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ORIGINAL ARTICLE

Biogas potential of organic waste onboard cruise ships — a yet untapped energy source

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Abstract
To tap the organic waste generated onboard cruise ships is a very promising approach to reduce their adverse impact on the maritime environment. Biogas produced by means of onboard anaerobic digestion offers a complementary energy source for ships' operation. This report comprises a detailed presentation of the results gained from comprehensive investigations on the gas yield from onboard substrates such as food waste, sewage sludge and screening solids. Each person onboard generates a total average of about 9 kg of organic waste per day. The performed analyses of substrates and anaerobic digestion tests revealed an accumulated methane yield of around 159 L per person per day. The anaerobic co-digestion of sewage sludge and food waste (50:50 VS) emerged as particularly effective and led to an increased biogas yield by 24%, compared to the mono-fermentation. In the best case, onboard biogas production can provide an energetic output of 82 W/P, on average covering 3.3 to 4.1% of the total energy demand of a cruise ship.

Keywords Anaerobic digestion · Biogas · Cruise ship · Food waste · Sewage sludge · Thermal energy

1 Introduction

In recent years, cruises have been very popular, and the industry has grown continuously for 20 years. As part of the globalisation, cruise ships have been spread over the whole world clustering in the most beautiful sites of the oceans. These include the most frequented regions, primarily the Caribbean and the Mediterranean [1]. The Cruise Liners International Association (CLIA) totals 19.1 million passengers for 2010 and records within 8 years growth about 50% to 28.5 million passengers in 2018 [1]. To meet this increasing demand, more and bigger cruise ships will be introduced within the next years; thus, for 2019, a total of 272 cruise ships were expected [1]. As a consequence of this growing sector, its environmental impact increased with the number of cruise ships and passengers, not sparing the most attractive and sensitive areas.

A recent study for the Baltic Sea from Wilewska-Bien et al. [2] shows that only limited information about the handling management of food waste and wastewater onboard passenger vessels is provided through websites of the shipping companies. In the last years, the increasing number of scientific publications on cruise ship-generated solid waste points out a rising interest [3]. Thus, Sanches et al. [3] provide a cross-disciplinary overview of the recent situation of solid waste from cruise ships. However, no detailed information on organic waste was given. Innovative approaches were pursued by Toneatti et al. [4]. These authors reported on the optimisation of waste management onboard cruise ships for glass, paper and cellulosic waste and the recovery of energy embedded in the unavoidable paper and cellulosic waste through the exploitation of the incinerator's exhaust flue gas or through syngas production [4]. Nevertheless, Vaneeckhaute and Fazli [5] presented in a case study the best management practices for ship-generated food waste and sewage in the region of the Baltic Sea. For wastewater, these practices consider the discharge to adequate port reception facilities (PRF) or an advanced treatment onboard. Noteworthy is the suggested

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handling of food waste as it comprises the shore-based conversion into biogas.

On shore, the anaerobic digestion (AD) technology used for biogas generation can be classified as mature because it has been extensively tested and applied over decades. In essence, any organic residual material is potentially suited as a substrate for biogas production. For instance, sewage sludge is converted to biogas in municipal sewage treatment plants, principally to sustain the internal energy supply. In the context of renewable energies, the production of biogas has also increased substantially in agriculture; thus, energy crops such as maize and organic residues from animal farms are used as substrates. However, in several European countries, food waste is also used as a substrate, especially in municipal wastewater treatment plants (WWTPs) when spare capacity permits co-digestion [6, 7]. In contrast, no implementation onboard vessels have been noted to date.

Cruise ships generate several tons of food waste every day. Sewage sludge and screening solids from the wastewater pretreatment further increase the organic residues. At present, the onboard management of organic residual materials only includes steps related to disposal. Prior to disposal, the food waste is shredded and homogenised. For final discharge to PRFs or incineration onboard, both food waste and sewage sludge require dewatering and drying to reduce the volume. The volume-reducing steps do not apply if the residues are legally disposed of at sea after shredding. This option is still used to a significant extent and is permitted within the legal framework of the international MARPOL convention (Annex V) [8]. For example, Carnival Corporation, the world's largest cruise company, disposed of 106,000 t of food waste at sea in 2015. This corresponds to 22% of the total waste generated onboard [9], confirming the findings of Strazza et al. [10]. The actual handling of ship-generated organic waste varies from ship to ship. Figure 1 illustrates possible paths and treatment steps of organic waste on modern cruise ships, considering the onboard WWTP. Vacuum piping systems are state of the art onboard and ensure sufficient mass transfer with minimal water demands. Both streams, organic waste and sewage are closely linked onboard. In particular, existing plants may have different or modified processes and procedures since cruise ships are equipped with different system solutions from different manufacturers and development stages. To exemplify, the Alaska Department of Environmental Conservation [11] assembled an overview of advanced wastewater treatment systems used on vessels in Alaska.

Currently, several cruise lines are aiming to increase the level of environmental protection on their ships. For instance, all new cruisers will come with "advanced wastewater treatment systems" [12], while the performance of these onboard systems does not reach state-of-the-art onshore treatment quality, yet. Improved environmental protection onboard can offer advantages if efficiency is increased, fossil fuels are substituted and organic as well as nutrient loads originating from waste streams are reduced. Anaerobic digestion as well as the associated biogas production and utilisation meet these criteria to a laudable extent. Until 2009, any use of fuel gases onboard ships was strictly forbidden or highly regulated, which prevented the onboard implementation of anaerobic technology. So far, biogas production onboard has not been considered as an available opportunity by shipbuilders or cruise lines. Now, with the approval of liquefied natural gas (LNG) as fuel and the introduction of gas-powered combustion engines onboard, it is possible to use gas as fuel [13]. This fact enables the application of anaerobic technology onboard to exploit a yet unused energy source. But, a specific legal classification for the onboard implementation of a biogas plant is not feasible, yet. To date, ship-specific feasibility studies have only been initiated in isolated cases, e.g. from Hudde and Orth (unpublished). To the best of the authors' knowledge, a comprehensive and fundamental investigation, which provides sufficient data on ship-generated biogas substrates, including corresponding biogas and energy potential, has not yet been carried out.

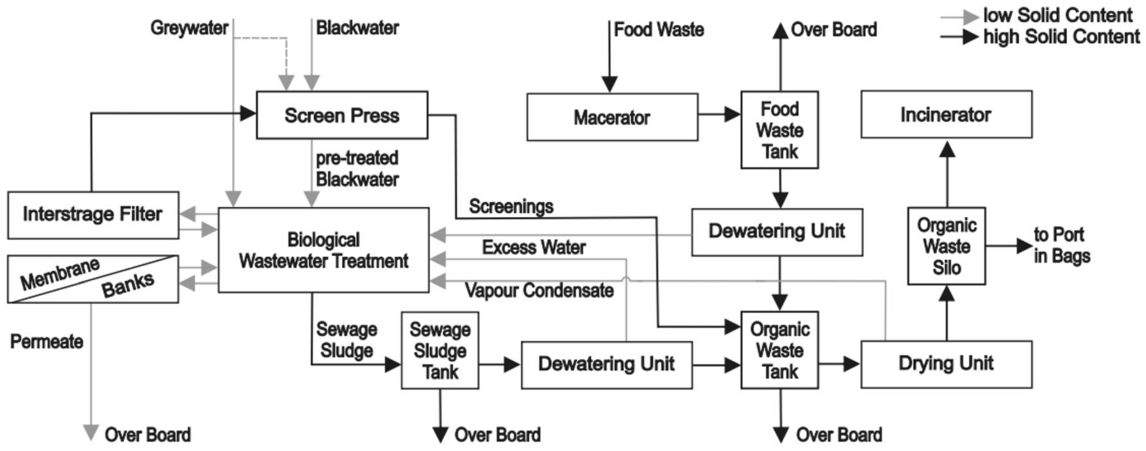


Fig. 1 Simplified illustration of the current handling of organic waste onboard modern cruise ships, considering the WWTP (dashed line: optional)

This paper gives first detailed insights of onboard accruing organic waste that can be valorised to biogas, focusing on food waste and sewage sludge. Besides quantification, a detailed characterisation of the substrates will be accomplished to provide sufficient information to derive potential energy yields and to design future adapted biogas plants onboard cruise ships. All results originate from the cooperative R&D project "**C**ruise **L**iners: **E**fficient onboard **A**naerobic digestio**N** of organic wastes for energy recovery" (CLEAN), which has been investigating anaerobic digestion technology onboard cruise ships since August 2017.

2 Materials and methods

For this analysis, existing knowledge on the occurrence and management of organic waste onboard cruise ships is summarised and combined. However, further information is needed to undertake a comprehensive investigation. Therefore, additional samples have been collected onboard and corresponding substrate characterisations have been conducted. Where ship-related data were not available in the literature or through our onboard investigations, previous studies focusing on land-based anaerobic digestion (AD) were deferred to. Data describing AD processes are highly abundant.

2.1 Literature review

The relevant literature was reviewed by focussing on topics such as "Waste and wastewater onboard cruise ships" and "Anaerobic (co-)digestion". As already noted, currently no anaerobic digestion plants exist onboard cruise ships; hence, there is a dearth of academic literature in this regard. However, there is one unpublished cruise ship–related feasibility study conducted by Hudde and Orth on behalf of a cruise line. Relevant sources in the context of cruise ships are limited to information on the quantities of organic waste streams. Only a few provide specific per capita data on food waste generation onboard, e.g. Wilewska-Bien et al. [14], Olson [15], EMSA [16], Strazza et al. [10] and Polglaze [17]. Sampling reports of four cruisers, created by the US Environmental Protection Agency, are the sole source for onboard accruing sewage sludge and screening solids [18–21].

No further studies appear to provide detailed data and information concerning the quantitative accumulation of sewage sludge or screening solids onboard. For that reason, a rough person-specific calculation of the expected amount of excess sludge (sewage sludge) from the WWTP onboard was carried out in accordance with the recent German design standard A131 [22] for single-stage activated sludge plants, including upstream denitrification. Köster et al. [23] provide data concerning wastewater composition onboard as a mix of grey and black water, which constitutes the basis for calculations of person-specific sewage sludge generation rates (Table 1). The considered wastewater temperature was 20 °C, which is the limit temperature for the guideline A131. Amounts of screening solids were derived, considering the expected removal efficiency of a screen press used onboard and the TSS load per capita per day (Table 1).

In addition to publicly accessible literature and data, comprehensive information on a cruise ship fleet was provided by a cruise line company. Besides piping and instrumentation diagrams of the waste and wastewater treatment for two ships, numbers of passenger and crew and data on sewage sludge and food waste generation were provided. Two cruise ship types were investigated with an occupancy ranging from 2500 to 5000 people, labelled as types A and B.

2.2 Selection and sampling of substrates

The CLEAN research project ensured access to different cruise ships, with sampling conducted on six dates on three cruise ships in total. Together with the crew, suitable sampling points were considered and selected. The samples included food waste (FW) separated by origin (passengers, crew, dewatered), sewage sludge (SS) from membrane-based wastewater treatment plants and screening solids from the mechanical wastewater pre-treatment. Depending on sample heterogeneity, the amount of substrate sampled rises to a maximum of 30 kg. Because of accessibility constraints in the engine room, only three sewage sludge samples and one sample of screening solids were taken. Furthermore, operational information was provided by the cruise line. FW was sampled manually in the different galleys. Thus, these samples represent direct leftovers and overproduced food, originating from the buffet-service for passengers and crew members. Following TUI Cruises & Futouris [26], this comprises already about 80% of the total onboard produced FW amounts. Sampling from the food waste collection tank which is part of the onboard vacuum disposal system was not operationally feasible during the period of data collection. For optimal sample conditioning, first, pre-homogenisation was carried out. Where sample analysis was not due to take place within the next 72 h, the relevant samples were stored at − 20 °C. Depending on the targeted laboratory procedure, the samples were homogenised through a regular commercial blender and/or a high-speed disperser (Ultra-Turrax) and diluted as required. Figure 2 shows three of the sampled substrates.

2.3 Data evaluation

2.3.1 Food waste

Detailed data on the filling level of the single food waste tank onboard a cruise ship for an evaluation period of 8 days were

Table 1 Wastewater pollutant load per person onboard cruise ships as a mixture of BW and GW (BW: black water, GW: grey water) as the basis for the calculation of the resulting amount of sewage sludge

Parameter	Unit	Wastewater mix (BW + GW); Köster et al. [23]	Screen press removal efficiency (%)
COD	g/(P·d)	350	35[a]
TSS	g/(P·d)	139	35[a]
NH_4-N	g/(P·d)	18.5	0
TN	g/(P·d)	24.5	8.6
TP	g/(P·d)	2.8	14[b]
Q	L/(P·d)	251	–

[a] Tchobanoglous et al. [24]; [b] Henze and Comeau Y. [25]

provided. First, a transformation into m^3 was conducted. Second, it was assumed that FW has a density of 1 kg/L, in accordance with US EPA [19]. Furthermore, the total amount of FW generated within the evaluation period was set to 100%. Thus, accruing FW is expressed in percentage of the total FW. The person-specific FW generation rates were derived, considering the actual number of persons onboard.

2.3.2 Sewage sludge

Data sets of five cruise liners were available, containing information on de-sludge amounts per day and corresponding total suspended solids (TSS) values of the bioreactor as part of the wastewater treatment plant onboard. These data enabled the calculation of sewage sludge (SS) amounts per capita per day, considering the actual number of persons onboard.

2.4 Laboratory analyses

The analyses undertaken for standard parameters are specified in Table 2.

Furthermore, four food waste samples were sent to an accredited service laboratory, LUFA Nord-West, to carry out proximate analysis. Under VO (EG) 152/2009 Annex III, the resulting parameters can be specified as dry mass, crude ash (CA), crude protein (CP), crude lipids (CL), and carbohydrates (CH) split into nitrogen-free extracts (NFE) and crude fibre (CF). Additionally, ultimate analyses (C, H, O, N, S) for five food waste samples were conducted by the accredited service laboratory AWV-Dr. Busse GmbH. Used methods were in accordance with the European standards: EN 15414-3:2007, EN 13137:2001 EN 15408:2011, EN 15407:2011, EN 15407:2011. Due to irregularities in two of five samples, an extra validation of the laboratory results has been conducted. For validation, the results of the proximate analysis were converted into its elementary composition by following the average elementary composition for the main components lipids, proteins and carbohydrates from Straka et al. [29]. Thus, the results of the proximate analysis served as validation reference.

Based on the elemental composition, the theoretical COD content ($COD_{theo.}$) of food waste was calculated in accordance with OECD Guideline 301, annexe IV [30]. By taking into account that 350 mL of methane are stoichiometrically obtained per gram of metabolised COD, the theoretical methane yield was derived.

2.5 Anaerobic digestion tests

Considering the German guideline VDI 4630 [31] and Holliger et al. [32], anaerobic lab-scale batch tests were carried out. These biochemical methane potential (BMP) tests were used for FW, SS and screening solids with a duration of up to 30 days at a temperature of 35 °C. Two types of BMP assays, volumetric (500 mL bottles) and manometric (1000 mL bottles) gas measurements, were used. Anaerobic sludge from the municipal wastewater treatment plant digester in Hanover-Herrenhausen (Germany) served as inoculum. Before applying, the inoculum was pre-incubated for 1 week. Every test run was carried out in triplicates and with an inoculum-substrate ratio of two, in terms of VS. To ensure anaerobic conditions, the head space of each bottle was flushed with nitrogen prior to incubation. Furthermore, blank assays with inoculum, but no positive controls were conducted. Positive controls in both test systems were performed once for validating, which showed a result deviation of 4%. While the used volumetric measured BMP test only revealed biogas results, the manometrically measured BMP test provided data on methane content by analysing the headspace with a gas

Fig. 2 Substrates onboard cruise ships: (left) food waste; (centre) dewatered food waste; (right) sewage sludge

Table 2 Analysed standard parameters, detection standards and methods

Parameter	Detection standard/method
Total solids (TS)	EN 12880:2001 [27]
Volatile solids (VS)	EN 15935:2012 [28]
pH value	inoLab - pH 7310 Set 2
Chemical oxygen demand (COD)	Cuvette tests Hach-Lange: LCK 514
Ammonium nitrogen (NH_4-N)	Cuvette tests Hach-Lange: LCK 303
Total nitrogen (TN)	Cuvette tests Hach-Lange: LCK 238

chromatograph (GC: Shimadzu GC-2014; column: Hayesep Q, mesh 80/100) at the end of each experiment. All results have been converted to dry gas under standard conditions (273.15 K; 1013 mbar).

2.6 Reference cruise ship

Besides determining person-specific details, an average reference cruise ship size with a total capacity of 3000 people onboard was chosen for this study. This allowed describing the ship's scale and quantifying the biogas and energy potentials. Moreover, the environmental impact of onboard-generated organic waste can be depicted. The chosen cruise ship size is based on the following data of the world's biggest cruise line company Carnival Corporation & plc [33]:

Passenger capacity:	232,000
Fleet size:	103
Ratio passenger/crew (estimated):	3:1
Passenger per cruise ship:	2250
Crew members per cruise ship:	750

Due to variations in passenger numbers and largely fix personnel, passenger-crew ratio varies typically from 2 to 4. Further deviations are caused by ship type and cruise company.

The mass balance for the reference cruise ship (Fig. 7) is based on the person-specific generation rates from Table 6, the biogas and methane yields from Table 8 and the COD substrate parameter based on volatile solids from Table 7. For screening solids, the COD content was derived according to the removal efficiency of the screen press in Table 1.

3 Results and discussion

3.1 Quantity and availability of substrates

The substrates available for biogas production introduced above are specified in terms of their volume and properties. For that purpose, information from the literature is pooled with the data collected for this study.

3.1.1 Food waste

Onboard FW can be classified into four categories: overproduction, plate leftovers, galley waste, and expired food. Regarding the generation of food waste (FW) onboard, significant differences can be revealed. Table 3 summarises the specific generation per person, and further breaking down per passenger and crew member, including specifications on the total and volatile solids. The analysis of a data set on food waste for 8 days on one specific cruise ship resulted in an amount of 1.365 kg on average per person per day. In contrast, literature references state higher rates from 1.4 to 3.5 kg FW per person per day (Table 3). Only Wilewska-Bien et al. [14] provided concrete data for the FW generation rate for crew members with 0.36 kg/(P·d), while passenger-related FW generation was estimated based on literature data. Design rates from the investigated ship operator range from 1.6 to 2 kg/(P·d). In view of a ratio of 3:1 for passengers and crew members, a general FW generation rate per person per day can be derived. Considering a FW production of 0.36 kg/(P·d) for crew member and 1.365 kg/(P·d) in general allows calculating a passenger FW rate of 1.7 kg/(P·d).

TS of the sampled FW for passengers and crew members was 22.9 wt.-% and 33.1 wt.-% and VS/TS accounted for 87.4% and 85.9%, respectively. Despite a dewatering step, no significant difference to passengers' FW can be declared for dewatered food waste. According to the ship operator, no water is added to the FW for further processing. The high solid content for crew FW is fully in line with findings of Wilewska-Bien et al. [14]. Sticking to the passenger:crew ratio, 93.4% of the total food waste is produced by passengers, while only 6.6% is assigned to crew members. Thus, crew FW plays only a minor part onboard cruise ships.

Figure 3 presents the daily variations of accruing FW during the evaluation period of 8 days onboard cruiser 2. Person-specific FW rates diverge − 20 to + 29% from the average while the trendline for accumulated FW develops linearly with an R^2 of 0.9971. Considering different day types like cruise, port and changeover days no consistent picture can be identified. The first 4 days included port stays with a duration of 7 to 11 h, with the lowest FW amount on day one. A high-FW day on day 5 (cruise) is followed by a below-average day (changeover), followed by a cruise day with an average FW generation. Sufficient storage volume of the actual food waste tank may compensate fluctuating FW amounts, since only 60% tank volume is used on average. Hence, a constant FW supply per day can be ensured.

Figure 4 shows 24-h trends of onboard-generated FW. Significant peaks are at breakfast (7:00–11:00) and dinner (20:00–23:00). Additionally, on cruise days and on the

Table 3 Person-specific generation rate of FW onboard cruise ships

Data source		Sampling			Dataset	Literature					
		3 cruisers types A & B			Cruiser 2 type B	Ship operator	Wilewska-Bien et al. [14]		Olson [15]	EMSA [16]	Toneatti et al. [4]
Parameter	Unit	Passenger	Crew	Dewatered	Person	Person	Passenger	Crew	Person	Passenger	Person
Data size	–	*n* =5	*n* =4	*n*=3	*n* =8 d	–	–	3	–	–	–
$g_{Substrate}$	$\frac{kg}{P \cdot d}$	–	–	–	1.365	1.6–2.0	2	0.36	1.4–2.4	≤3.5	2.0–2.4
Ø TS	wt.-%	22.9	33.1	23.2	–	10.0	–	29.1	–	–	20
Ø VS/TS	%	87.4	85.9	89.2	–	–	–	–	–	–	–

changeover day, peaks at lunch (13:00–16:00) can be identified. Minimal food waste amounts show up from 15:00 to 20:00 and 00:00 to 03:00. Due to a comprehensive food supply onboard, FW accrues throughout the whole day with periods of high and low volume. This may be caused by the preparation of mealtimes, FW disposal afterwards and FW of additionally operating snack bars.

A study on food waste reduction from TUI Cruises & Futouris [26] states that 51% of the FW is related to overproduction, while 29%, 18% and 2% are related to plate leftovers, galley waste and expired food, respectively. Here, food overproduction is the biggest issue to tackle. Food overproduction describes preventively prepared food that has not been consumed, e.g. in buffet-based restaurants and food that was prepared but remained in the galley. Proposals acquired within this report to reduce FW involve means like changing buffet equipment, changes in refill behaviour and open communication with passengers. As consequence, a reduction of 17.4% was achieved [26]. Reducing food waste onboard is only possible to a limited extent without disrupting the expected marine holiday atmosphere. A reduction of 17.4% would decrease the FW generation for passengers to 1.4 kg/(P·d) and save about 300 g food (waste) per day per passenger.

Regarding the hospitality sector onshore, a survey of ten restaurants in the UK reports an average FW generation of about 0.48 kg per served person ($n = 1247$ meals) [34]. Similar findings were also presented by Papargyropoulou et al. [35] for the hospitality sector in Malaysia where on average 0.53 kg FW per meal was produced. In this connection, a five-star hotel restaurant meant for tourists had the highest FW amount with more than 1 kg/customer. Transferring these outcomes to an onshore hotel resort with full board service that considers at least three meals per day per person, a specific FW production rate of about 1.5 kg/(P·d) can be derived. This result is similar to the calculated FW production rate onboard of 1.7 kg/(P·d). Therefore, it stands to reason that the hotel industry onshore and on cruise ships might generate similar amounts of FW per person.

Compared to common households ashore, FW generation onboard is significantly higher. Jörissen et al. [36] give an overview for household FW in six European countries with a minimum volume of 153 g in Austria and a maximum volume of 1500 g in Germany per capita per week. The reason for these distinct variations was explained with changing FW definitions, which may include only edible food waste or every food-related waste like kitchen waste, excluding packaging waste [36]. For this potential analysis, the latter appears to fit the above-presented definition. However, onboard food waste production for passenger is at least eight times higher when compared to common households. Extrapolated for 3000 people accommodated on a cruise ship, the FW volume results in a household-equivalent of 19,000 inhabitants, a so-called small city.

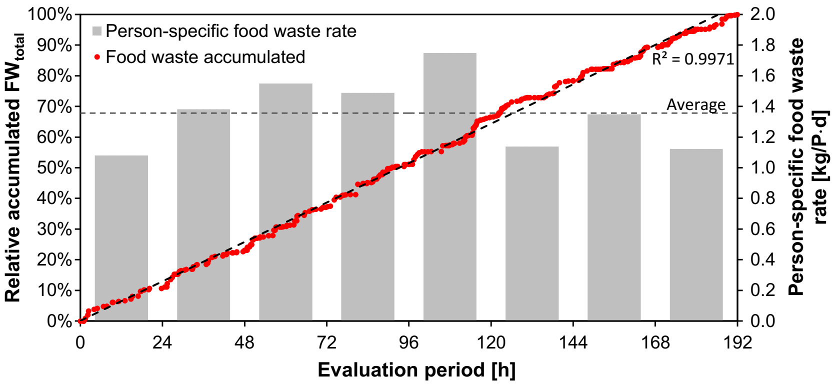


Fig. 3 Trend of accumulated food waste during the evaluation period and corresponding person-specific food waste rates onboard cruiser 2

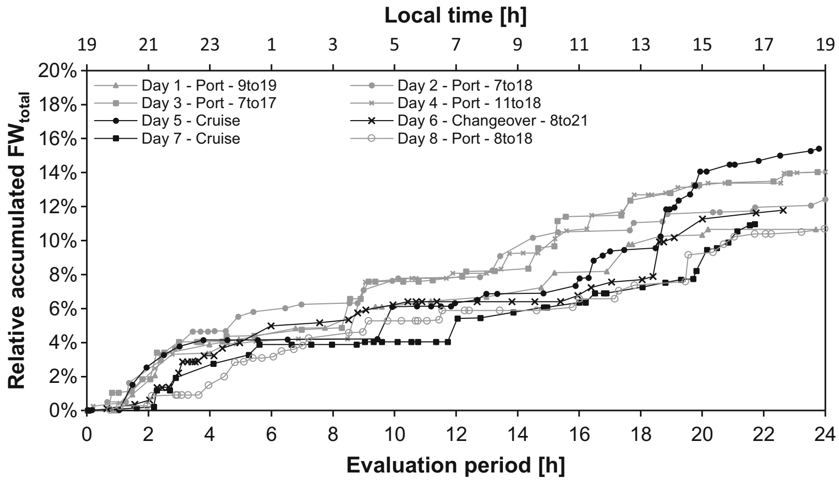


Fig. 4 Separated diurnal flow of accumulated food waste during the evaluation period of 8 days onboard cruiser 2 (grey: port day, black: cruise and changeover day)

3.1.2 Sewage sludge

Sewage sludge (SS) is waste-activated sludge that originates from onboard biological wastewater treatment. The quantity of sewage sludge to be disposed of is mainly determined by the water content of the excess sludge, and the available dewatering facilities onboard. Because of its high water content, SS represents the biggest volumetric fraction of the onboard-generated substrates. Table 4 presents an overview of person-specific SS amounts and corresponding solid contents. In compliance with the effluent standards that are required for certification of a sewage treatment plant for special areas (MEPC.227(64)), the calculated sludge production rate of 97 g TSS/(P·d) leads to a daily SS generation of 8.81 kg/(P·d), considering a TSS of 1.1 wt.-%. On the other hand, analysing data sets of five cruise ships revealed a wide spectrum of SS generation from 33 to 169 g TSS/(P·d). However, the data sets of two cruise ships contained a comprehensive evaluation period of 180 and 218 days. Thus, the resulting and profound SS generation for these vessels was 97 g TSS/(P·d) and 169 g TSS/(P·d) on average and consequently within the upper range. A similar spectrum was presented by the US EPA for four cruisers while in Alaska waters, ranging from 8 g TSS/(P·d) up to 143 g TSS/(P·d) [18–21]. Here, it must be noted that the US EPA only considered single grab samples and typical SS amounts per day reported by the crew. Overall, three out of the nine considered cruise ships were in the range of the predicted sludge amounts.

Typical sludge production rates for municipal WWTPs onshore are in a range of 30 g TSS/(P·d) and, therefore, roughly three times lower than onboard [37]. Comparing the person-specific wastewater pollutant loads onboard (Table 1) with pollutant loads in domestic wastewaters from Friedler et al. [38] reveals a two to three times higher COD and TSS load per person per day onboard. This may explain the significantly higher SS generation on cruise ships.

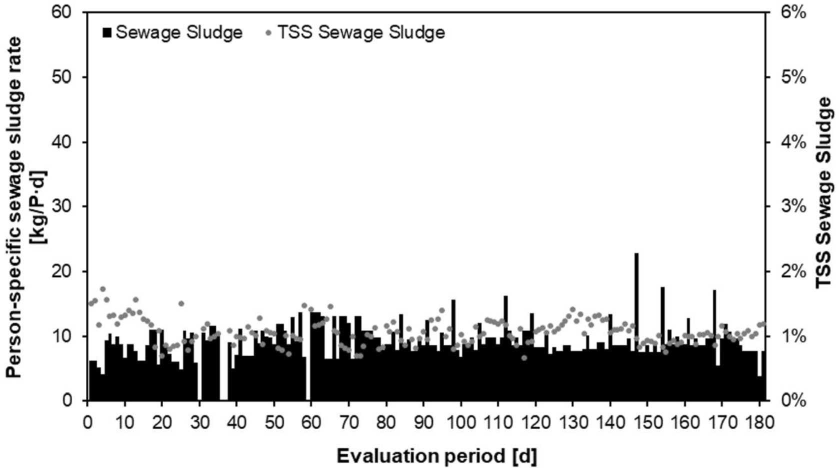
Various reasons may explain the wide range of SS generation rates onboard cruise ships. Firstly, numerous advanced wastewater treatment systems exist, which are based mainly on membrane technology, but also comprise flotation systems or reverse osmosis units for side stream treatment. Secondly, not all wastewater streams occurring onboard are always treated, since only black water is formally defined as sewage [39]. This results in clearly varying loads for the WWTP. Thirdly, the plant operation onboard is not consistent, due to a regularly shifting and limited crew staff. Thus, operational problems will be fixed individually. As an example, Fig. 5 and Fig. 6 illustrate differences in the occurrence of SS. While cruiser 1

Table 4 Person-specific generation rate of SS onboard cruise ships

Data source		Literature[a]	Sampling	Datasets				
Parameter	Unit	Calculation[b]	2 cruiser type A	Cruiser 1 type A	Cruiser 2 type B	Cruiser 3 type B	Cruiser 4 type B	Cruiser 5 type B
data size	–	$n=\infty$	$n=3$	n =180 d	n =218 d	n =31 d	n=31 d	n =17 d
$g_{\mathrm{Substrate}}$	$\frac{\mathrm{kg}}{\mathrm{P\cdot d}}$	8.81	–	9.24	13.85	2.98	3.33	7.40
$g_{\mathrm{Substrate,dry}}$	$\frac{\mathrm{g\ TSS}}{\mathrm{P\cdot d}}$	97	–	97	169	45	33	97
Ø TSS	wt.-%	1.1[e]	1.32[d]	1.05	1.22	1.51	0.99	1.31
Ø VS/TS	%	60–85[c]	85.1	–	–	–	–	–

[a] Köster et al. [23]; [b] DWA [22]; [c] Tchobanoglous et al. [24]; [d] measured as TS; [e] assumption

Fig. 5 Amount of sewage sludge per day and corresponding TSS concentration during evaluation period onboard cruiser 1



de-sludges consistently SS every day, cruiser 2 de-sludges inconsistently ranging from once per day to every fifth day with higher sludge amounts. The gap in Fig. 6 is related to a maintenance stay at the yard.

For the future, CLIA declared that every new cruise ship will be equipped with an advanced wastewater treatment plant [12]. Thus, sewage sludge amounts from wastewater treatment will occur successively on more cruise ships.

Utilising SS as second main feedstock for biogas production, a constant supply is required, too. Therefore, the figures above need to be considered for a sufficient substrate supply or sufficient storage volume. While the SS storage tank of cruiser 1 could take up a daily generation of up to 11.7 kg/(P·d), cruiser 2 has no separated SS storage tank. Instead, a biosludge tank collects both SS and screening solids. The daily average generation of SS alone would correspond to 110% biosludge tank storage volume. To ensure a constant SS volume per day for a biogas plant, a steady and daily de-sludge can be recommended.

However, to ensure sufficient storage volume and adjusting the water content for the AD, a dewatering step could easily reduce the accruing water volume by more than 50%. Typically, sludge dewatering units are integrated onboard, where a TS of up to 30 wt.-% can be expected. Reducing the water volume by 75% means tripling the TS content. Thus, a SS with 1.1 wt.-% TS would be adjusted to 3.2 wt.-% TS. In general, thickened SS for AD varies from 3 to 8 wt.-% [37]. The separated excessive water can be re-inputted into the onboard sewage treatment process. Modern cruise ships may already ensure a sufficient and constant substrate supply if an adapted sludge removal concept and a dewatering step are implemented.

3.1.3 Screening solids

Screening solids arise as a result of the mechanical treatment of wastewater. Commonly used onboard systems are coarse screens, vibrating screens or screen presses [11]. Depending on the installed equipment, wet or dry screening solids occur [40] and are collected separately or mixed in holding tanks, discharged at the port or to sea or incinerated onboard. On account of their origin, screening solids can be classified as a kind of primary sludge and act as the third main feedstock for the pursued onboard AD. The gathered data are shown in

Fig. 6 Amount of sewage sludge per day and corresponding TSS concentration during evaluation period onboard cruiser 2

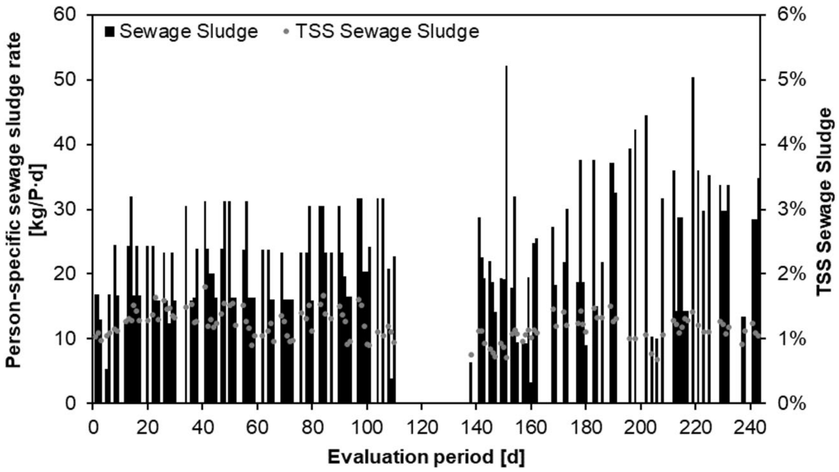


Table 5 Person-specific generation rate of screenings solids onboard cruise ships

Data source Parameter	Unit	Sample	Calculation	Ship operator	Literature Primary sludge
Data size	–	$n = 1$	–	–	–
$g_{\text{Substrate}}$	$\frac{g}{P \cdot d}$	–	122	–	583–4500[a]
$g_{\text{Substrate,dry}}$	$\frac{g\ TS}{P \cdot d}$	–	49	–	35–45[a]
Ø TS	wt.-%	49	40	35–45	1–6[b]
Ø VS/TS	%	97.3	–	–	60–85[b]

[a] Sperling and Goncalves [37]; [b] Tchobanoglous et al. [24]

Table 5. About 49 g TS/(P·d) of screening solids were calculated to be generated with a TS of 40 wt.-%. However, a one-time grab sample showed a higher TS content of 49 wt.-% and a VS/TS of 97.3%. Such a high volatile solid fraction indicates an appropriate biodegradability.

In comparison, the US EPA [18, 21] reports, as sole cruise ship reference, amounts of only 6 and 10 g TS/(P·d). No explanation for such low values could be found. A primary sludge generation of about 40 g TS/(P·d) for domestic wastewaters (Table 5) contradict the stated screening solid amounts of the US EPA [18, 21], since the wastewater pollutant loads onboard are up to 3 times higher than domestic wastewaters. On the contrary, rather higher amounts of screening solids are to be expected.

Similar to SS, screening solid volume depends primarily on the water content after screening. In the case of the grabbed sample with 49 wt.-% TS, 100 g/(P·d) screening solids can be expected, which is a negligible amount compared to previous substrates. As a consequence, no further storage volume was considered necessary.

3.1.4 General overview

To quantify the total substrate potential onboard, each above-presented waste stream must be included. Table 6 disaggregates the total specific quantity of organic waste. Per person per day onboard, an amount of 8.8 kg organic waste was calculated. This results further in 0.467 and 0.411 kg dry mass and volatile mass, respectively.

Stating person-specific quantities of organic waste facilitates the transfer of findings to different ship sizes. Importantly, the amount of volatile solids (VS) is required for calculating resulting biogas yield per ship. By assuming a 3:1 ratio for passengers and crew members, the average expected substrate quantity onboard can be calculated as VS per day (Eq. 1).

$$\text{VS cruise ship in total}: VS_{\text{Total}}[kg/d] = 0.4106 * x_P \tag{1}$$

where x_P = people onboard cruise ship.

Furthermore, Table 6 allows quantifying substrates for passengers and crew members separately using Eqs. 2 and 3.

$$\text{VS passengers}: VS_{\text{Pax}}[kg/d] = 0.3525 * x_P \tag{2}$$

$$\text{VS crew members}: VS_{\text{Crew}}[kg/d] = 0.058 * x_P \tag{3}$$

where x_P = people onboard cruise ship.

For instance, it is expected that an average cruise ship accommodating 3000 people generates 1232 kg VS per day. Taking water content into account, the individual substrate volumes are as follows: 4095 kg FW, 22,027 kg SS and 365 kg screening solids. In total, 26,486 kg organic waste is produced per day. Due to the high water content, a density of 1 kg/L can be assumed, which further results in a volume of 26.5 m^3 per day.

3.1.5 Additional substrates

Additional organic waste streams onboard which may be also in the focus for anaerobic digestion are grease and black water.

Table 6 Quantities of organic waste onboard cruise ships per person

Parameter	Unit	Food waste	Sewage sludge	Screening solids	Total organic waste
Generation rate	kg/(P·d)	1.365	7.342	0.122	8.829
	kg TS/(P·d)	0.322	0.097	0.049	0.467
	kg VS/(P·d)	0.281	0.082	0.047	0.411
TS	wt.-%	23.6	1.32	40.0	5.3
VS/TS	%	87.3	85.1	97.3	87.9

Table 7 Chemical characterisation of onboard sampled food waste and sewage sludge

Substrate		Food waste for proximate analysis				Food waste for ultimate analysis				Sewage sludge*			
Parameter	Unit	Mean	Data size	Min	Max	Mean	Data size	Min	Max	Mean	Data size	Min	Max
TS	wt.-%	26.33	n=4	16.60	30.10	25.28	n =5	17.90	30.20	1.32	n =3	0.72	1.67
VS/TS	%	91.53	n=4	89.16	93.54	97.75	n=5	95.30	100.00	85.10	n=3	83.55	87.70
Crude ash	wt.-%^{d}	8.47	n=4	6.46	10.84	2.25	n=5	0.00	4.70	14.90	n=3	12.30	16.45
Crude protein	wt.-%^{d}	30.91	n=4	24.10	38.36	–				–			
Crude lipids	wt.-%^{d}	20.04	n=4	16.87	22.45	–				–			
Crude fibre	wt.-%^{d}	1.80	n =4	0.00	4.82	–				–			
N-free extracts	wt.-%^{d}	39.10	n=4	29.11	43.98	–				–			
NH_4-N*	g/kg	0.14	n=4	0.13	0.15	–				0.36	n=3	0.19	0.64
pH*	–	5.13	n=4	4.90	5.33	–				6.41	n=2	6.19	6.63
C	wt.-%^{d}	45.81	n=4	43.42	47.33	49.23	n =3	46.90	53.20	–			
N	wt.-%^{d}	5.72	n=4	4.46	7.10	4.72	n=5	4.00	6.30	9.16	n=3	7.03	10.82
S	wt.-%^{d}	0.15	n=4	0.12	0.19	0.26	n=5	0.23	0.29	–			
H	wt.-%^{d}	6.81	n=4	6.63	7.06	6.91	n=5	6.79	7.07	–			
O	wt.-%^{d}	33.36	n=4	30.71	35.11	37.27	n=3	33.20	41.80	–			
C/N	–	8.20	n=4	6.50	9.74	10.36	n=3	7.56	12.37	–			
COD_{theo}	g/kg	382	Based on average			402	Based on average			21.5	n=3	8.90	28.62
COD_{theo}	g/kg VS	1586	Based on average			1627	Based on average			1828	n=3	1480	2047

*measured; ^{d} dry base

Grease consists primarily of galley waste oil and grease from the separation process of galley wastewater. Both investigated ship types collect grease in oil drums or containers for subsequent disposal at the port. Once onshore, a common and environmentally friendly valorisation route can be implemented through conversion of grease into biodiesel. An inferior route would be the incineration onboard, as reported by Hung et al. [41]. Due to already appropriate handling of ship-generated grease, there is no need for an alternative disposal route. Accordingly, it is not considered as potential substrate in this study.

Black water (BW) is highly concentrated wastewater (COD > 6000 mg/L, $n = 5$, self-measured) mainly from vacuum toilets, urinals and sickbay drainage with an average generation rate of about 32 L/(P·d) [40]. No crucial differences in BW composition from onshore vacuum systems can be identified, e.g. Wendland [42].

For the adequate treatment of BW onboard modern cruise ships, substantial energy amounts are necessary. Considering AD as a pre-treating step has the potential to decrease the energy consumption of the WWTP, reduce SS generation and simultaneously gain energy-rich biogas. However, currently sufficient onboard treatment of BW is implemented. On that account, this study does not consider AD of BW in more detail. A comprehensive study that deals with the feasibility of combined AD of BW and FW onshore was carried out by Wendland [42]. Nevertheless, SS produced from BW during the aerobic treatment process is still included in this investigation. For the future, AD of BW could be considered

Table 8 Biogas yield and composition of substrates onboard cruise ships

		Mono-digestion									
Substrate		Food waste				Sewage sludge				Screening solids	
Parameter	Unit	Mean	Data size	Min	Max	Mean	Data size	Min	Max	Mean	Data size
y_{Biogas}	L/kg VS	620	n =7	512	688	314	n=2	313	315	570	n=1
$V_{CH4,Biogas}$	Vol.-%	69.4	n=3	67.3	72.2	76.2	n=1	–		65.92	n=1
$y_{Methane}$	L/kg VS	430.8	*Based on average*			239.4	*Based on average*			376.0	–
$y_{Methane,theo,COD}$	L/kg VS	569	*Based on average*			640	*Based on average*			–	

y_{Biogas}: specific biogas yield; $y_{Methane}$: specific methane yield; $V_{CH4,Biogas}$: methane content; $y_{Methan,theo,COD:}$ theoretical specific methane yield based on COD

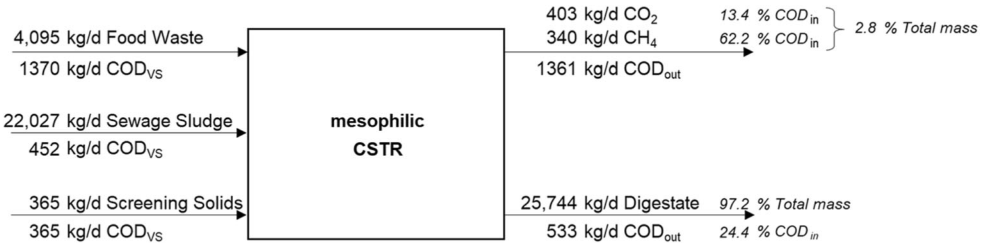


Fig. 7 Simplified mass balance for a biogas plant onboard a cruise ship accommodating 3000 people

for new and revised onboard WWTP. It is necessary to note that AD of BW will have a significant impact on the WWTP, due to a decreased COD load and steady total nitrogen load.

3.2 Chemical characterisation of substrates

The analytical results for the chemical characterisation of FW and SS samples are listed in Table 7. FW samples were examined by means of proximate analysis and ultimate analysis. For the proximate analysis the main components protein, lipids and carbohydrates were, on a dry basis, 30.91 wt.-%, 20.04 wt.-% and 40.9 wt.-%, respectively.

The heterogeneity of FW caused a carbon content ranging from 43.42 to 53.20 dry wt.-%. In addition, nitrogen content varied from 4.00 to 7.10 dry wt.%. The C/N ratio of FW was between 6.5 and 12.37. In terms of elementary composition, as well as the chemical oxygen demand (COD) of about 1600 g COD/kg VS, FW showed a similar range for land-based investigations by Heo et al. [43], Zhang et al. [44], Curry and Pillay [45] and Fisgativa et al. [46]. However, those authors reported higher C/N ratios in a range from 13 to 18. A possible explanation for the lower C/N ratios might be the extensive and surplus provision of nitrogen-rich food onboard, especially considering higher meat and protein content.

A total nitrogen (TN) content of 1.21 g/kg on average for SS resulted in a proportion of 9.16 wt.-%, on a dry basis. Furthermore, a mean COD content of 21.5 [g COD/kg] or 1.828 [g COD/kg VS] was measured. Avellaneda et al. [47] reported about biosolids as a mixture of SS and screening solids onboard cruise ships. A similar mean value for TN was presented while the TSS mean value was slightly higher.

Common C/N ratios for primary and excess sludge vary from 6 to 8 according to Cheng et al. [48], Heo et al. [43], Elsayed et al. [49] and Ahn and Speece [50]. Moreover, those authors specified TN contents on a dry basis of 4% and 7%. Thus, the expected C/N ratio of the sampled SS (TN: ca. 9 wt.-%[d]) can be assumed to be in the range of 5. This low ratio is essentially caused by the unforeseen presence of a significantly high amount of ammonium nitrogen which indicates insufficient nitrification in the WWTP onboard.

Even if no specific laboratory analyses have been performed for the screening solids from mechanical wastewater treatment, their characteristics can be assumed to be similar to conventional primary sludge, due to origin, high content of volatile solids and high biogas potential. In accordance with Park et al. [51], the substrate accessibility of screening solids can be classified higher than SS but lower than FW.

Overall, both investigated substrates revealed a lower C/N ratio than the recommended ratio of 20 to 30 for an optimal AD process [52]. For the AD of SS and screening solids, co-digestion with FW would nonetheless lead to an enhanced C/N ratio.

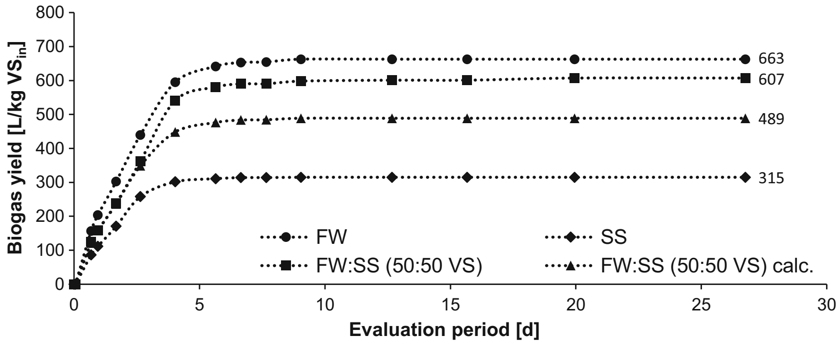
3.3 Gas yield and mass balance

The potential biogas and methane quantities for a whole cruise ship can be predicted by considering the specific biogas yields of the sampled substrates and their given quantities. Table 8 details the specific biogas and methane yields from the conducted biogas potential tests for FW, SS and screening solids. According to these experiments, the specific biogas yields were 0.620 m^3/kg VS for FW and 0.314 m^3/kg VS for SS with a methane content of 69.45% and 76.22%, respectively. The biogas potential of screening solids was 0.570 m^3/kg VS with a methane content of 65.92%. To evaluate the gained biogas data, the theoretical methane yield of 0.57 m^3/kg VS and 0.64 m^3/kg VS was derived for FW and SS, respectively. The biodegradability of 76% for FW was about two times higher than for SS with 37% when considering the theoretical methane yields as the basis. Heo et al. [43] reported a biodegradability of 86% and 29% for similar substrates in BMP tests with a well-adapted inoculum by using Buswell's equation to determine the theoretical methane yield [53]. The same result for FW could be proven by using Buswell's equation.

As a preliminary mass balance, Fig. 7 specifies the input and output streams of a biogas plant onboard the reference cruise ship, accommodating 3000 people. About 743 kg/day biogas or 340 kg/day methane and 25,744 kg/day digestate will result when the daily available organic waste amount of 26,487 kg/day is fed. The AD process reduces the total input mass by 3% while the corresponding COD$_{in}$ load is diminished by 75.6% with 62.2% assigning to the methane production. Even though AD reduces merely little the total mass of the organic waste, only a quarter of the original COD load remains inside the digestate.

In contrast to the present handling of organic waste onboard cruise ships, AD technology reduces the organic load of organic waste significantly while converting organic matter

Fig. 8 Biogas potential test for ship-generated FW, SS and a corresponding mix



into renewable fuel for a direct use onboard. Alternative processing steps as drying and incineration of organic waste are demanding supplementary energy and increase the overall CO_2 emissions without generating any advantages, except for complete elimination.

No significant differences for FW onboard cruise ships were revealed when compared to land-based literature, e.g. Zhang et al. [54] reported an average yield of 435 L CH_4/kg VS. Slightly higher methane yields were reported by Banks and Heaven [52] for typical food remains. Additionally, conducted biogas potential tests showed similar biogas yields (339 L/kg VS, $n = 3$) for waste-activated sludge from the WWTP Herrenhausen. However, the land-based scientific literature reports higher [55] as well as lower [51, 56] biogas and methane yields for waste-activated sludge (here: SS). A typical range of 190 to 240 L CH_4/kg VS is referred by Bachmann [57]. Clearly higher methane yields (314–400 L CH_4/kg VS) for primary sludge are in line with the gained methane yield for screening solids [57]. These findings strengthen the assumption that screening solids can be classified as ship-generated primary sludge.

Variations in biogas and methane yields may be based on performed BMP tests with inocula which are more or less adapted to the investigated substrates. Especially the heterogeneity of FW leads to a wide range of results. Overall, no divergent findings on the biogas potential of ship-generated organic waste were gained, compared to ashore.

Nevertheless, cruise ships possess a unique opportunity to implement combined AD of organic waste streams, without costly substrate transportation. Anaerobic co-digestion involves at least two or more substrates and is applied to utilise spare capacities, to increase the biogas productivity or to stabilise the biological process. Xie et al. [58] reported that co-digestion of FW and SS significantly improves specific methane yields. Their results were two times higher compared to mono-digestion experiments. Similar findings are also reported by Sosnowski et al. [59]. Dai et al. [60] came to another conclusion and ascertained no effect on specific methane yield depending on mono- or combined digestion or certain mixing ratios. However, the authors emphasised the positive effects of co-digestion on process stability (e.g. compensation of Na^+-inhibition) and noted additional biogas yields by adding FW to the sludge digestion process.

To prove the findings above, anaerobic digestion tests for FW, SS and a mixture of the same FW and SS were performed (Fig. 8). While the mono-digested FW and SS are in the range of the reported biogas potential, the mixture (50:50 VS) achieved 607 L/kg VS. This is an improvement of about 24%, compared to the calculated yield of 489 L/kg VS on the basis of mono-digestion. According to Heo et al. [43], a VS-mixing ratio of 50:50, for FW and SS ensures high methane yields and stable process conditions. The situation onboard reveals a FW:SS:screening solids ratio of 68:20:12 if all accruing substrates are applied and a ratio of 77:23 if only FW and SS are considered.

Assuming that an optimal mono-digestion process of all substrates takes place, 227.1 L of biogas and 158.5 L of methane per person per day can be produced onboard. The resulting thermal power output is thus 66 W per person, given a calorific value of 10 kWh/m^3 for methane. Table 9 provides a detailed overview.

For instance, an average cruise ship with 3000 people onboard would potentially provide 198 kW thermal power. The available power through AD of all available substrates

Table 9 Substrate specific biogas and methane yields per person per day ($y_{Biogas,p}$/$y_{Methane,p}$) and the corresponding thermal power $P_{p,th}$ and thermal energy $E_{P,th}$ equivalent for separated mono-digestion

Parameter	Unit	Food waste	Sewage sludge	Screening solids	Total
$y_{Biogas,p}$	L/(d·P)	174.2	25.9	27.0	227.1
$y_{Methane,p}$	L/(d·P)	121.0	19.7	17.8	158.5
$P_{p,th}$	W/P	50.4	8.2	7.4	66.0
$E_{P,th}$	kWh/P·d	1.2	0.2	0.2	1.6

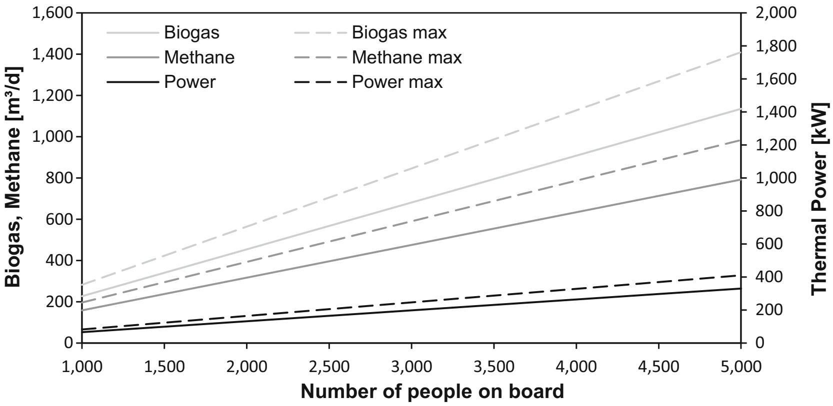


Fig. 9 Biogas and methane yields and corresponding thermal power depending on the number of people onboard

onboard according to the actual number of persons onboard can be seen in Fig. 9. To include the advantage of co-digestion, the additional 24% biogas yield was considered as maximum yield (dashed lines) and leads to a potential thermal power of 82 watts per person.

A case study by Baldi et al. [61] for a cruise ship operating daily cruises in Northern Europe with a capacity of 1800 passengers (assumed passenger-crew ratio 1:3) was used to estimate the energy and heat demand for passenger vessels. Their findings reflect that on average 45% and 28% of the total energy demand onboard were allocated to the ship's propulsion and heat supply, respectively. Baldi et al. [61] state an average consumption of 4500 to 5000 kW for their cruise ship; thus, a person-specific power consumption of around 2000 W/P could be derived. Considering the specific thermal power of 66 W/P and 82 W/P, the energy supply through AD can cover up to 3.3% and 4.1% of the total average energy demand onboard, respectively.

The heat supply profiles revealed a spectrum from 0.29 to 1.17 kW/P, which is mainly influenced by the outer temperature [61]. This implies that the potential energy provided by the onboard organic waste can cover up to 28% of the heat demand onboard, assuming a biogas valorisation in an ideal boiler system for heat generation. It is noteworthy that FW alone can provide about 76% of the estimated thermal energy.

From another perspective, one person onboard would provide enough potential energy through onboard AD of organic waste to cover the energy demand for treating one's own wastewater of about one kWh/m^3 [62]. Thus, an energy-self-sufficient operating wastewater treatment system would be introduced. At the same time, surplus energy can be contributed to the onboard heating system, e.g. for heating of the required biogas reactor or providing hot water.

4 Conclusions

The present study provides evidence that by means of anaerobic digestion, organic waste generated onboard cruise ships can make a significant contribution towards a more efficient ship energy system. Furthermore, the energy conversion directly onboard prevents shipping companies from discharging untreated organic waste into the marine environment. Nonetheless, the onboard implementation of a large-scale biogas plant is a challenging undertaking, considering that, to date, no experience on system integration or operation exists while strict regulations for the onboard gas handling have to be met. However, putting AD technology into action would be another contribution towards minimising ship emissions. About 76% of the COD load of organic waste will be diminished if AD technology is applied.

Profound findings were provided with regard to quantities and characteristics of suitable substrates for onboard biogas generation, such as food waste, sewage sludge and screening solids. Per person per day, potentially 159 L of methane can be produced, which results in 66 W per person and 198 kW per reference cruise ship. The circumstances onboard allow the application of co-digestion of organic waste streams. It could be proven that this combined digestion leads to methane biogas yields and improves process stability. Anaerobic digestion tests revealed an improvement of 24% in biogas yield when applying co-digestion (FW$_{VS}$:SS$_{VS}$ = 50:50) and led to a thermal power supply of up to 82 W/P. This may seem small in view of the overall energy consumption of about 2000 W/P, but it is nevertheless an additional contribution to improved environmental protection onboard.

In periods of lower heat demand, e.g. in summer or while cruising through the Caribbean, up to 28% of the total heat demand onboard could be covered through onboard AD of organic waste. Applying the findings of this analysis to an average cruise ship accommodating 3000 people, the potentially provided thermal power would be up to 246 kW, equal to the theoretical energy content of 537 kg heavy fuel oil (11 kWh/kg) per day. Depending on the efficiency of the ship engines, even higher substitution rates can be achieved. Sticking to the theoretical energy content, around 196 t fuel could be compensated per ship per year or 65 kg heavy fuel oil per person onboard per year could be substituted. However, considering a decreasing passenger FW generation through an improved restaurant service would reduce providable power.

The key criterion for a feasible implementation of an anaerobic digestion plant onboard is its space requirement. This study even permits initial statements to be made on the design of possible AD systems onboard. The preparatory work described here is a prerequisite for explicit, robust, adapted and verified design suggestions for onboard AD reactors. A rough estimated initial reactor size of 50 L/P can be evaluated as a manageable and implementable size onboard, especially when the environmental systems onboard (cruise ships 1 & 2) provides about 17 L/P storage capacity for organic waste and several hundreds of litres of storage capacity per person for the wastewater system or the ballast water system. Further issues will have to be tackled to support the AD concept, such as the proper implementation of gas use and the environmentally friendly handling of digestate.

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Code availability Not applicable.

Authors' contributions K. Schumüller: methodology; investigation; validation; writing—original draft; visualization; project administration

D. Weichgrebe: writing—review and editing

S. Köster: conceptualization; writing—review and editing; supervision

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Data availability Further information on the project can be found at **www.clean-biogas.de**.

Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest.

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