 04347 Leipzig, Germany

<sup>b</sup> INC Leipzig, Permoserstraße 15, 04318 Leipzig, Germany

<sup>c</sup> Cooperative State University of Saxony, Staatliche Studienakademie Glauchau, Kopernikusstraße 51, 08371 Glauchau, Germany



## ABSTRACT

This study used quantitative biogas measurements from four full-scale biogas plants to determine which trace components can be expected in biogas from biogenic agricultural or municipal residues. The objective was to identify trace compounds that could damage the catalyst when biogas is used as a feedstock for a catalytic conversion. Knowing the exact composition of the biogas, including for example all sulfur-containing molecules, is therefore essential for the process's operational expenditures (OPEX). The results of this investigation add to a database of fully measured biogases and can be used to select suitable biogas purification steps. Trace compounds found in all measured biogas samples were ethanol, acetone, toluene, alpha-pinene and 3-methylfuran. However, biogases from different substrates contain distinctive trace components. The biogas from organic waste shows the highest amount of S-containing molecules (up to 14.7 ppm in total), while the biogas from wastewater sludge shows higher amounts of siloxanes (50 mg m<sup>-3</sup>STP) and the biogases from agricultural waste contain oxygenates like acetone and 2-butanone. Measurements taken at various points along the process chain indicate that activated carbon is sufficient for removing most of the trace components from biogas. However, it was observed in one plant that the activated carbon must be replaced before it reaches its adsorption limit to avoid the desorption of volatile organic compounds. Biogas or the biogenic CO<sub>2</sub> are well-suited to be used in downstream processes, but analytical monitoring of the biogas composition and a suitable connection between plant and downstream process are required.

## 1. Introduction

The political goal of the European Green Deal of largely or completely eliminating the use of fossil carbon sources to reach net carbon neutrality in the European Union by 2050 requires specific solutions for the supply of carbon to the chemical industry and the transport sector (Fetting, 2020). To make these carbon-based products more sustainable, it is necessary to use the renewable carbon sources biomass, CO<sub>2</sub> from the air and CO<sub>2</sub> from the exhaust gases of conversion processes (Gabrielli et al., 2020). Among these sources, biomass is the carbon source of choice to produce bioenergy, bio-based products and fuels.

Anaerobic digestion (AD) generates renewable energy and is also a sustainable waste management practice with low energy demand (Atelge et al., 2021). The produced methane (CH<sub>4</sub>) can be used in heat and power production or as fuel in the transport sector, and the remaining digestate can be processed into a fertilizer and soil improver (Carchesio et al., 2014). In this way, AD makes a double contribution to the circular economy. To avoid competition with food and feed supply, residual biomass should be used as source. Suitable waste biomass can

vary from region to region and is divided into two categories: urban biomass, such as biowaste, green waste, and sewage sludge; and agricultural biomass, such as livestock manure and straw.

The biogas produced in the AD process contains a mixture of CH<sub>4</sub>, CO<sub>2</sub>, water vapor and various trace compounds. Untreated biogas is water-saturated and contains 5–10 % of water, which is usually removed by water traps before the biogas is further used. (Ryckebosch et al., 2011). Biogases may also contain nitrogen (N<sub>2</sub>) and O<sub>2</sub> up to 10 vol% (Pera et al., 2024). These do not originate from the decomposition of biomass, but are introduced by the addition of air in the fermenter for coarse desulfurization. Impurities in biogas can include traces of hydrogen (H<sub>2</sub>), hydrogen sulfide (H<sub>2</sub>S), ammonia (NH<sub>3</sub>) and siloxanes, as well as various volatile organic compounds (VOCs), including alcohols, ketones, aromatic and cyclic compounds, and other hydrocarbons (Randazzo et al., 2022). The concentration of these trace compounds is usually in the ppm or ppb range (Pera et al., 2024). However, these small concentrations could negatively impact subsequent gas processing steps, especially in the case of siloxanes and sulfur-containing molecules, and must be removed beforehand. Concentrations of siloxanes are in the range of mg m<sup>-3</sup>, but they can damage system components by oxidizing

\* Corresponding author at: DBFZ - Deutsches Biomasseforschungszentrum gGmbH, Torgauer Straße 116, 04347 Leipzig, Germany.

E-mail addresses: [selina.niess@dbfz.de](mailto:selina.niess@dbfz.de) (S. Nieß), [mathias.stur@dbfz.de](mailto:mathias.stur@dbfz.de) (M. Stur), [mikow@inc-leipzig.de](mailto:mikow@inc-leipzig.de) (U. Mikow), [marcel.pohl@dbfz.de](mailto:marcel.pohl@dbfz.de) (M. Pohl), [marco.klemm@dbfz.de](mailto:marco.klemm@dbfz.de), [marco.klemm@dhsn.de](mailto:marco.klemm@dhsn.de) (M. Klemm).

<https://doi.org/10.1016/j.wasman.2025.115330>

Received 16 October 2025; Received in revised form 17 December 2025; Accepted 30 December 2025

Available online 6 January 2026

0956-053X/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

to SiO<sub>2</sub> on hot surfaces (Shen et al., 2018). Such deposits shorten equipment life and increase maintenance costs. If the biogas is to be further processed in a catalytic process, siloxanes must also be removed to prevent fouling of the catalyst (Calbry-Muzyka et al., 2022). Furthermore, sulfur-containing molecules are known to be catalyst poisons. The strong adsorption of sulfur on transition metals blocks the active sites of the catalysts and the adsorption of other reactants is either prevented or modified (Rasi et al., 2011). Another catalyst poison found in biogas is NH<sub>3</sub>, which poisons acidic solids, such as silica-alumina and zeolites that act as support materials (Bartholomew, 2001). Catalysts are necessary for converting the CO<sub>2</sub> in biogas and mobilizing this second stream of biogenic carbon, in addition to the CH<sub>4</sub> in biogas. Since it has no calorific value, biomass-derived CO<sub>2</sub> is currently a largely unused gas and could be a useful feedstock in the future to produce chemicals including urea, pharmaceuticals and fuels (Cordova et al., 2023; Gulzar et al., 2020). It is of particular interest, as it is bio-based, produced continuously and in high concentrations. Additional benefits such as negative CO<sub>2</sub> balances are also possible (Jafri et al., 2022). The following catalytic processes are currently being investigated for the use of biogas without prior separation of CO<sub>2</sub> and CH<sub>4</sub>: biogas methanation (Han et al., 2022; Hillestad, 2022; Zhang et al., 2022), biogas reforming (Ha et al., 2022; Yin et al., 2020), and oxidative coupling of methane to ethane (Penteado et al., 2021; Penteado et al., 2018).

With further by-products like digestate, AD can be the center of a biorefinery concept, where multiple products are obtained from biomass. Biogas plants as a potential source of CO<sub>2</sub> are widespread in Germany and many other countries. According to an article from 2023, there are about 9,500 biogas plants in Germany (Thran et al., 2023). If the CO<sub>2</sub> was captured, a potential of more than 10.4 Mt CO<sub>2</sub> would be available (Billig et al., 2019). In order to use biogas in a catalytic process, it is necessary to know what trace components are present in the gas. Gas cleaning can then be tailored to these interfering by-products to protect the catalyst and achieve long catalyst life. However, there are only few studies that published exact trace components and their concentrations found in biogases (Rasi et al., 2011).

The aim of this work is to clarify the quantitative composition of specific biogases from residual and waste biomass through a measurement campaign to identify harmful trace components for a downstream catalytic conversion. These are especially H<sub>2</sub>S and organic sulfur, which poison the active metals of common catalysts but also siloxanes and VOCs, which may harm system components (Calbry-Muzyka et al., 2019). This is an essential investigation at the beginning of the Pilot-SBG (Pilot plant for Synthesized Biogas) project, for which this work was carried out. In this project, a biorefinery pilot plant was commissioned in 2024 in Leipzig, Germany, in which biomass is fermented to biogas, whose contents in CO<sub>2</sub> are subsequently catalytically converted to methane to be used as a fuel. The selection of biogas plants for the measurement campaign was based on their substrates. As a foundation for experimental design, plants were selected that use urban or agricultural residues that will also be used in the pilot plant. All four plants are located in Germany. The novelty of this study is the application-oriented measurement of biogas, where measurements were taken at various points in the process chain, from raw biogas to purified biogas. In addition, the comparison of biogas measurements along the process chain is used to evaluate the quality of the biological desulfurization and activated carbon cleaning processes. Today, there are very few studies in which the composition of biogas, including trace substances, has been measured in such detail. The present work is therefore intended to contribute to the validation of the values already obtained and to expand the available data base. This knowledge is considered indispensable for known and future CO<sub>2</sub>-utilization processes in biorefinery concepts.

## 2. Materials and methods

### 2.1. Biogas plants setup

The percentage of the substrate composition in each plant is given in the following sections. The four plants are numbered consecutively and are labeled “U” for using urban biomass or “A” for using agricultural biomass.

The substrates for Plant U1 are organic waste and green cuttings (Fig. 1) and Plant U2 is a wastewater treatment plant (Fig. 2). In the Pilot-SBG project, cattle manure and straw are in use as agricultural substrates, which is not yet common practice. Therefore, the two identically constructed plants Plant A3 and Plant A4 with their substrate mixtures of different agricultural residues (Fig. 3) serve as a comparison. The three figures of the process chains also show the sampling points. They are labeled with consecutive numbers along the process chain.

#### 2.1.1. Plant U1

In Plant U1, a substrate mixture of 90 wt% organic waste, 8 wt% green cuttings and 2 wt% grain husks was used as substrate. The pre-treatment of the input material consists of a disintegration, magnetic separation and star screen-assisted sieving. The biomass is then anaerobically digested in a dry fermentation process in two parallel plug flow reactors as the main digesters. Thermophilic operation is provided by jacket heating. In the next step, the digestate from the main digester stage is separated and divided into a solid phase, which is transferred to a post-composting unit and a liquid phase, which is further separated. Finally, the liquid portion of the digestate is fed into two digestate storage tanks. The biogas produced in the two main digesters and in the two digestate storage tanks is fed into a reactor for external biological desulfurization. By adding atmospheric O<sub>2</sub> via 30 m<sup>3</sup> h<sup>-1</sup> air injection, the H<sub>2</sub>S content is metabolized and reduced by microorganisms as a coarse filter stage. To support metabolism, nitrogen, phosphorus and potassium fertilizers are added as nutrients for the microorganisms. After biological desulfurization, the gas is passed through an activated carbon filter that specializes in removing H<sub>2</sub>S and other S-containing molecules such as sulfur dioxide, disulfides, mercaptans and thiols. However, at the time of the measurement, the activated carbon filter had been in use for over a year and needed replacement. Before further use, the biogas is indirectly dehumidified by a gas cooling system, leaving the digestate storage tanks at a temperature ranging from 30 to 10 °C. The purified biogas is used on-site in two combined heat and power (CHP) units to produce electricity and heat. During the campaign, accessible sampling points were located directly after the digester, before and after the external biological desulfurization, and after the activated carbon filter (Fig. 1).

#### 2.1.2. Plant U2

At Plant U2, 100 wt% wastewater is first mechanically cleaned in a wastewater treatment plant with coarse screens, fine screens, grit traps and grit washers, followed by conventional wastewater treatment in several process stages. The resulting sewage sludge is then anaerobically treated in an energy-efficient main digester to further degrade the organic content. Wall and floor heating and exterior wall insulation enable mesophilic operation. Part of the H<sub>2</sub>S in the sewage gas is removed by an external biological desulfurization system before the coarse-filtered sewage gas is finely filtered through an activated carbon that specializes in adsorbing siloxanes, VOCs and terpenes. The methane-containing sewage gas is used on-site in a CHP unit to feed electricity into the grid and in a boiler to extract heat, e.g. for heating the reactor. The accessible sampling points during the campaign were after the external biological desulfurization process and after the activated carbon filter (Fig. 2).

#### 2.1.3. Plant A3 and Plant A4

These two plants are identical in design and use typical agricultural

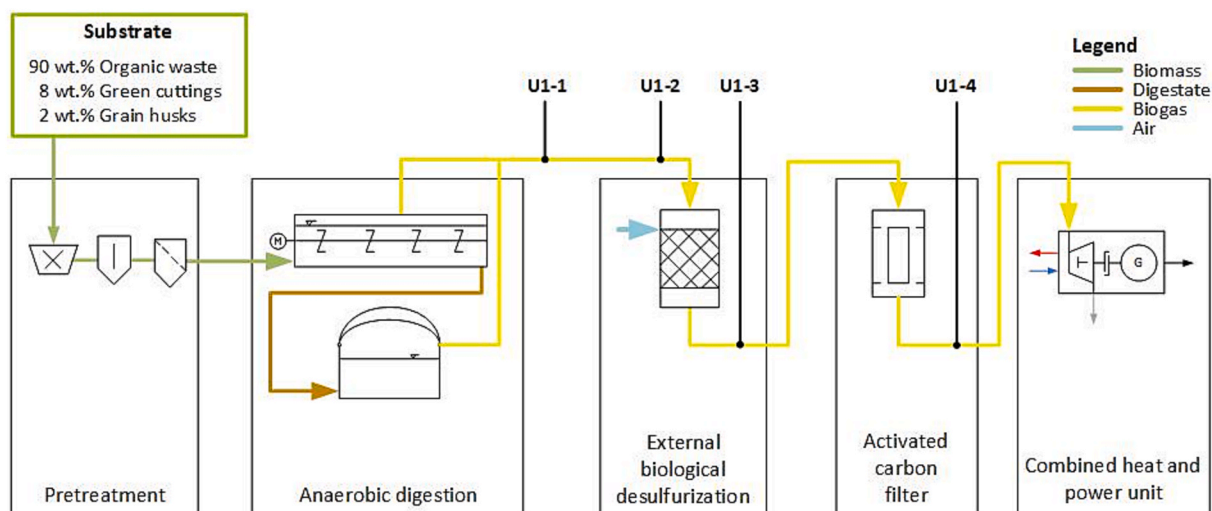


Fig. 1. Process diagram of Plant U1 using a mixture of organic waste, green cuttings and grain husks as substrates for anaerobic digestion. U1-1 to U1-4 are the sampling points.

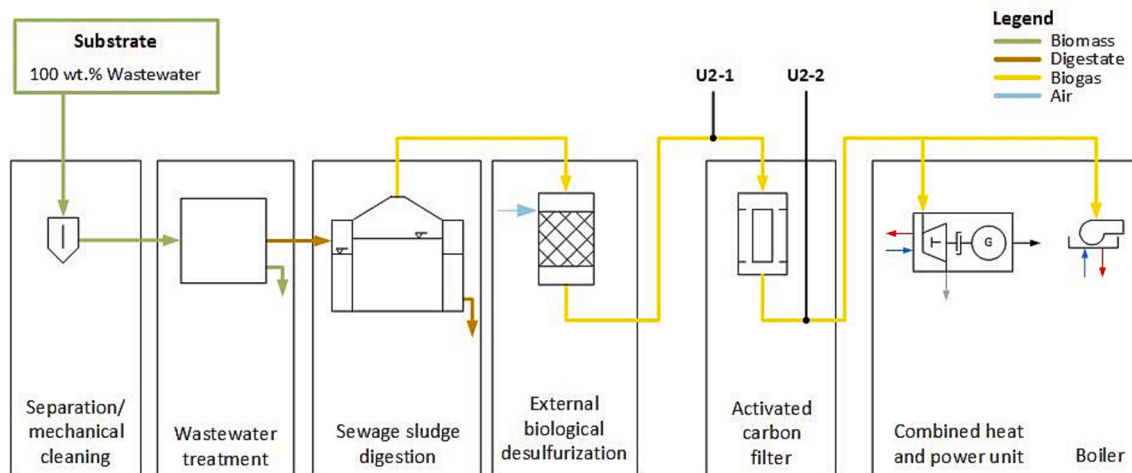


Fig. 2. Process diagram of Plant U2 setup using wastewater sludge as the substrate for the anaerobic digestion. U2-1 and U2-2 are the sampling points.

input materials. Plant A3 is operated with 49 wt% maize silage, 26 wt% whole-plant silage, 16 wt% wilted silage and 10 wt% stable manure. Plant A4 is fed with 55 wt% maize silage, 17 wt% dry chicken manure, 16 wt% turkey manure, 6 wt% wilted silage and 6 wt% whole-plant silage. The input materials are disintegrated, mixed in a silo and blended with additives. Each plant consists of a main digester, a post digester and two unheated digestate storages connected in series. The operating temperature is in the mesophilic range. Internal chemical coarse desulfurization is achieved by adding iron-containing additives to the fermentation medium and internal biological coarse desulfurization is achieved by adding air to the gas-carrying area inside the main digester and the post digester. The raw biogas produced is partially dehumidified in condensate shafts in the downstream pipeline periphery and finely desulfurized by an activated carbon filter specialized in the removal of  $\text{H}_2\text{S}$ . The energetic utilization of the purified biogas is carried out by a CHP unit to provide electricity. The accessible sampling points were downstream the second digester, before and after the activated carbon filter (Fig. 3).

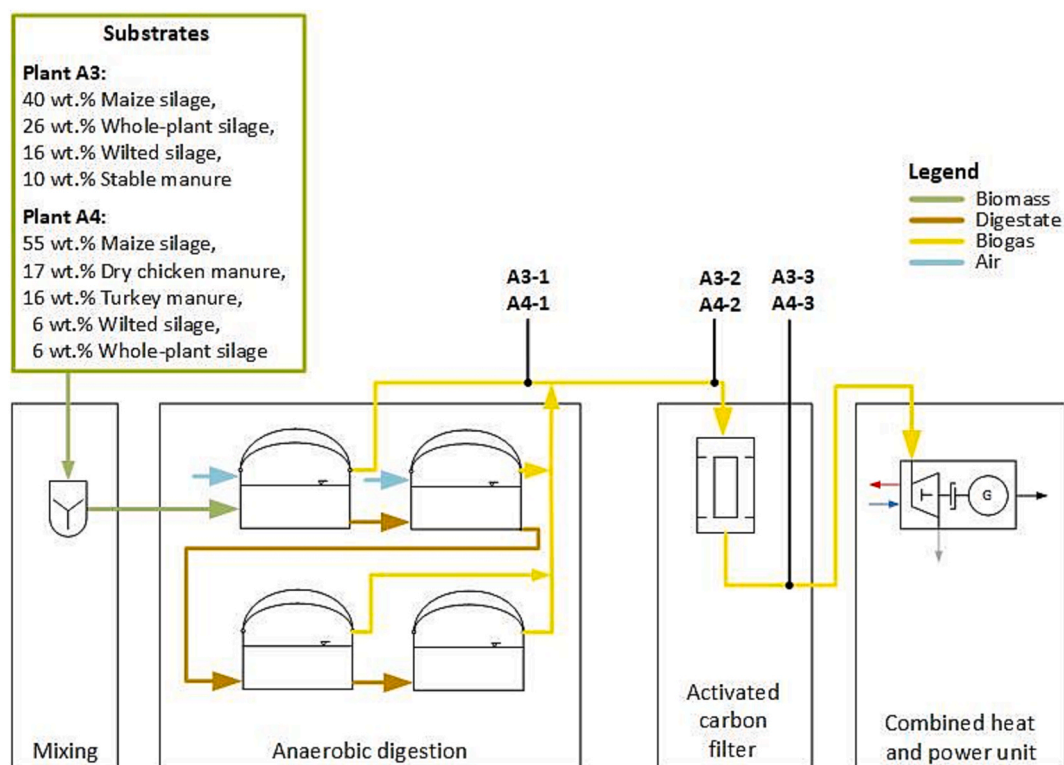
## 2.2. Measurement setup

During the sampling campaigns, biogas was collected from the pipes

of the biogas plants at suitable gas sampling points. The biogas was sampled with a flow rate of approximately  $40 \text{ l h}^{-1}$ . For the measurement of the main gas composition and the most common trace impurities ( $\text{N}_2$ ,  $\text{O}_2$ ,  $\text{H}_2$ ,  $\text{NH}_3$ ,  $\text{H}_2\text{S}$ , thiols and sulfides), gas was filled into portable 100 ml or 150 ml glass gas sampling tubes (DURAN® Borosilicate glass 3.3). The gas sampling tubes are fitted with two stopcocks and a septum in the center to allow gas extraction for measurements. Before sampling, the sampling tubes were filled with argon to avoid contamination with ambient air. During sampling, the biogas was passed through an empty wash bottle as a condensate trap to separate water from the gas prior to collection in the sampling tubes. For the determination of the other trace compounds (VOCs, siloxanes and organic sulfur), defined quantities of gas (18–120 l, see supplementary material), were passed through activated carbon tubes (Type G, Dräger). At the sampling points after biogas treatment, a higher amount of gas was passed through the activated carbon to better concentrate the secondary components. All measurements were performed off-line. The volumetric values of the results in  $\text{mg m}^{-3}$  refer to the standard condition according to DIN 1343 (DIN Deutsches Institut für Normierung e.V., 1990).

### 2.2.1. Measurements from gas sampling tubes

The main components  $\text{CH}_4$ ,  $\text{CO}_2$ ,  $\text{N}_2$  and  $\text{O}_2$  as well as  $\text{H}_2$  as trace



**Fig. 3.** Process diagram of the identically constructed plants Plant A3 and Plant A4 with different agricultural residues as substrates. A3-1 to A4-3 are the sampling points.

component were measured off-line with a gas chromatograph with thermal conductivity detector (GC-TCD, Chrompack CP 9001) from gas sampling tubes. The gas sample was taken on the day of sampling through the septum in the center of the gas sampling tube. A volume of 100  $\mu\text{l}$  was injected into the GC-TCD injector by using a gas-tight syringe. These measurements were determined in duplicate. As the two measurements did not show any major deviations in any case, no further measurements were carried out. GC-TCD measurements are normalized to 100 %.

Analysis and quantification of the main sulfur-containing trace compounds ( $\text{H}_2\text{S}$ , thiols and sulfides) and  $\text{NH}_3$  was carried out off-line using a gas chromatograph with flame photometric detector (GC-FPD, Agilent 6890 N) for sulfur compounds and with GC-TCD with sample loop (Agilent 490 Micro GC) for  $\text{NH}_3$ . From each of the gas sampling tubes, 500  $\mu\text{l}$  of gas was injected into the injectors of the GC-FPD. In cases where  $< 1$  ppm  $\text{H}_2\text{S}$  was present in the biogas, another measurement was performed with a 1000  $\mu\text{l}$  injection.

#### 2.2.2. Measurements from activated carbon tubes

The analysis of the adsorbed compounds was carried out one or two days after sampling according to the ASTM D3687–01 method. Meanwhile, the tubes were stored at room temperature. The main adsorption layer of the activated carbon tube was weighed into a 20 ml headspace vial, mixed with 2 ml dichloromethane, transferred to an autosampler of a headspace GC and shaken at 40 °C for 50 min. The liquid sample was then removed from the vial and analyzed by gas chromatography using flame ionization detector (FID) and mass spectrometry (MS) detection. The quantified trace components are calibrated against appropriate standards.

### 3. Results and Discussion

#### 3.1. Coarse gas composition measured via gas sampling tubes

The measurement results from the gas sampling tubes are discussed in the following sections. Table 1 summarizes the results of the measurements taken on the rawest biogas accessible, together with the gas composition after the final cleaning stage. The only exception is Plant U1, where it was not possible to obtain a representative gas sample after the activated carbon filter. Instead, the measurement after biological desulfurization is given in the table.

##### 3.1.1. $\text{CH}_4$ and $\text{CO}_2$

As expected, typical biogas compositions with  $\text{CH}_4 \geq 50$  vol% and  $\text{CO}_2 \leq 50$  vol% are measured at the first sampling points of all biogas plants. The highest methane content measured in the raw biogas was 60 vol% for the biogas from wastewater treatment (Plant U2). This is a typical methane content for biogas from wastewater, according to a study of biogas plants in North America (Lackey et al., 2015). Also, the measured values of  $\text{CH}_4$  and  $\text{CO}_2$  for the biogases from agricultural waste and wastewater are within the range given in a review article (Atelge et al., 2021). The methane content of the measured biogases is in the lower part of the given range (50–80 % for agricultural waste and 60–70 % for wastewater), while the  $\text{CO}_2$  content is in the upper part of the given range (19–50 % for agricultural waste and 19–40 % for wastewater) (Atelge et al., 2021). Since the plants are all different and the biogas samples could only be taken at different points in the process chain, it is difficult to directly compare the values between the different plants. A direct comparison is only possible for Plant A3 and Plant A4, which are identical in design, located at the same site, and have access to the same sample points (Fig. 3). The coarse composition of these two biogases does not differ much within the measurement uncertainty (Table 1). This may be due to the very similar biomass substrates. The substrates consist of the same plant silages in similar proportions and

**Table 1**

Composition of the main biogas components in vol% and the most abundant trace compounds in ppm contained in the most untreated and the most treated biogas accessible in the four biogas plants investigated (n.m. = not measured, < x.x = below detection limit).

Plant:	U1		U2		A3		A4	
Substrate:	Organic waste, Green cuttings, Grain husks		Wastewater sludge		Plant silages, Stable manure		Plant silages, Dry chicken manure, Turkey manure	
Sampling point:	U1-1	U1-3	U2-1	U2-2	A3-1	A3-3	A4-1	A4-3
CH <sub>4</sub> /vol%	57.4 ± 0.3	52.8 ± 0.3	60.0 ± 0.3	61.0 ± 0.3	50.0 ± 0.3	51.3 ± 0.3	51.9 ± 0.3	52.1 ± 0.3
CO <sub>2</sub> /vol%	41.5 ± 0.4	37.8 ± 0.4	37.1 ± 0.4	38.7 ± 0.4	45.6 ± 0.5	46.3 ± 0.5	46.2 ± 0.5	46.2 ± 0.5
N <sub>2</sub> /vol%	0.9 ± 0.2	8.0 ± 1.7	2.3 ± 0.5	0.3 ± 0.1	3.6 ± 0.8	1.9 ± 0.4	1.6 ± 0.3	1.3 ± 0.3
O <sub>2</sub> /vol%	0.2 ± 0.1	1.5 ± 0.7	0.5 ± 0.2	0.1 ± 0.1	0.8 ± 0.4	0.4 ± 0.2	0.3 ± 0.2	0.3 ± 0.2
H <sub>2</sub> /vol%	0.1 ± 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
H <sub>2</sub> S/ppm	185 ± 6	1 ± 1	< 1	< 1	96 ± 3	< 1	116 ± 3	< 1
DMS/ppm	15 ± 1	9 ± 1	< 1	< 1	< 1	< 1	< 1	< 1
NH <sub>3</sub> /ppm	n.m.	n.m.	n.m.	n.m.	151 ± 5	< 20	229 ± 7	< 20

differ mainly in the type and proportion of animal waste in the substrate mix. The higher proportion of manure in plant A4 appears to result only in a slightly higher proportion of H<sub>2</sub>S and NH<sub>3</sub> in the raw gas composition. It should be noted that the measurements are a snapshot in time and that there may be variations in biogas composition over time. Examining variation over time was not the focus of this study. However, for some plants, the coarse biogas composition was measured at two equivalent sampling points at two different times but on the same day, such as U1-1 and U1-2 (Fig. 1) and A4-1 and A4-2 (Fig. 3). In both cases, the same values of biogas composition were measured at the equivalent sampling points within the measurement uncertainty range (data available in the Supplementary material). Only the N<sub>2</sub> content differs slightly (< 0.7 vol%) between the measuring points U1-1 and U1-2. In general, there is a tendency for the two biogas plants with urban biomass (Plant U1 and U2) to achieve 1–10 vol% higher CH<sub>4</sub> contents in the cleaned biogas than Plant A3 and A4. Consequently, the two biogas plants with typical agricultural substrates achieve slightly higher CO<sub>2</sub> levels (8–9 vol%) than the urban biogas plants. This is due to the different biochemical compositions of the biomasses. Sewage sludge contains high amounts of protein and crude fat, which both lead to a CH<sub>4</sub>-rich biogas (Alves et al., 2009). Agricultural biomass is rich in crude fiber and carbohydrates, which contain a higher number of oxygen molecules within their chemical structures. The latter form a biogas with a 1:1 composition of CH<sub>4</sub> and CO<sub>2</sub> (Alves et al., 2009). These composition trends can be detected even in the digestates (Klöpffel et al., 2023). If CO<sub>2</sub> is used to produce bio-based products, it can be considered a renewable carbon source for further organic chemistry. In this case, a higher CO<sub>2</sub> content would not be a disadvantage.

### 3.1.2. Air components and H<sub>2</sub>

Air components such as N<sub>2</sub> or O<sub>2</sub> are rather atypical in biogas and mainly occur when air or pure O<sub>2</sub> is added to the digester for coarse desulfurization. This phenomenon is evident in the results from Plant U1. Both the raw biogas (at U1-1) and the biogas after a desulfurization stage with air addition (at U1-3) were accessible for sampling. In the raw biogas, the N<sub>2</sub> and O<sub>2</sub> contents are both < 1 vol%. After the external biological desulfurization step with air addition, the concentrations increase to 8.0 ± 1.7 vol% N<sub>2</sub> and 1.5 ± 0.7 vol% O<sub>2</sub>. In this case, the addition of air has a significant effect on the methane concentration in the product gas, which decreases by 4.6 ± 0.6 vol% compared to the raw biogas (Table 1). The result is a reduction in the calorific value of the biogas. A high N<sub>2</sub> content is also critical when separating CO<sub>2</sub> from methane for further synthesis into other products. Depending on the separation technology used, the N<sub>2</sub> remains in the CH<sub>4</sub> phase and reduces the heating value or purity of the CH<sub>4</sub>, or the N<sub>2</sub> passes into the CO<sub>2</sub> phase, which means the CO<sub>2</sub> may not be pure enough for certain syntheses or applications. Air is also added at Plant A3 and Plant A4, but the concentrations of N<sub>2</sub> and O<sub>2</sub> are not as high (max. 3.6 vol% N<sub>2</sub> and 0.8 vol% O<sub>2</sub>) as in the biogas of Plant U1. In the measurements after the activated carbon filters, there is a tendency for the N<sub>2</sub> and O<sub>2</sub> concentrations to decrease compared to the biogas further up

the process chain. A common reaction mechanism describes that oxygen is required for the oxidation of H<sub>2</sub>S to elemental sulfur during activated carbon desulfurization (Yang et al., 2023), which explains the observed O<sub>2</sub> decrease.

The detected H<sub>2</sub> content is negligible (≤ 0.1 vol%) in all measured biogases. In most cases, such as when biogas or CO<sub>2</sub> from biogas is to undergo further processing under hydrogenation conditions, the H<sub>2</sub> content in the feed stream is irrelevant.

### 3.1.3. Trace components H<sub>2</sub>S, dimethyl sulfide and NH<sub>3</sub>

In the gas samples of the sampling points with the most untreated biogas, H<sub>2</sub>S was detected in all biogases except the biogas from Plant U2. In Plant U2, the first accessible sampling point was after the biological coarse desulfurization, which is very effective, as the H<sub>2</sub>S content is below the detection limit and no dimethyl sulfide (DMS) could be detected. However, upstream of U2-1, a higher H<sub>2</sub>S content is expected in the raw biogas of the wastewater treatment plant, which can be around 1000 ppm according to literature (Rasi et al., 2011). In plants A3 and A4, coarse desulfurization with air has been carried out in the digester, which has already reduced the content of S-containing molecules at the first sampling points A3-1 and A4-1 (Fig. 3). As expected, the raw biogas from Plant U1 contains the highest levels of H<sub>2</sub>S and DMS, followed by Plant A4, Plant A3 and Plant U2. In the latter plant, no S-containing components were detected in the gas sampling tubes. DMS at levels above 1 ppm was detected only in the measured biogas samples from Plant U1, but not in any of the biogases from the other three plants. This might be due to an effective biological desulfurization in plants U2, A3 and A4, removing the DMS content from the raw biogas.

Only the agricultural biogas plants Plant A3 and Plant A4 were measured for NH<sub>3</sub>. In general, biogas can contain up to 1 % NH<sub>3</sub> (Ryckebosch et al., 2011). The NH<sub>3</sub> concentrations in the measured biogases were already significantly lower at 151 ± 5 ppm (A3) and 229 ± 7 ppm (A4). This may be due to the fact that NH<sub>3</sub> is also removed from the biogas in the biological desulfurization step (Ryckebosch et al., 2011).

Comparing the measured concentrations of the trace components H<sub>2</sub>S, DMS and NH<sub>3</sub> along the process chains, it is clear that the biogas cleaning technologies reduce the levels of all three components in all cases. In most cases even below the detection limit. The selected processes therefore appear to be particularly suitable for coarse desulfurization.

### 3.2. Trace components measured via activated carbon tubes

The trace components were measured at the same sampling points (Fig. 1 – Fig. 3) on the same day, but at a different time. Since another focus of this study was to quantify the suitability of activated carbon for biogas purification, Table 2 lists the concentration of trace components, grouped by chemical composition, present in the biogases before and after the activated carbon filter. Groups with concentrations < 1 mg m<sup>-3</sup> (mercaptanes, thiophenes, esters and aldehydes) were not included in

**Table 2**

Quantified trace components, grouped according to their chemical composition, from the biogas before and after the activated carbon filter of the four biogas plants investigated (< 0.1 = below detection limit).

Plant:	U1		U2		A3		A4	
Substrate:	Organic waste, Green cuttings, Grain husks		Wastewater sludge		Plant silages, Stable manure		Plant silages, Dry chicken manure, Turkey manure	
sampling point:	U1-3	U1-4	U2-1	U2-2	A3-2	A3-3	A4-2	A4-3
Alkyl sulfides <sup>a</sup> /ppm	9.6 ± 0.6	6.3 ± 0.4	0.1 ± 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Siloxanes <sup>b</sup> /mg m <sup>-3c</sup>	1.3 ± 0.1	0.7 ± 0.1	50.1 ± 2.6	0.1 ± 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Alcohols/mg m <sup>-3</sup>	1.7 ± 0.1	1.4 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	1.6 ± 0.1	1.9 ± 0.1	2.5 ± 0.1	1.4 ± 0.1
Ketones/mg m <sup>-3</sup>	88.7 ± 4.7	76.3 ± 4.0	1.5 ± 0.1	0.5 ± 0.1	3.0 ± 0.2	0.1 ± 0.1	31.6 ± 1.7	1.9 ± 0.1
Paraffin/mg m <sup>-3</sup>	0.5 ± 0.1	2.2 ± 0.1	4.7 ± 0.2	< 0.1	1.5 ± 0.1	0.4 ± 0.1	0.4 ± 0.1	0.2 ± 0.1
Aromatic/mg m <sup>-3</sup>	3.8 ± 0.2	32.4 ± 1.7	24.9 ± 1.3	0.1 ± 0.1	1.1 ± 0.1	0.1 ± 0.1	0.6 ± 0.1	< 0.1
Cyclic/mg m <sup>-3</sup>	22.9 ± 1.2	129.2 ± 6.8	8.2 ± 0.4	0.3 ± 0.1	1.0 ± 0.1	< 0.1	0.1 ± 0.1	0.1 ± 0.1

<sup>a</sup> Mono-, Di-, Tri- and Tetra-sulfides, <sup>b</sup> Including Trimethylsilanol, <sup>c</sup> all mg m<sup>-3</sup> refer to standard temperature and pressure.

the table. The concentration of the chemically grouped trace components in the first sampling points are shown in Fig. 4. The exact components measured and their individual concentrations can be found in the Supplementary material.

In general, the measurements show that almost all concentrations of the individual components in Plant U2, Plant A3 and Plant A4 have decreased after the activated carbon filter. This trend is also reflected in Table 2 for the chemically grouped compounds. On the other hand, in Plant U1, it was observed that certain substances, in particular large and cyclic or aromatic compounds, accumulated behind the activated carbon. In this case, this is due to the fact that the activated carbon has reached the end of its life and needs to be replaced, as confirmed by the operator. When activated carbon is used up, many of the biogas's secondary constituents have accumulated on the surface. Gas components with a high affinity can then displace adsorbed gas components with a lower affinity for the activated carbon, leading to desorption (Le-Minh et al., 2018). VOCs for example are mainly bound to activated carbon by physisorption. They can be displaced by chemisorption of S-containing molecules (Le-Minh et al., 2018), especially in the case of the activated carbon in Plant U1, which is specialized in H<sub>2</sub>S removal. These facts may explain why, in the case of Plant U1, there is a higher concentration of VOCs downstream of the carbon filter. In addition to the chemical groups listed in Table 2, internal measurement standards for halogenated compounds were used in the GC measurements. However, no halogenated compounds were detected in any of the gases. According to the literature, halogenated compounds can primarily be found in landfill gas, originating from refrigerants or degreasers. In biogas from source separated waste or agricultural residues, they are usually not expected (Li et al., 2019), unless the biomass was in contact with contaminated air

(Randazzo et al., 2022).

### 3.2.1. Sulfur-containing compounds

This section discusses all sulfur-containing compounds except H<sub>2</sub>S. Different mono-, di-, tri- and tetra sulfides, as well as thiophene and ethyl mercaptan were quantified in the measurements. For better comparability with Table 1 and other publications, the measured values have been converted to ppm. This makes it easy to compare the DMS concentrations measured by the carbon tubes with those measured by the gas sampling tubes in section 3.1. The results of the two different measurement methods were consistent with each other. DMS was detected at concentrations > 0.1 ppm only in Plant U1 with results between 2 – 13 ppm. Minor deviations are probably due to the time offset of the measurements. Only three S-containing molecules, DMS, thiophene and 2-methyl thiophene, could be detected in the two agricultural plants A3 and A4, where a coarse desulfurization by air dosing into the digester was already performed. All three molecules are present at very low concentrations of < 0.1 ppm at all sampling points (Fig. 3) in both plants. Thiophenes were also measured, but their concentrations were below 0.1 ppm at all sampling points, which is why they are not listed as a group in Table 2.

In Plant U2, only one S-containing compound, methyl propyl disulfide, could be quantified upstream of the activated carbon filter (at U2-1). This compound is present at a very low concentration of 0.1 ppm. After the activated carbon filter, no more sulfur compounds could be detected at this plant. However, it should be noted that the first measurement took place after biological desulfurization and therefore some S-containing components had already been removed from the raw biogas.

The highest amount of different sulfur compounds, up to 12 molecules, was quantified in the biogas from Plant U1. The most abundant are DMS and other alkyl mono sulfides, but the concentrations of all individual compounds were well below the concentration of H<sub>2</sub>S measured with the glass gas sampling tubes.

### 3.2.2. Siloxanes

Trimethylsilanol (TMS), two linear (L2 and L3) and four cyclic siloxanes (D3 to D6) were detected in the biogases of the four plants studied. It was noticeable that these compounds were found only in the plants using urban biomass, but not in the biogas plants using agricultural biomass as substrate. This is in line with expectations, as siloxanes are artificial molecules widely present in personal care products, which end up in wastewater sludge with their use (Genualdi et al., 2011). In the AD process, the volatile siloxanes end up in biogas (Shen et al., 2018). Siloxanes are not expected in biogases from agricultural biomass, because this type of biomass usually does not come into contact with personal care products. While the concentrations of all individual siloxanes detected in Plant U1 were ≤ 1.5 mg m<sup>-3</sup> STP, significantly higher concentrations of the individual siloxanes D4, D5 and D6 (up to 25.2 mg m<sup>-3</sup> STP) were measured at Plant U2 in front of the activated carbon filter (U2-1, Fig. 5). These cyclic siloxanes can be traced back to

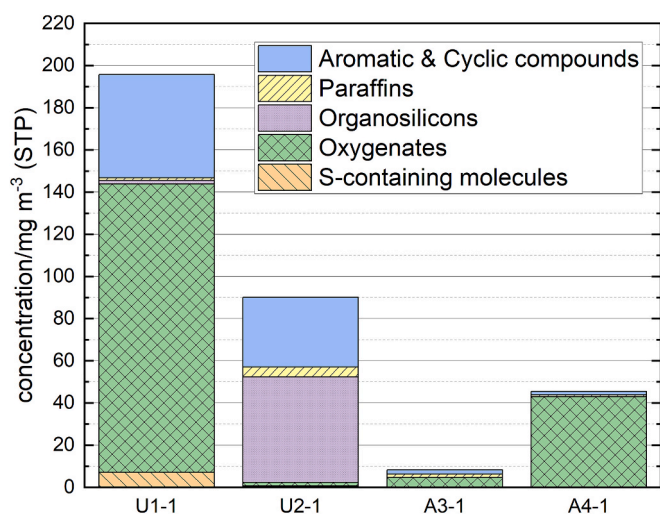


Fig. 4. Chemically grouped trace component compositions of the biogases measured at the first sampling points.

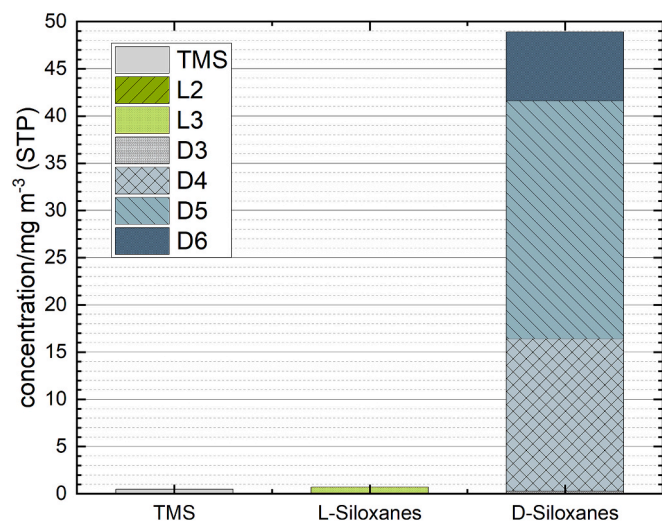


Fig. 5. Individual siloxane concentrations measured at sampling point U2-1.

personal care products, where D5 is dominantly used, followed by D6 and D4 (Genualdi et al., 2011). The linear siloxanes are less prevalent in biogas, because they tend to accumulate in the water phase (Shen et al., 2018). Downstream of the activated carbon, all siloxane concentrations were reduced to  $\leq 0.1 \text{ mg m}^{-3}$  STP in Plant U2 (Table 2). The activated carbon appears to adsorb both linear and cyclic siloxanes well. TMS was only detected in the biogas from wastewater at Plant U2 ( $0.5 \text{ mg m}^{-3}$  STP). While the trace concentrations of siloxanes may be easy to handle in small plants, they might cause a problem in large-scale plants. This is due to the greater volume of gas per unit of surface area, which could result in a faster deposition of silica on hot surfaces.

### 3.2.3. Oxygenates

Oxygenates, especially ketones and alcohols were detected in all biogases measured. With 15 different substances, most of the oxygenates could be quantified in the raw biogas from Plant U1. The highest concentrated substances ( $10.6 \pm 0.6 - 103.5 \pm 5.5 \text{ mg m}^{-3}$  STP) at sampling point U1-1 are 2-butanone, acetone and 2-butanol. 2-Butanone and acetone are also quantified after biological desulfurization at U1-3 ( $60.8 \pm 3.2 \text{ mg m}^{-3}$  STP and  $22.1 \pm 1.2 \text{ mg m}^{-3}$  STP) and after the activated carbon filter at U1-4 ( $56.6 \pm 3.0 \text{ mg m}^{-3}$  STP and  $14.0 \pm 0.7 \text{ mg m}^{-3}$  STP). They also belong to the oxygenates with the highest measured concentrations in the biogases from the first sampling points of Plants A3 and A4 ( $0.5 \pm 0.1 - 21.7 \pm 1.1 \text{ mg m}^{-3}$  STP). Ketones may cause problems in small systems that use seals, as they could corrode the seals. They are less critical in large-scale plants. In the plants with agricultural biomass, 11 different oxygenates were detected. All individual concentrations of the 11 compounds detected in Plant A3 are very low with  $\leq 1.4 \text{ mg m}^{-3}$  STP. In Plant U2, only five different oxygenates were detected. All of which are present at low concentrations (Table 2).

The only oxygenates found in all four biogases are acetone, ethanol, 2-propanol, and 2-methyl-3-pentanone. Although oxygenates are found in higher concentrations than sulfur-containing compounds or siloxanes, their presence in biogas is less critical. In general, oxygenates are not known to be problematic for high temperature processes or catalysts. However, they can interfere with gas cleaning processes by competing for adsorption sites and thus reducing the adsorption capacity of adsorbents for catalyst poisons (Calbry-Muzyka et al., 2022).

### 3.2.4. Paraffins, aromatic and cyclic compounds

These compounds do not play a major role in the biogases studied. The largest number of paraffins was detected in the biogas from Plant U2, but their individual concentrations were all  $\leq 1.8 \text{ mg m}^{-3}$  STP. After cleaning with the activated carbon filter, no more

paraffins could be quantified in the biogas of this plant. The activated carbon used for the removal of siloxanes seems to be a good adsorbent for hydrocarbons as well.

Among the aromatics detected are numerous terpenes. Since terpenes are corrosive (Gupta et al., 2023) to plastic parts, piping and seals, they should be removed from the biogas stream, e.g. by activated carbon filters. Aromatic and cyclic compounds were mainly detected in the two plants with urban biomass and do not seem to play a major role in biogases from agricultural residues. This is consistent with a study that statistically examined trace compounds in biogas and found that aromatics and hydrocarbons are formed primarily from substrates derived from household and industrial waste (Chin et al., 2020). In the raw biogas of Plant U1 (U1-1), p-cymene, limonene, alpha- and beta-pinene were particularly noticeable due to increased concentrations (up to  $13.6 \pm 0.7 \text{ mg m}^{-3}$  STP). In Plant U2, an increased content of toluene ( $23.8 \text{ mg m}^{-3}$  STP) was found at U2-1. Toluene, alpha-pinene and 3-methylfuran were detected in the biogases of all plants. These seem to be typical representatives of trace substances in biogases from different substrates. After the activated carbon filters, the measurements showed a significant reduction in aromatic and cyclic compounds. Only Plant U1 showed an increase in certain concentrations, especially of terpenes, as a result of the exhaustion of the carbon filter.

### 3.3. Discussion

The measured values of coarse gas composition and trace components are in the same ranges as those reported in the literature for similar substrates (Atege et al., 2021; Calbry-Muzyka et al., 2022; Pera et al., 2024). Most concentrations of the individual trace components were below  $30 \text{ mg m}^{-3}$  STP. Only specific oxygenates like 2-butanone showed higher concentrations of up to  $171 \pm 9 \text{ mg m}^{-3}$  STP in individual biogas samples. Most VOCs are not expected to harm the catalyst in a downstream catalytic conversion. However, it is possible that specific components like acetone could damage seals used in smaller plants. In the case of offline measurements, due to the low concentration of trace components, it cannot be guaranteed that all components in the biogas are actually measured. It is possible that certain biogas components cannot be detected using the selected gas chromatography methods, for instance due to their low volatility. In addition, there may be biogas components that do not adsorb on the activated carbon used to concentrate the secondary components and therefore were not collected during the measurement campaign. It is also possible that individual components cannot be solved by subsequent extraction and are therefore not detected. Nevertheless, this brief study can provide insight into what trace components may be expected in the biogas of the urban and agricultural residue substrates studied. The study shows that biogases from urban biomass contain more S- and Si-containing molecules than biogases from agricultural biomass. This makes the latter biogases interesting for further conversion, as these are the molecules in biogas, which pose the greatest risks for catalysts. Sulfur forms strong bonds with transition metals, which are used in heterogeneous catalysis and blocks them for reaction. Siloxanes, on the other hand, adsorb onto the support material, blocking pores and thus the access to active sites (Calbry-Muzyka et al., 2019). These compounds must be removed from the biogas, especially if the biogas or the separated  $\text{CO}_2$  is to be used in a downstream catalytic process. If the  $\text{CO}_2$  is separated, it is of particular interest which components would accumulate in the  $\text{CO}_2$  stream. This certainly depends on the separation method, but nothing more specific has been found in the current literature. Since the use of  $\text{CO}_2$  as a resource for the synthesis of chemicals and everyday products will become increasingly important in the future, this would be an interesting approach for further research. Depending on the purity of the  $\text{CO}_2$  separated from the biogas and the trace components present, the  $\text{CO}_2$  can be further processed in a suitable downstream process. For example, if  $\text{CO}_2$  is to be converted to methane with  $\text{H}_2$ , it is not necessary to remove residual  $\text{CH}_4$  or  $\text{H}_2$  from the biogas. On the other hand, it can be

difficult to economically produce food grade CO<sub>2</sub> with more than 99 % CO<sub>2</sub> purity from biomass, which adds many different trace compounds to the biogas. Coupling of a suitable biogas or CO<sub>2</sub> source with a suitable process is another interesting topic for further investigation. If the biogas or the CO<sub>2</sub> contained in the biogas is to be converted into other products, the addition of air to the fermenter should be avoided, as this will cause a high proportion of N<sub>2</sub> and O<sub>2</sub> to enter the biogas. These air components can only be removed with great difficulty. As the biogas measurements have shown that activated carbon is very suitable for desulfurization and siloxane removal, the coarse desulfurization stage might be omitted in these cases. In addition, activated carbon has been shown to remove VOCs, but these are desorbed again when the adsorption capacity of the activated carbon is reached, contaminating the biogas again. However, if biogas plants are to act as suppliers of biogas or CO<sub>2</sub> for synthesis purposes, on-line measurement of the biogas quality, including trace components, is required. This is the only way to ensure that the gas quality required for downstream processes is achieved. Until now, the analysis of trace components in biogas has been time-consuming and labor-intensive in the laboratory. Therefore, it would be useful to develop suitable on-line measurement techniques for the analysis of trace compounds in biogas.

#### 4. Conclusions

This is the first time that a measurement campaign has been carried out at several biogas plants measuring the actual biogas composition including trace components, at different points along the process chain. The most significant trace components were H<sub>2</sub>S (in the biogas from both agricultural biogas plants and in the biogas from organic waste), siloxanes (in the biogas from wastewater) and ketones such as 2-butanone and acetone, present in almost all measured biogas samples. Besides H<sub>2</sub>S, 14 other sulfur-containing molecules were detected, which can potentially harm transition metal-based catalysts. S-containing compounds and siloxanes were identified as the compounds most harmful to the catalytic conversion of biogas. With this measurement campaign, it was clearly shown that activated carbons are well suited to remove trace substances from biogas. The cleaned biogas is therefore suited for catalytic conversion. However, regular tracking of catalyst-harming components is recommended. Depending on the quality requirements for further processing or use, there are several utilization paths for CO<sub>2</sub>, CH<sub>4</sub> and biogas. In the case of CO<sub>2</sub> capture for biogas upgrading or further CO<sub>2</sub> utilization, it would be interesting to investigate in which gas stream (CO<sub>2</sub> or CH<sub>4</sub>) the respective trace components remain. To the best of our knowledge, this study is the first reliable report of trace gas concentrations along different sampling points of the process chain from full-scale AD plants. It therefore poses a valuable foundation for the planning of biogenic CO<sub>2</sub>-utilisation processes.

#### CRediT authorship contribution statement

**Selina Nieß:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Mathias Stur:** Writing – original draft. **Ute Mikow:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Marcel Pohl:** Writing – review & editing, Writing – original draft. **Marco Klemm:** Writing – review & editing, Writing – original draft, Supervision.

#### Declaration of competing interest

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

#### Acknowledgements

The authors would like to thank Ronny Neuenfeldt (DBFZ) for his

work during the measurement campaign and Rico Ehrentraut (DBFZ) for his good ideas for the graphical abstract. We would also like to thank the operators of the biogas plants who gave us the opportunity to carry out our measurement campaign. This publication was carried out on behalf of the Federal Ministry of Transport under file number G26/3552.1. The sole responsibility for the content lies with the author.

#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.wasman.2025.115330>.

#### Data availability

The data supporting this article have been included as part of the Supplementary material.

#### References

- Alves, M.M., Pereira, M.A., Sousa, D.Z., Cavaleiro, A.J., Picavet, M., Smidt, H., Stams, A. J.M., 2009. Waste lipids to energy: how to optimize methane production from long-chain fatty acids (LCFA). *J. Microbiol. Biotechnol.* 2, 538–550. <https://doi.org/10.1111/j.1751-7915.2009.00100.x>.
- Atelge, M.R., Senol, H., Djaafri, M., Hansu, T.A., Krisa, D., Atabani, A., Eskicioglu, C., Muratçobanoğlu, H., Unalan, S., Kalloum, S., Azbar, N., Kıvrak, H.D., 2021. A critical Overview of the State-of-the-Art Methods for Biogas Purification and Utilization Processes. *Sustainability* 13, 11515. <https://doi.org/10.3390/su132011515>.
- Bartholomew, C.H., 2001. Mechanism of catalyst deactivation. *Appl. Catal. A* 17–60.
- Billig, E., Decker, M., Benzinger, W., Ketelsen, F., Pfeifer, P., Peters, R., Stolten, D., Thrän, D., 2019. Non-fossil CO<sub>2</sub> recycling - the technical potential for the present and future utilization for fuels in Germany. *J. CO<sub>2</sub> Util.* 30, 130–141. <https://doi.org/10.1016/j.jcou.2019.01.012>.
- Calbry-Muzyka, A., Madi, H., Rüsich-Pfund, F., Gandiglio, M., Biollaz, S., 2022. Biogas composition from agricultural sources and organic fraction of municipal solid waste. *Renew. Energy* 181, 1000–1007. <https://doi.org/10.1016/j.renene.2021.09.100>.
- Calbry-Muzyka, A.S., Gantenbein, A., Schneebeli, J., Frei, A., Knorrp, A.J., Schildhauer, T.J., Biollaz, S.M., 2019. Deep removal of sulfur and trace organic compounds from biogas to protect a catalytic methanation reactor. *Chem. Eng. J.* 360, 577–590. <https://doi.org/10.1016/j.cej.2018.12.012>.
- Carchesio, M., Tatàno, F., Lancellotti, I., Taurino, R., Colombo, E., Barbieri, L., 2014. Comparison of biomethane production and digestate characterization for selected agricultural substrates in Italy. *Environ. Technol.* 35, 2212–2226. <https://doi.org/10.1080/09593330.2014.898701>.
- Chin, K.F., Wan, C., Li, Y., Alaimo, C.P., Green, P.G., Young, T.M., Kleeman, M.J., 2020. Statistical analysis of trace contaminants measured in biogas. *Sci. Total Environ.* 729, 138702. <https://doi.org/10.1016/j.scitotenv.2020.138702>.
- Cordova, S.S., Gustafsson, M., Eklund, M., Svensson, N., 2023. What should we do with CO from biogas upgrading? *J. CO<sub>2</sub> Util.* 77, 102607. <https://doi.org/10.1016/j.jcou.2023.102607>.
- DIN, n.d., Deutsches Institut für Normung e.V., January 1990. Reference conditions, normal conditions, normal volume: Concepts and values. Beuth Verlag GmbH, Berlin. <https://dx.doi.org/10.31030/2333155>.
- Fetting, C., 2020. *The European Green Deal. ESDN Report*.
- Gabrielli, P., Gazzani, M., Mazzotti, M., 2020. The Role of Carbon Capture and Utilization, Carbon Capture and Storage, and Biomass to Enable a Net-Zero-CO<sub>2</sub> Emissions Chemical Industry. *Ind. Eng. Chem. Res.* 59, 7033–7045. <https://doi.org/10.1021/acs.iecr.9b06579>.
- Genualdi, S., Harner, T., Cheng, Y., Macleod, M., Hansen, K.M., van Egmond, R., Shoeb, M., Lee, S.C., 2011. Global distribution of linear and cyclic volatile methyl siloxanes in air. *Environ. Sci. Technol.* 45, 3349–3354. <https://doi.org/10.1021/es200301j>.
- Gulzar, A., Gulzar, A., Ansari, M.B., He, F., Gai, S., Yang, P., 2020. Carbon dioxide utilization: a paradigm shift with CO<sub>2</sub> economy. *Chem. Eng. J. Adv.* 3, 100013. <https://doi.org/10.1016/j.cej.2020.100013>.
- Gupta, P., Kurien, C., Mittal, M., 2023. Biogas (a promising bioenergy source): a critical review on the potential of biogas as a sustainable energy source for gaseous fuelled spark ignition engines. *Int. J. Hydrog. Energy* 48, 7747–7769. <https://doi.org/10.1016/j.ijhydene.2022.11.195>.
- Ha, Q.L.M., Atia, H., Kreyenschulte, C., Lund, H., Bartling, S., Lisak, G., Wohlrab, S., Armbruster, U., 2022. Effects of modifier (Gd, Sc, La) addition on the stability of low Ni content catalyst for dry reforming of model biogas. *Fuel* 312, 122823. <https://doi.org/10.1016/j.fuel.2021.122823>.
- Han, D., Cho, W., Baek, Y., 2022. CO<sub>2</sub> Methanation of Biogas over Ni-Mg-Al: the Effects of Ni Content, Reduction Temperature, and Biogas Composition. *Catalysts* 12, 1054. <https://doi.org/10.3390/catal12091054>.
- Hillestad, M., 2022. Systematic generation of a once-through staged reactor design for direct methanation of biogas. *Chem. Eng. Process. - Process Intensif.* 181, 109112. <https://doi.org/10.1016/j.cep.2022.109112>.
- Jafri, Y., Ahlström, J.M., Furusjö, E., Harvey, S., Pettersson, K., Svensson, E., Wetterlund, E., 2022. Double yields and negative Emissions? Resource, climate and

- cost Efficiencies in Biofuels with Carbon Capture. Storage and Utilization. *Front. Energy Res.* 10, 797529. <https://doi.org/10.3389/fenrg.2022.797529>.
- Klöpffel, C., Herklotz, B., Biller, P., 2023. Influence of processing conditions and biochemical composition on the hydrothermal liquefaction of digested urban and agricultural wastes. *Fuel*. <https://doi.org/10.1016/j.fuel.2023.129016>.
- Lackey, J.C., Peppley, B., Champagne, P., Maier, A., 2015. Composition and uses of anaerobic digestion derived biogas from wastewater treatment facilities in North America. *Waste Manag. Res.* 33, 767–771. <https://doi.org/10.1177/0734242X15589781>.
- Le-Minh, N., Sivret, E.C., Shammay, A., Stuetz, R.M., 2018. Factors affecting the adsorption of gaseous environmental odors by activated carbon: a critical review. *Crit. Rev. Environ. Sci. Technol.* 48, 341–375. <https://doi.org/10.1080/10643389.2018.1460984>.
- Li, Y., Alaimo, C.P., Kim, M., Kado, N.Y., Peppers, J., Xue, J., Wan, C., Green, P.G., Zhang, R., Jenkins, B.M., Vogel, C.F.A., Wuertz, S., Young, T.M., Kleeman, M.J., 2019. Composition and Toxicity of Biogas Produced from Different Feedstocks in California. *Environ. Sci. Technol.* 53, 11569–11579. <https://doi.org/10.1021/acs.est.9b03003>.
- Penteado, A.T., Kim, M., Godini, H.R., Esche, E., Repke, J.-U., 2018. Techno-economic evaluation of a biogas-based oxidative coupling of methane process for ethylene production. *Front. Chem. Sci. Eng.* 12, 598–618. <https://doi.org/10.1007/s11705-018-1752-5>.
- Penteado, A.T., Lovato, G., Pérez Ortiz, A., Esche, E., Domingues Rodrigues, J.A., Godini, H.R., Orjuela, A., Gušča, J., Repke, J.-U., 2021. Economic potential of Bio-Ethylene Production via Oxidative Coupling of methane in Biogas from Anaerobic Digestion of Industrial Effluents. *Processes* 9, 1613. <https://doi.org/10.3390/pr9091613>.
- Pera, L., Gandiglio, M., Marocco, P., Pumiglia, D., Santarelli, M., 2024. Trace contaminants in biogas: Biomass sources, variability and implications for technology applications. *J. Environ. Chem. Eng.* 12, 114478. <https://doi.org/10.1016/j.jece.2024.114478>.
- Randazzo, A., Folino, A., Tassi, F., Tatàno, F., de Rosa, S., Gambioli, A., 2022. Volatile organic compounds from green waste anaerobic degradation at lab-scale: evolution and comparison with landfill gas. *Detritus* 63–74. <https://doi.org/10.31025/2611-4135/2022.15188>.
- Rasi, S., Läntelä, J., Rintala, J., 2011. Trace compounds affecting biogas energy utilisation – a review. *Energy Convers. Manag.* 52, 3369–3375. <https://doi.org/10.1016/j.enconman.2011.07.005>.
- Ryckebosch, E., Drouillon, M., Vervaeren, H., 2011. Techniques for transformation of biogas to biomethane. *Biomass Bioenergy* 35, 1633–1645. <https://doi.org/10.1016/j.biombioe.2011.02.033>.
- Shen, M., Zhang, Y., Hu, D., Fan, J., Zeng, G., 2018. A review on removal of siloxanes from biogas: with a special focus on volatile methylsiloxanes. *Environ. Sci. Pollut. Res. Int.* 25, 30847–30862. <https://doi.org/10.1007/s11356-018-3000-4>.
- Thran, D., Deprie, K., Dotzauer, M., Kornatz, P., Nelles, M., Radtke, K.S., Schindler, H., 2023. The potential contribution of biogas to the security of gas supply in Germany. *Energy Sustain Soc* 13. <https://doi.org/10.1186/s13705-023-00389-1>.
- Yang, C., Wang, Y., Liang, M., Su, Z., Liu, X., Fan, H., Bandosz, T.J., 2023. Towards improving H<sub>2</sub>S catalytic oxidation on porous carbon materials at room temperature: a review of governing and influencing factors, recent advances, mechanisms and perspectives. *Appl. Catal. b: Environ.* 323, 122133. <https://doi.org/10.1016/j.apcatb.2022.122133>.
- Yin, W., Guilhaume, N., Schuurman, Y., 2020. Model biogas reforming over Ni-Rh/MgAl<sub>2</sub>O<sub>4</sub> catalyst. effect of gas impurities. *Chem. Eng. J.* 398, 125534. <https://doi.org/10.1016/j.cej.2020.125534>.
- Zhang, L., Ma, F., Zeng, Q., Peng, F., Hu, Q., Wu, K., Yang, Y., Lu, H., Liang, B., 2022. Direct Methanation of CO<sub>2</sub> in Biogas with Hydrogen from Water Electrolysis: the Catalyst and System Efficiency. *Energy Fuels* 36, 4416–4426. <https://doi.org/10.1021/acs.energyfuels.2c00437>.