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Review

Carbon Footprint and Energy Recovery Potential of Primary Wastewater Treatment in Decentralized Areas: A Critical Review on Septic and Imhoff Tanks

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Abstract: The present work is a critical review on the carbon footprint and energy recovery potential of septic and Imhoff tanks for primary wastewater treatment. From an online search of research papers, a lack of up-to-date research about gas emissions from Imhoff tanks emerged. Additionally, available literature data should be extended to incorporate the effect of seasonal variations, which may be relevant due to the fact that both systems work under environmental conditions. The literature generally agrees on the positive effect of temperature increase on biogas and methane production from both septic and Imhoff tanks. Additionally, sludge withdrawal is an important operational feature for gas production in these reactors. More recently, the application of electrochemical technologies and the installation of photovoltaic modules have been studied to enhance the sustainability of these decentralized solutions; in addition, sludge pretreatment has been investigated to raise the obtainable methane yields due to limited sludge biodegradability. Further research is needed to assess the effective sustainability of biogas collection and valorization from existing septic and Imhoff tanks, considering the limited biogas generation and the implementation of these systems in decentralized wastewater treatment scenarios (rural or mountain areas). Contrary to the intensive research on greenhouse gas mitigation strategies applied to centralized systems, solutions specifically designed for gas emission mitigations from septic and Imhoff tanks have not attracted the same scientific interest up to now. More generally, given the widespread application of these two options and their potential significant contribution to the overall carbon footprint of wastewater treatment technologies, much more research must be performed in the future both on the quantification of gas production and on the applicable strategies to reduce their carbon footprint.

Keywords: biogas; anaerobic digestion; carbon footprint; renewable energy; septic tanks; Imhoff tanks; GHG emissions; decentralized systems; wastewater treatment; circular economy

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1. Introduction

Primary treatment technologies (PTTs) are typically employed to make urban wastewater suitable for either direct discharge into the environment [1,2] or secondary treatment [3,4] by removing a significant fraction of particulate organic matter, usually around 30–70% [5–8]. For a long time, PTTs have demonstrated their potential for successful performance when well operated and maintained [3,6,9–12]. The fundamental working principle of these technologies is based on physical and/or biological processes. Specifically, while some PTTs typically remove suspended solids only through physical processes such as settling [13] or filtration [14–17], other PTTs such as septic and Imhoff tanks incorporate an additional removal mechanism, namely anaerobic digestion [18,19]. The latter occurs consequently to the fact that, differently from primary clarifiers or rotating filters where separated solids are continuously removed, within septic and Imhoff tanks the solids are allowed to accumulate in the system over long periods. Within these periods, thanks to the absence of oxygen, bacteria mediating anaerobic processes in the accumulated solid mass can build up. As a result of their microbial activities, gases such as methane (CH_4), carbon dioxide (CO_2), molecular hydrogen (H_2), and hydrogen sulfide (H_2S) are generated [18,20,21]. Concerns regard the emissions of CH_4 and CO_2, two greenhouse gases that may have a negative impact on the ecosystem if emitted considerably, especially in the case of CH_4, given its high global warming potential (20–25 times that of CO_2). While CH_4 gas emitted from anaerobic technologies such as up-flow anaerobic sludge blankets or anaerobic filters, which are ranked as high rate according to [22], is often collected and exploited for energy recovery [23–25], this is not always the case for low-rate anaerobic technologies such as septic and Imhoff tanks. The lower rate of anaerobic processes in these treatment systems can be largely attributed to the rather limited mixing conditions that hinder the direct availability of carbon-based substrate to the biomass for biological reactions and consequent conversion into biogas. In turn, the less reliable CH_4 production in these systems has made the installation of equipment for energy recovery not always economically convenient [20,26,27]. When CH_4 is not collected and burnt, the same CH_4 is typically vented out in the environment, which in turn may make some PTTs strong emitters of harmful greenhouse gases and thus environmentally unsustainable. Nevertheless, there are documented instances when CH_4 from Imhoff tanks was captured and exploited for energy production [6,18,28–30]. It is also important to note that proper collection and flaring of gases produced during anaerobic processes can benefit the environment and the human beings living in the surrounding area by preventing the release of explosive, odorous, and health-threatening chemicals [18,20,21,31]. In addition, the production of energy from human excreta can reduce the need to resort to external non-renewable sources such as fossil fuels whose availability in the long run is not guaranteed [32,33]. Given that the adoption of septic and Imhoff tanks is already widespread as decentralized systems around the globe, not only in developing and underdeveloped countries [27,34–36] but also in economically developed countries [1,37–39], the need for investigating their environmental impact becomes relevant. While a single septic or Imhoff tank serving a small agglomeration may present a negligible carbon footprint, when these technologies are considered as a whole, their contribution to the global carbon footprint of wastewater treatment may become relevant [37,40]. A more conscious management of PTTs with enhanced energy recovery is in line with the Sustainable Development Goals [41], requiring sanitation of water for all (Goal 6) while avoiding climate change by minimizing the emission of greenhouse gases (Goal 13) [42,43] and ensuring affordable and clean energy (Goal 7) [44]. So far, some research about the energy recovery and carbon footprint of septic and Imhoff tanks has been carried out [10,18,19,30,40,45]. However, an analysis about the consistency, the intensity, and the research gaps in this field is lacking. Literature reviews compiling the knowledge acquired so far are missing. With the aim of understanding the state of the art of the environmental impact of PTTs, such as septic and Imhoff tanks, identifying the key mechanisms which impact on their carbon footprint and promoting energy recovery, as well as pointing out the research gaps in this field, a review paper summarizing the knowledge acquired in this respect is needed. For these reasons, this work presents a systematic critical review about the research on carbon footprint and energy recovery potential of septic and Imhoff tanks for primary wastewater treatment in light of a more sustainable wastewater treatment for decentralized applications. This review considers all relevant works where gas measurements were taken from septic and Imhoff tanks as well as those works describing energy recovery from the same technologies.

2. Materials and Methods

An online search of all the works on septic and Imhoff tanks with specific focus on their carbon footprint, gas production, and energy recovery potential was carried out by variably combining keywords such as "septic", "methane", "gas", "Imhoff", "wastewater", "carbon footprint", and "energy". The search was kept open to consider not only research articles but also official reports, books, and master's and PhD theses regardless the year in which they were published. As a database employed for the search, Google Scholar [46] was used first, followed by Google to search for a few materials referenced in Google Scholar but without available text. Within Google, Internet Archive [47] was identified as a useful webpage to find some books such as [48]. In addition, cited literature within the identified material of interest was also checked to achieve further information contributing to the subject.

From this search, the works were selected based on whether direct measurements were provided or not. In addition, works discussing operational conditions affecting biogas production from both technologies were considered as well. While research based on assumed fixed emission factors from the literature may be valuable when performing life cycle assessments or comparing the carbon footprints of decentralized and centralized technologies [35,49–54], it provides only very limited information with respect to the operational conditions potentially affecting the emissions of greenhouse gases (GHGs) from the investigated technologies. Based on this, these articles were not further considered.

Only works reporting and discussing gas emissions from septic and Imhoff tanks receiving urban, domestic, or blackwater were considered, while gas emissions from septic or Imhoff tanks also receiving solid waste were not considered. For the sake of unbiased comparison, experimental works where peculiar experimental operational strategies different from the typical operation of these tanks were excluded as well. On the other hand, works presenting experimental or field experiences regarding anaerobic digestion and the gas produced thereby within normally operated septic and Imhoff tanks were analyzed and further considered. More specifically, works variably providing information regarding CH_4 and CO_2 emission factors (expressed as daily mass of gas emitted per capita), overall carbon footprint and carbon footprint contributions by the two gases, volumetric biogas composition to understand CH_4 percentage and flammability, and/or biogas emission factors for both septic and Imhoff tanks were further analyzed, in addition to those reporting trends between operational variables and gas emissions.

Information missing from the selected works was deduced by making few assumptions. More precisely, in case a work reported only the overall per capita volumetric biogas production along with its composition, CH_4 and CO_2 emission factors and their relative contribution to the carbon footprint were deduced by converting the volumes of the emitted gases into masses assuming the respective gas density at atmospheric pressure and temperature of 20 °C (i.e., 667.6 $g \cdot m^{-3}$ for CH_4 and 1838.6 $g \cdot m^{-3}$ for CO_2) [19,40,45,48,55,56]. Conversely, the estimation of biogas composition in terms of relative volumetric presence of CH_4 and CO_2 from the emission factors was not carried out due to the unquantified—yet possibly significant—presence of other gases such as dinitrogen (N_2) and hydrogen (H_2) [31,57]. Unreported per capita carbon footprint expressed as the amount of equivalent CO_2 was calculated using a global warming potential (GWP) for CH_4 of 21 g $CO_{2eq} \cdot g^{-1}$ CH_4, assuming all gas is emitted without being burnt.

3. Technology Description

In this section, an overall description of the two technologies considered in this work is provided. Specifically, the basic working principles of septic tanks (see Section 3.1) and Imhoff tanks (see Section 3.2) are provided. Both septic and Imhoff tanks are generally used for the primary treatment of urban sewage in decentralized areas not served by public sewers to reduce the environmental impact given by the discharge of untreated wastewater. Remarkably, they are widespread not only in underdeveloped or developing countries but also in developed countries, where rural or mountain areas, characterized by low population density, are present. About 10–15% of the population in Canada, Australia, and the United States relies on these simple solutions for decentralized wastewater treatment [58–61]. According to another source [62], 20% of Australian households result to be treated through onsite sanitation systems, of which septic tanks are the most common technology employed. Nearly 25% of American households rely on septic systems [63]. Reportedly, one third of Irish households rely on individual septic tank systems [64]. In Honduras, about 40% of the total wastewater infrastructure consists of Imhoff tanks [65], while in Malaysia they still represent a widely adopted option for sewage treatment [34]. These technologies are characterized by very simple operating principles in order to reduce their maintenance and operating costs.

3.1. Septic Tanks

Septic tanks consist of one or more large rectangular or cylindric chambers where separation between solid and liquid components of urban sewage occurs. The construction materials—often concrete based—are durable and resistant to corrosion and decay. As presented in Figure 1, which shows a simplified layout of a typical one-chamber septic tank, the most relevant components of the system are the inlet and outlet baffles, which respectively prevent short-circuiting across the top of the reactor and keep the scum layer inside the system, avoiding wash-out [66]. These systems are typically located underground but there are cases where they are located partially underground and above ground. The presence of inspection and access ports allows users to view the presence of operating issues and extract the accumulated sludge from the system, respectively.

Due to gravity, the solid fraction present in the influent wastewater settles at the bottom of the tank, forming a sludge layer. Oils and greases typically float on the surface of the liquid, forming a variably thick scum layer. The liquid fraction can be either discharged into a drainage field, consisting of either a soak-away or sub-surface irrigation pipes that allow the effluent to percolate into the surrounding soil [67], or can be directed to secondary treatment [68–71].

The hydraulic retention time is normally longer than 24 h during which the separation of the solid fraction limits clogging in the other components of the system, especially the outlet device [66]. A settling period longer than the ideal one tends to produce a septic effluent, which is detrimental to the operation of oxidizing beds, should such treatment be required [10]. Solid decomposition, which typically happens under anaerobic conditions [67], can reach up to 50%, while the residual solids accumulate in the tank and thus must be periodically withdrawn to prevent their overflow with the liquid effluent [66]. Normally the anaerobic digestion process is uncomplete, mostly depending on reactor size, temperature, and cleaning frequency [67], factors whose influence on digestion are discussed in detail in Section 5.

A simplified design of septic tanks can be made according to the number of served people and the interval of sludge discharge, which is normally in the order of magnitude of several months [67]. The design of the drainage field is as important as that of the septic tank itself, but normally receives less attention: soil characteristics (type, permeability, etc.) must be assessed, and percolation tests are required to calculate the pipe length or the soak-away size [67]. Effluent quality is not expected to be high and can be comparable to that obtained after primary sedimentation in conventional WWTPs. No biological or chemical additives are usually needed to operate the system. Multiple chambers can be installed in series to enhance the overall system performances, maintaining the design and operation simplicity.

Despite being widely applied throughout the world, septic tanks suffer from common issues related to inappropriate location, poor maintenance, and drainage field design. The symptoms of these issues in system operations include odor generation due to inadequate ventilation or blocked drainage field, solids discharge due to an undersized tank or tank full of sludge, and local groundwater and watercourse pollution [67]. A study highlighted that most of the septic tanks in Tanzania are improperly designed and installed; in addition, negative factors affecting the overall sanitation performances were shown to be the suboptimal desludging frequency, the low priority of sanitation issues, and the limited public awareness [72].

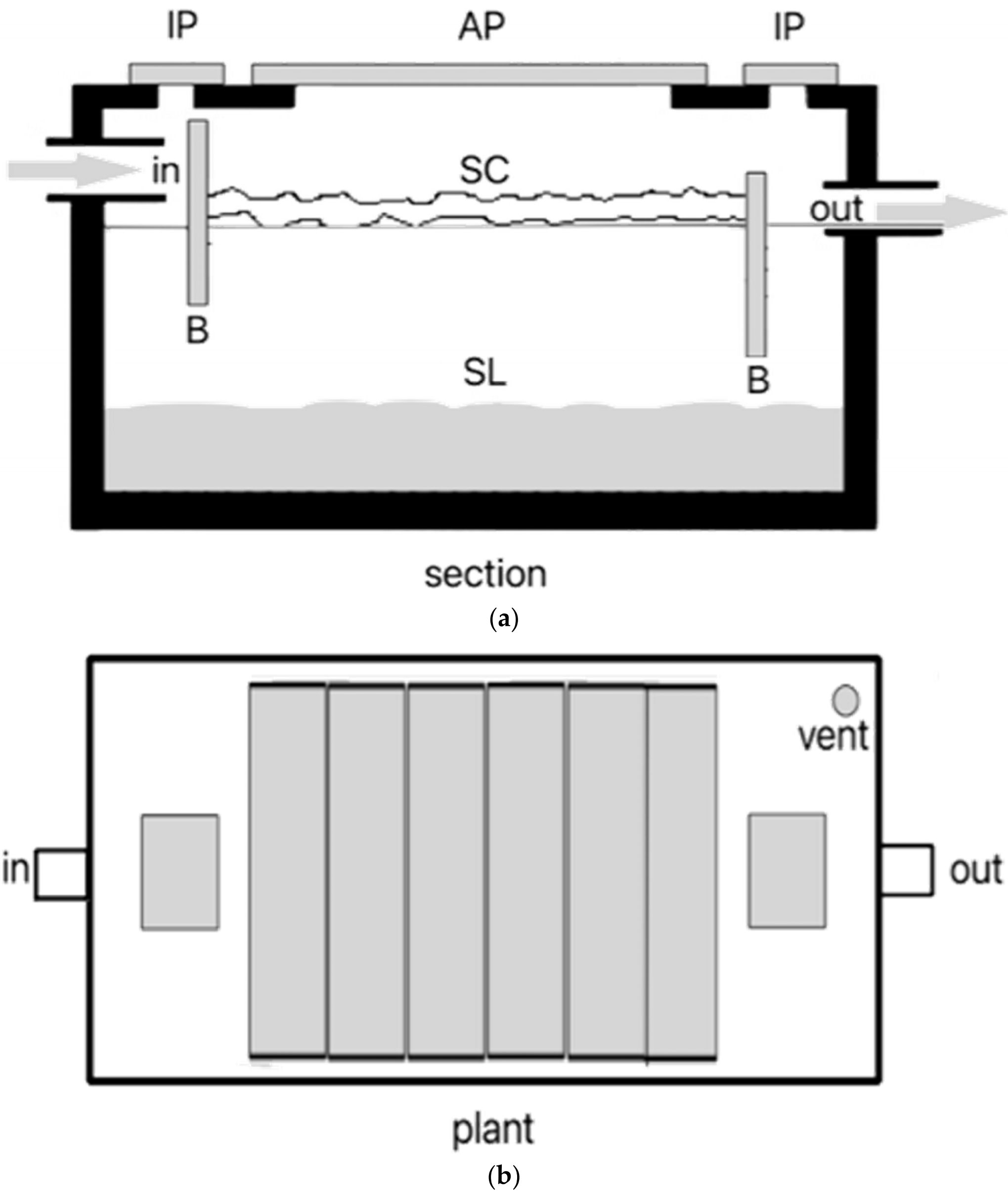

Figure 1. (**a**) Typical cross-section elevation adapted from [66] and (**b**) typical plan view of septic tank. Legend: IP = inspection port; AP = access port; SC = scum; B = baffles; SL = sludge.

More recently, modifications to the conventional design of septic tanks have been proposed, including the addition of packaging materials, the introduction of multiple anaerobic/aerobic phases, and the implementation of additional baffles [73–75]. The modified systems generally show a significantly higher removal of organic matter (>80% for 5-day biochemical oxygen demand, BOD_5, >70% for chemical oxygen demand, COD) and total suspended solids (TSS, >80%), while nutrient abatement is still limited, especially for nitrogen (<60% for ammonia, nitrate, and total Kjeldahl nitrogen, TKN) [58,74,75]. In particular, excellent organic matter and TSS removal were obtained in a modified septic tank consisting of three anaerobic chambers followed by a final aerobic/settling step, where the treated effluent showed characteristics amenable for wastewater reuse, if proper disinfection was provided [58]. Another remarkable opportunity is the implementation of remote sensing devices (e.g., ultrasonic sensors) in septic tanks, which may help to accurately determine sewage level inside the chamber, avoiding overflows into the environment and promptly detecting malfunctioning [76].

3.2. Imhoff Tanks

Developed by the German engineer Karl Imhoff, Imhoff tanks are a substantially improved version of the original septic tank described in Section 3.1. Specifically, as can be seen in Figure 2, Imhoff tanks are designed as two-stage systems, where the first stage consists of a settling tank and the second consists of a digestion compartment with the main purpose of biologically degrading the separated solids [77]. The latter is located in a lower position compared to the former, so that the gas produced does not interfere with the settling process, contrary to what could easily happen in a septic tank. Another advantage is the avoided mixing between septic sludge and fresh sewage in the same chamber.

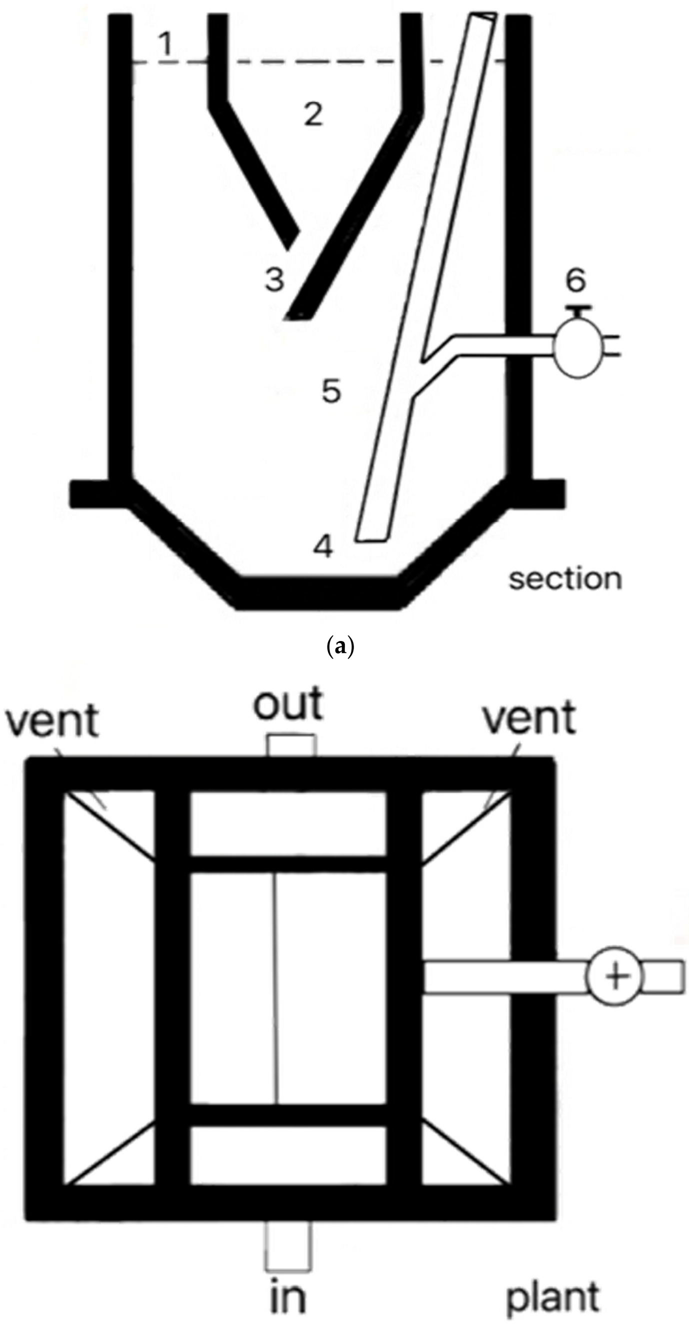

Figure 2. (**a**) Typical cross-section adapted from [77] and (**b**) typical plan of an Imhoff tank. Legend: 1. Scum chamber; 2. Settling chamber; 3. Slot overhang; 4. Sludge digestion chamber; 5. Neutral zone; 6. Sludge removal valve.

The digestion tank is equipped with biogas vents and pipes for excess sludge extraction. The digested sludge is typically extracted after 6–9 months of digestion. Regarding construction materials, concrete is still the most widely applied solution, although high-density polyethylene was shown to have a lower environmental impact concerning greenhouse gas emissions and abiotic depletion through a life cycle assessment analysis [78].

Typical removal efficiencies of Imhoff tanks range between 20% and 70% for TSS and between 10% and 40% for BOD_5 [7,65]; nevertheless, the specific performances depend case by case on the influent water quality (which is often very diluted due to low population density and freshwater infiltration in the sewer pipes), as well as on the actual hydraulic retention time. The combination of Imhoff tanks and constructed wetlands (CWs) was recently proposed in the literature as an efficient way to remove pathogens (coliforms, parasite eggs, protozoan cysts) from domestic wastewater; this solution can be particularly adapted to developing countries, where water shortage and high costs of centralized wastewater treatment are encountered. By further implementing a final disinfection phase, an interesting perspective in the circular economy framework could be the potential reuse of the treated effluent for irrigation [79]. Similarly, other research demonstrated that an Imhoff tank followed by three stages of CWs allowed excellent TSS (97%), BOD_5 (97%), COD (95%), total nitrogen (TN) (71%), and PO_4^{3-}-P (82%) removal in the treatment of wastewater from a rural Tunisian settlement [80]. More generally, Imhoff tanks alone can be considered only as a pretreatment, analogously to septic tanks, although adding more tanks in series allows improvement in the removal of pollutants, especially pathogens [79].

Chemically enhanced primary treatment, with alum addition at a dosage of 150 $mg \cdot L^{-1}$ (17% Al_2O_3), has been recently proposed to improve the performances of Imhoff tanks; despite being useful for improving pollutant removal, chemical addition is unavoidably characterized by high costs and technical issues in preparing and injecting the solutions [65]. As a further alternative, vermifiltration has been proposed in combination with Imhoff tanks to respect the effluent discharge limits in rural Peruvian communities [81], proving that simple decentralized treatment technologies can often be sufficient to achieve local effluent quality standards. An efficient exploitation of the produced biogas may help to enhance local renewable energy generation, while stabilized sludge (eventually after a further composting process) may be applied to agricultural soils as an amendment. Treated effluent reuse can also be considered, especially if Imhoff tanks are combined with CWs or other nature-based technologies.

4. Quantification and Monitoring of Biogas Production and Composition

The online search about biogas production from septic and Imhoff tanks revealed few works describing direct gas measurements from septic tanks, both from outdated and recent research [19,40,45,48,55,82], while only outdated works investigated gas production from Imhoff tanks [6,18,30,31,83,84]. The works by [19,45] present the same results with the difference that [19] provides more considerations and details about the day-by-day measurements. As previously disclosed, in the last two decades there has been basically no published research studying biogas production from Imhoff tanks, apart from [54] who estimated methane production according to the methods proposed by [85] without validating those results with any direct measurements.

Table 1 shows an overview of the gas quantifications from septic and Imhoff systems based on the literature. Specifically, the emission factors for both CH_4 and CO_2 (expressed as per capita daily mass of emitted gas), the per capita carbon footprint originated by the emissions of these two gases and their relative contribution, the per capita daily biogas emissions (expressed as per capita daily volumes of emitted gas), and its volumetric composition in terms of CH_4 and CO_2 are reported. Missing data were deduced where possible as described in Section 2. Importantly, with the aim of knowing how the various monitoring approaches may have affected the results, the monitoring methodology adopted to measure the gaseous products—where reported—is included as well.

As a first observation from Table 1, data about gas production from Imhoff tanks appear to be scarcer compared to those about septic tanks, as research about gas production in Imhoff tanks in recent years has virtually not been carried out anymore and only outdated data are available. Given their widespread application and their substantial differences from septic tanks described in Section 3, production of biogas, composition, and consequent carbon footprint related to Imhoff tanks will deserve more attention in future research.

Analyzing the data reported in Table 1, some preliminary considerations regarding the variability of emission factors can be made. Specifically, it can be seen that the coefficient of variation (CV) for the CH_4 emission factor estimated by [40] is larger than 100%, indicating a very large data dispersion. In this case, the obtained mean value lacks representativeness. To avoid the problem related to high data dispersion, [55] preferred to present the emission factors by considering the middle value of measurements instead of the mean values. Looking at the results, data dispersion in general seems to be a common problem that does not always allow for a reliable estimation of gas emission factors for septic tanks: only [45] was able to obtain emission factors with low CV. Data dispersion for Imhoff tanks was not explicitly reported with a mean and a standard deviation for the various emission factors, although the considered works clearly revealed strong temporal fluctuations of the emission factors [30,84]. In general, data dispersion for CH_4 and/or CO_2 emissions can be attributed to various factors such as strong temporal changes in environmental conditions (especially temperature), different design, and different geographical location of the studied systems, among others.

Table 1. (**a**) Reported and estimated biogas data, and (**b**) description of the monitoring approach adopted for septic and Imhoff systems. n.a.: not available.

(a)								
Per Capita Carbon Footprint [(b)]	**CH_4 Contribution to Carbon Footprint** [(b)]	**CO_2 Contribution to Carbon Footprint** [(b)]	**CH_4 Emission Factor**	**CO_2 Emission Factor**	**Per Capita Biogas Production**	**Biogas Composition**		**Source**
[g CO_{2eq}·d^{-1}·Capita ^{1}]	**[%-CO_{2eq}-Mass]**		**[g CH_4·d^{-1}·Capita ^{1}]**	**[g CO_2·d^{-1}·Capita ^{1}]**	**[L·d^{-1}·Capita ^{1}]**	**[%-CH_4 vol]**	**[%-CO_2 vol]**	
SEPTIC TANKS								
310.44 [(c)]	92.3	7.7	13.64 ± 5.05 [(c)]	24.00 ± 10.34 [(c)]	33.5 [(g)]	n.a.		[55]
265.9	86.9	12.5	11 ± 2.2	33.3 ± 2.7	34.6 [(g)]	35–65 [(f,g)]	65–35 [(f,g)]	[19,45]
621.7	36.14	53.9	10.7 ± 1.7	335 ± 2.1	198.2 [(g)]	n.a.		
391	54	37.4	11 ± 12	160 ± 3.2	103.5 [(g)]	n.a.		[40]
214.3 [(a)]	99 [(a)]	1 [(a)]	10.1	2.18 [(d)]	16.3 [(g)]	75.2	5.9	[48]
236.6 [(a,e)]	97.8 [(a)]	2.2 [(a)]	11.02	5.16	22.65 [(d)]	72.9	12.4	[82]
15.6	47.8	52.2	0.35	8.14	4.95 [(g)]	n.a.	n.a.	[56]
IMHOFF TANKS								
121.4 [(a)]	97.6	2.4	5.7	3	11.5	74.4	14.2	[28]
135.4 [(a)]	97.5	2.5	6.4	3.4	12.46	76.6	14.7	[30,86]
Not computable	n.a.	Not computable	n.a.	3.24–4.05	11.9–14.7	n.a.	15	[84]

Table 1. *Cont.*

(b)

Period of Measurement	Number of Measurement Days Per Septic or Imhoff System	Overall Number of Measurements Per Septic or Imhoff System	Number of Septic or Imhoff Systems Analyzed	Measurement Location in the Septic or Imhoff System	Location of Measurements	Temporal Range of Measurements	Source
SEPTIC TANKS							
1 week for each septic tank	1→2	1→2	10	Liquid surface	Hanoi, Vietnam,	June and July, 2019	[55]
2 months and 2 weeks	2→5	6→36	8	Liquid surface	Davis and Cool, CA, USA	September to December, 2009	[19,45]
	1→5	1→9	2	Gas vent			
3 months	n.a.	Minimum 3 samples per septic system	7	Gas vent	New York, NY, USA	June to August, 2014	[40]
1 year	n.a.	15	n.a.	Liquid surface	Worcester, MA, USA	Unknown, in 1902 or a year prior to 1902	[48]
10 months	Per capita biogas production from first compartment was calculated based on assumptions, while gas composition was measured for several days within a month for each septic tank		7	Liquid surface	n.a.	Unknown, in 1984 or in a year prior to 1984	[82]
446 days	13–14 for CO_2 8–9 for CH_4	13–14 for CO_2 8–9 for CH_4	2	Liquid surface	County Limerick, Ireland	June/July 2017 to July/August 2018	[56]
IMHOFF TANKS							
1 year	365	365 *	1	Digestion compartment vents	Calumet, Chicago, USA	1927	[28]
1 year	365	365 *	1	Digestion compartment vents	Calumet, Chicago, USA	September 1926 to August 1927	[30,86]
1 year	365	365 *	6	Digestion compartment vents	New Castle, Pennsylva-nia, USA	June 1929 to May 1930	[84]

[(a)] N_2O contribution neglected. [(b)] Computed assuming GWP_{CH4} equal to 21 and GWP_{N2O} equal to 310 in virtue of [19]. [(c)] Middle value average and standard deviation. [(d)] Estimated. [(e)] Computed using middle value of the reported ranges. [(f)] First value for 7 out of 8 septic tanks, second value for 1 out of 8 septic tanks. [(g)] Estimated assuming biogas is made of only CH_4 and CO_2. * Deduced from considerations reported in the text.

Another observation can be made with regard to the lack of data regarding biogas composition for septic tanks in recent works. In more detail, volumetric percentages of CH_4 and CO_2 in the biogas were missing in [40,55,56], while [19,45] made an estimation assuming CH_4 and CO_2 were the only components present in the measured gas. While this information is not needed when considering the carbon footprint of the studied systems, biogas composition and—more importantly—methane percentage are of utmost importance to understand biogas flammability and its energy recovery potential [20,21]. Contrarily, biogas composition was reported in two of the three case studies on Imhoff tanks [28,30,86].

A CH_4 content of about 75% was reported in both these works, which can be considered good for flammability purposes. This is within the same order of magnitude of the reported volumetric CH_4 content in the septic tanks by [48,82]. Though not included in Table 1 due to the missing emission factors, other outdated works report biogas composition for septic and Imhoff tanks [21,31]. According to these works, CH_4 content can vary approximately between 60% and 85% while CO_2 content can vary approximately between 3% and 35%. Indeed, the high CH_4 content of biogas suggests good flammability of the gas mixture from both septic and Imhoff tanks.

An additional factor worthy of being noted is that the measured amounts of biogas produced in septic systems change according to the measurement location within the systems. Specifically, measurements were carried out either from the liquid surface inside the tank [45,55,82] or from the gas vent typically located on top of the building served by the same tank [40,45]. From the results, larger amounts of biogas were found when measurements were taken from the vents. However, a closer look into the specific emission factors for CH_4 and CO_2 reveals a much larger contribution by carbon dioxide compared to measurements taken from the liquid surface. The reason for this discrepancy was attributed to the fact that the gas measured from septic tank vents incorporates a contribution from the effluent disposal into the soil where bacteria produce a large amount of CO_2 starting from the residual organic carbon content in the septic tank effluent. This CO_2 may be partly recirculated inside the tank through the normally occurring air circulation within septic systems, thus ending up in the vented gas along with the biogas produced within the tank [45].

Regardless of the measurement location, per capita methane emissions from septic tanks seem to be consistent within the various research works, ranging approximately between 7 and 13.5 g_{CH4} capita^{-1} d^{-1}, apart from the case by [56] who reported a value lower by an order of magnitude. Aside from the latter, CH_4 emission factors closer to the lower boundary range of septic tank values are reported for the few studies on Imhoff tanks. However, this different behavior between emissions from septic and Imhoff tanks must be confirmed with more recent studies on Imhoff tanks. Different emission values could also be partly attributed to more advanced measurement tools employed in the most recent years.

With regard to carbon dioxide, per capita emissions from septic tanks are more dispersed, widely ranging between 2 and 33.3 g_{CO2} capita^{-1} d^{-1} when measurements were taken from the septic tank liquid surface and between 160 and 335 g_{CO2} capita^{-1} d^{-1} when measurements were taken from the vents due the previously described contribution by the effluent dispersal to the soil. Per capita CO_2 emissions from Imhoff tanks were found to be around the lower boundary of CO_2 emission factors for septic tanks where measurements were taken from the septic tank liquid surface. The issue of CO_2 produced in the effluent soil disposal was not reported in the works measuring biogas from Imhoff tanks, likely due to the fact that measurements were recorded from the gas vent with equipment submerged within the liquid surface of the digestion chamber as carried out in [28]. Considering the biogas coming from septic tanks, the carbon footprint contribution by methane results preponderant, ranging from 87 to 99%, while it becomes comparable—and sometimes even lower—than the carbon dioxide contribution when considering the overall gas vented out from the septic system. Only [56] found a similar contribution of methane to the case of vent measurements by [40,45], despite measuring biogas emission from the liquid surface. The same preponderant contribution by CH_4 could also be observed for Imhoff tanks when measurements are taken from the septic tank surface water. For the sake of completeness, it is important to consider that, when gas is measured from septic tank vents, there is an additional non-negligible carbon footprint contribution by nitrous oxide (N_2O) [40,45], due to the occurrence of nitrification and denitrification processes in the effluent dispersal to the soil and recirculation back to the system, similar to the case of CO_2 [45]. However, this last work revealed a huge uncertainty in the N_2O emission factor estimation with a CV largely surpassing 100%. N_2O was mainly measured in the recent works by [40,45,55,56], while [48,82] did not measure it. This can be attributed to the fact that N_2O emissions from wastewater treatment technologies have become a concern only in recent decades. For the same reasons, no N_2O emissions were reported for the outdated works about Imhoff tanks.

Besides the measurement location, with the aim of understanding the reliability and the limitations of the emission factors provided by the various studies, it is important to also analyze the measurement frequency and the number of investigated septic systems.

From Table 1, it can be seen that the number of septic systems analyzed in each research work varies between seven and ten with the exception of one work which evaluated the emissions only from two septic tanks [56]. Gas emissions from roof vents were measured only in two works, and one of them carried out these analyses only in two septic systems [45]. Indeed, increasing the number and—possibly—the variety of septic systems from which measurements are taken could help avoid the inclusion of peculiar context-specific factors, such as the size and the lifestyle of the population served as well as system design features, in the overall estimated emission factor. While gas emissions from the septic tank liquid surface better describe the rate of biological processes in the accumulated sludge, vent emissions may represent more realistic quantifications of the carbon footprint of septic systems as they incorporate a portion of GHG likely produced in the septic tank effluent dispersal to the soil. For these reasons, more GHG emission measurements from septic tank vent systems need to be carried out in the future. However, from a gas collection and exploitation perspective, collecting gas from the liquid phase of the septic tank can provide a more easily inflammable mixture than collecting gas from the vent, given the relatively higher CH_4 contribution in the former case.

The time period within which measurements are taken is another important feature determining the reliability of emission factor estimations. Indeed, a sufficiently large number of measurements homogeneously spread through lengthy periods of time allows reduction of the effect of specific seasonal conditions on the emission factors. On the other hand, measurements circumscribed to a short time span (such as a week or a month) may be heavily affected by the climate condition of that particular period. In this regard, temperature is expected to be an important environmental condition which speeds up all biological processes, including those responsible for biogas production [87]. Underestimations or overestimations of biogas emission factors may occur simply due to the fact that measurements were taken only in winter or summer, respectively. Furthermore, population behavior and lifestyle, on which wastewater characteristics fed to septic tanks strictly depend, may change as a function of season. In the case of the measurements from septic tanks displayed in Table 1, the largest time span when measurements were carried out occurred in [48,82], while the most recent research by [40,45,55] presented much shorter time spans, ranging from one week to a maximum of three months. Exceptionally, [56] carried out measurements over a very long period of time but only from two septic tanks. Furthermore, as presented in the Supplementary Materials of the same work, methane measurements were not taken at a constant frequency throughout the monitoring period, which could in turn have undermined a thorough estimation of the CH_4 emission factors which resulted much lower than other literature values. Similarly, Imhoff tank emission factors were all estimated using measurements taken throughout a one-year time span [28,30,84].

The number of measurements within the chosen time span has a similar importance to the time span during which measurements are taken. In general, assuming these measurements are equally spread throughout a fixed period, the higher the measurement frequency is, the higher the accuracy of the emission factor can be expected. The authors of [55] presented a peculiarly low frequency of measurements, where each of the analyzed septic tanks was measured a maximum of twice within a period of only one week. However, thanks to the relatively larger number of systems from which measurements were taken, some correlations between emitted gases and operating conditions in the tanks (Section 5) could be deduced. Indeed, measurement frequency is obviously a crucial parameter for emission factor estimation. As a matter of fact, if measurements are too few, normal alterations of gas emissions occurring within the time span from a measurement to the next one may be wrongfully neglected. In the Imhoff tank cases, gas collection was carried out continuously and data were likely recorded on a daily basis, which indeed can be considered a good and reliable monitoring practice. Nevertheless, contrary to what was carried out for septic tanks where several systems were analyzed, in the case of Imhoff tanks two of the reported measurements were limited to only one system [28,30], while a single work reported measurements from six Imhoff tanks [84].

As a more general consideration by looking at Table 1, a strong variation of the employed monitoring methods can be noted. The number of samples for each tank and the number of analyzed tanks varies greatly. This highlights the need for defining standard protocols for gas measurements from septic tanks to obtain reliable emission factor estimations.

5. Environmental and Operational Factors Affecting Biogas Production and Composition

Table 2 summarizes the environmental and operational factors affecting biogas production and composition in septic tanks, while Table 3 provides those affecting biogas production and composition for Imhoff tanks.

Table 2. Effect of investigated environmental/operating factors on: (**a**) CH_4 emissions and (**b**) CO_2 emissions from septic tanks (effect is reported as: "Positive" if an increase in the factor analyzed leads to an increase in CH_4 or CO_2 emissions, "Neutral" if an increase or a decrease in the factor analyzed does not lead to either an increase or a decrease in the emissions, "Negative" if an increase in the factor analyzed leads to a decrease in CH_4 or CO_2 emissions).

(a)

Factor	Effect	Source
Temperature	Neutral	[45,55]
	Positive	[48]
Septage storage time	Positive	[55]
COD content in septage	Positive	[55]
BOD content in septage	Positive	[55]
ORP	Negative	[55]
Dissolved oxygen	Neutral	[55]
Scum layer thickness	Neutral	[45]
Household greywater disturbance	Positive	[19]

(b)

Factor	Effect	Source
Water hardness (measured as calcium carbonate)	Negative	[45]
Scum layer thickness	Neutral	[45]
Household greywater disturbance	Neutral	[19]

As can be observed from Tables 2 and 3, the main environmental factor whose effect on biogas production in both septic and Imhoff tanks has been widely investigated in the literature is temperature [6,18,28,30,45,48,55,57,82–84,88,89]. When talking about temperature effects, it is important to discriminate the studies that investigated the effect of seasonal temperature (i.e., atmospheric temperature) from those that investigated the effect of temperature of the sewage fed to the system, as well as that of the liquid phase inside the tank and the sludge [30,57]. This discrimination is important because, while for centralized wastewater treatment systems the difference between environmental temperature and liquid temperature is negligible, for decentralized systems such as septic and Imhoff tanks this difference may be more relevant. In fact, liquid temperature of wastewater leaving a nearby household carried to septic or Imhoff tanks can more directly affect the temperature inside the tank compared to what happens in centralized systems. In general, the use of hot water in households can directly affect temperature inside the tanks due to the fact that the water heat is not dissipated in the short time between household discharge and the entry into the tank [19]. In addition, the temperature of white waters collected and carried to septic and Imhoff tanks can more directly affect the temperature inside the tanks. For instance, the melting of snow and cold rains can lower down the temperature of the sewage going into these tanks [6]. Furthermore, since tanks may be placed partially or totally underground compared to what happens in centralized facilities, oftentimes the mass of accumulated sludge within the tank is more thermically insulated from the air and has a more constant temperature compared to the influent sewage [11,57]. Therefore, changes in the external temperature have a milder effect on sludge digestion and consequent biogas production when tanks are installed partially or totally underground compared to the case when they are located above the ground [88].

In septic tanks, liquid temperature failed to correlate with methane emissions according to [45,55], while a clear positive correlation was found in [48]. The missed correlations can be easily attributed to the very short surveillance periods, which led to very narrow ranges within which the liquid temperature could vary (i.e., 1.1 °C in [55] and 5 °C in [45]). Conversely, when the measurement period involved the entire year and temperature ranged more widely, a clear correlation was identified [48]. These outcomes highlight the importance of carrying out long-term measurement campaigns for a reliable quantification of biogas production and composition and the identification of the influence of operating conditions. The same positive correlation between biogas production and either environmental (air) or sludge/sewage temperature was identified in other works dealing both with septic and Imhoff tanks [6,18,28,30,82–84]. The explanation for the positive effect of temperature on biogas and methane production is immediate: temperature speeds up all biological processes including hydrolysis, fermentation, and, more importantly, methanogenic activity, resulting in higher biogas production, especially when moving from psychrophilic to mesophilic conditions [90,91]. In general, during cold seasons digestion is significantly slowed down and this results in an increased sludge accumulation [84], while summer temperatures allow for faster hydrolysis of biodegradable organic carbon and methanization with much lower sludge accumulation [92,93]. A positive effect of temperature on digestion till a threshold of 25–26.7 °C was reported, above which a further increase could slightly slow down the digestion and gas production [86].

It is important also to note that correlations were studied considering temperature and methane (or biogas) as daily averages. Only [19] reported a limited study on the daily trend of methane emissions where higher methane emissions at particular times of the day corresponded to specific household activities producing large amounts of grey waters that might have disturbed the accumulated sludge in the tank, thus causing the stripping of the gas accumulated within it. Nevertheless, only methane seems to follow this behavior, while the same cannot be said for carbon dioxide. In general, in the same study no clear daily periodicity could be observed for either methane or carbon dioxide. In view of understanding in more detail the potentiality of Imhoff and septic tanks to produce methane that could be exploited for household needs, many more studies elucidating the daily trends of methane and biogas production from these technologies are needed.

Secondary to temperature, the effect of sludge withdrawal frequency appears to be relevant for the gas production in both Imhoff and septic tanks. There is an overall agreement in the literature that an increased sludge withdrawal frequency decreases gas production in both septic and Imhoff tanks [6,19,30,84]. This is expected since an increased sludge-cleaning frequency reduces the sludge accumulation and, along with it, the number of bacteria responsible for organic carbon conversion into biogas. Nevertheless, [11] suggests frequent withdrawals of small amounts of sludge compared to removing large amounts of sludge at a single time for an optimal gas production in Imhoff tanks to provide sufficient time for bacteria in the accumulated sludge to regenerate. Therefore, the ideal withdrawal frequency is strictly connected to the amount of sludge withdrawn each time. However, the sludge withdrawal frequency should not be confused with the overall amount of sludge inside the tanks which can be larger in winter due to a much slower particulate matter hydrolysis, corresponding a lower biogas production [83]. Comparable to the sludge withdrawal frequency effect is the septage storage time which was found to be positively correlated to the methane production in [55]. Indeed, a larger sludge residence time inside septic tanks is expected to increase the formation of anaerobic bacteria responsible for organic matter degradation. In the same study, septage COD and BOD concentrations were found to be positively correlated to gas production, as they are indicators of substrate availability. Based on this, BOD and COD contents in septage should be considered promotors of biogas production from septic tanks.

pH is a frequently discussed parameter affecting biogas production in Imhoff tanks. In more detail, pH was found to drop to critical levels in Imhoff tanks especially during the start-up period due to a fast volatile fatty acid (VFA) production not counterbalanced by an increased methanogenic activity. If an increased methanogenic activity does not correspond to the VFA production increase [11,18,94], the imbalance between the amount of produced and consumed VFA leads to VFA accumulation and pH drop, worsening the methanogenic activity [95]. Low pH does not only reduce biogas production but also reportedly changes its composition. Specifically, a 50% CO_2 content in biogas was detected at a sludge pH between 5.2 and 6.8 [30], indicating incomplete digestion with accumulation of CO_2 produced during fermentation and not enzymatically reduced into CH_4 by methanogens [96]. An increase in the CO_2 content of biogas up to 63% during the transition period from a pH of 5.1 to a pH between 7.3 and 7.6 was reported [18]. In several studies, the addition of lime—often referred to as liming—was considered essential to increase the pH to optimal ranges and thus achieve complete sludge digestion and improved methane production [11,84,95,97]. The optimal pH range was found to be between 6.5 and 7.5 by [30], while other works on Imhoff tanks reported improved gas production when pH was increased to a maximum of 7.3–7.8 [18,98]. In the study by [84], lime needed to be added in early spring when temperatures did not allow for a prompt methanogenic activity, which in turn caused VFA build-up and related pH drop to 6.6, if not lower. Liming resulted more important for Imhoff tank start-up while only limited amounts of lime were needed once the tank was fully operating and the sludge ripened [98]. Specifically, ripened sludge, namely sludge that has been stored in Imhoff tanks for a while, needs only small amounts of lime for optimal digestion and has been suggested as ideal inoculum to start up Imhoff tanks [11,94]. According to [95], pH control is particularly successful in Imhoff tanks thanks to the sludge freshness. Opposed to sludge freshness is the characteristic of septicity, which is caused by storing sludge for too long; this has been reported to lead to a higher acidity [95]. Septicity is generally avoided in Imhoff tanks thanks to the fact that these systems are continuously added with fresh sludge from the sewage. Conversely, in separate sludge digestion tanks, when solids come from a previous sedimentation tank where they accumulate for too long, there is an increased risk of feeding the digestion tank with septic sludge and lime addition may be ineffective unless high amounts are dosed [95].

It must be acknowledged that all the previously described research concerning pH effects on biogas production investigated Imhoff tanks, while very limited research about the pH effect on septic tank biogas production has been published so far. Only [45] monitored pH contextually in biogas measurements but no attempted correlations were reported. The related work by [19], which described in more detail all the obtained results, showed a detailed monitoring frequency of water pH from the analyzed septic tanks but did not present any identified correlation between pH and methane or biogas emissions. From the reported values, pH measurements were almost always within the optimal range identified in the previously mentioned works on Imhoff tanks, which may explain the missed correlation. The lack of research in this field does not imply that pH is not a relevant parameter for septic tanks; instead, it may be connected to the fact that most of the published research was carried out when the start-up period was already over, and the issue of pH decrease below the optimal range for methanogens was not encountered. Even in Imhoff tanks, pH was found to be a critical parameter especially during start-up, while much fewer problems were encountered afterwards.

While the pH effect was not discussed, [45] hypothesized a possible negative correlation between CO_2 emissions and water hardness in septic tanks. Specifically, thanks to a peculiarly higher water hardness in one of the septic tanks showing lower CO_2 emissions compared to another one presenting low water hardness, [45] inferred that some of the biologically produced CO_2 could react with the calcium dissolved in water instead of stripping as a gas. It must be pointed out that more research is needed to confirm this interesting hypothesis.

Oxygen reduction potential (ORP) was negatively correlated to methane production in the septic tanks studied by [55] and also to the septage storage period. ORP was negative throughout the operations, indicating a highly reducing environment. Since CH_4 is produced consequently to anaerobic reactions enzymatically reducing organic and inorganic carbon [96], the lower the ORP is, the larger CH_4 production is expected to be. ORP was also measured in one septic tank by [45] with a detected value of +200 mV, indicating the complete lack of reduction reactions and therefore of anaerobic digestion. No investigation between ORP and methane or biogas production was reported in the case of Imhoff tank research. Nevertheless, given the relevance of the ORP and the clear correlation found by [55], ORP measurements can represent an important and easy-to-perform way to quantify the anaerobic activity inside septic and Imhoff tanks, especially when it is difficult to perform gas measurements continuously.

In addition to these factors, the effect of the thickness of the scum layer formed on top of the liquid passing through septic tanks on gas emission was investigated by [45]. The scum layer may be determined by the served people's diet as reported by [19] which in turn may affect sewage composition and biogas production. Nevertheless, no correlation between septic tank gases and scum layer thickness could be found. On the other hand, no attempted correlation between gas production and scum layer thickness was presented in the works about Imhoff tanks. Conversely, pressure was found to negatively affect gas emissions from Imhoff tanks. In [30], a slight decrease in pressure resulted in an increase in gas emissions from an Imhoff tank. The proposed mechanisms possibly explaining the impact of pressure on gas emissions are the following: (i) a decrease in pressure tends to volatize more gases toxic to digestion, thus reducing the inhibition on the process, or (ii) a decrease in pressure simply enhances the stripping of gas produced, including methane and carbon dioxide. Indeed, this is a topic that needs further investigation as only few outdated studies have addressed this issue. No impact of pressure on septic tank gas production or emissions has been reportedly investigated.

Table 3. Effect of investigated environmental/operating factors on biogas production in Imhoff tanks (effect is reported as: "Positive" if an increase in the factor analyzed leads to an increase in biogas emissions, "Neutral" if an increase or a decrease in the factor analyzed does not lead to either an increase or a decrease in the emissions, "Negative" if an increase in the factor analyzed leads to a decrease in biogas emissions).

Factor		Effect	Source
Temperature	Environmental (air)	Positive	[18,30]
	Digestion compartment	Positive	[28,30,83]
		Positive till 25–26.7 °C. If temperature increases further, negative	[86]
	Sewage	Positive	[6,30,84]
pH		Positive till optimal value	[18,30,84,95,97,98]
Sludge accumulation/withdrawal		Positive/Negative	[6,11,30,83,84]
Pressure		Negative	[30]

Contrary to the intensive research on greenhouse gas mitigation strategies applied to centralized systems [99], strategies specifically designed for gas emission mitigations for septic and Imhoff tanks have not attracted much interest up to now. Aside from flaring biogas emitted to convert methane into carbon dioxide, only one strategy has been recently proposed by [100], where a light source was positioned inside the septic tank to promote algal growth. These algae consume CO_2 and prevent CH_4 formation through oxygen release, which leads to a significant greenhouse gas emission reduction of the whole system. At the same time, potentials for energy recovery from biogas (extensively discussed in the next section) are zeroed since too little CH_4 is produced.

6. Energy Recovery from Septic and Imhoff Tanks

As direct analyses on the carbon footprint have been focusing only on septic tanks, the carbon footprint of Imhoff tanks does not seem to be a huge concern in research. This can be first attributed to the fact that research quantifying gas emission from Imhoff tanks was carried out in a period of time when the carbon footprint of wastewater treatment was not a concern. It is also true that, while CH_4 and CO_2 gases from septic tanks are usually vented out freely in the environment, the same gases from Imhoff tanks appear to be more suitable for collection and energy recovery purposes given the large amount of research investigating this practice. Indeed, methane burning reduces the carbon footprint of the gas stream by converting methane into carbon dioxide according to Equation (1), and it is a strategy adopted to effectively reduce the carbon footprint of landfills even when the heat produced thereby is not recovered for energy purposes [101].

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (1)$$

In conventional anaerobic digesters, torches are normally installed to burn the produced biogas, thereby avoiding the direct venting of methane and recovering energy to partly heat up the digestion reactors and obtaining stabilized sludge [102,103]. Nevertheless, in the case of Imhoff tanks, it is important to consider that the produced methane is not always used for energy production, and when it is exploited, the carbon footprint is reduced but not zeroed since the burning process simply converts methane into carbon dioxide, as expressed in Equation (1).

Biogas, compared to natural gas, shows different flammability limits, meaning the range of fuel concentrations in which the gas mixture can be ignited in air and support flame propagation: due to the significant CO_2 presence in biogas (sometimes up to 50%), lower and upper flammability levels rise from 5.2% and 11.4% methane content in air (typical of natural gas) up to 10.4% and 22.8% biogas content in air (considering dry gas at 20 °C) [104]. Obviously, a higher CO_2 content in biogas negatively affects the calorific value of the biogas itself with negative impacts on the amount of recoverable energy [105]. As presented in Table 1, Imhoff and septic tanks normally show higher and variable CO_2 content than high-rate anaerobic processes, and the overall amount of biogas that is produced is limited by the fact that the process occurs at ambient temperature and by the limited size of the population served, which makes the anaerobic digestion much less profitable compared to larger-scale installations [106]. In any case, in order to be exploitable in high-efficiency energy production systems such as gas turbines, CO_2 and H_2S removal from the biogas is mandatory to avoid corrosion and reach a good calorific value, so the profitability of biogas exploitation from septic and Imhoff tanks is apparent only when the treated capacity reaches at least some hundreds of inhabitants [107].

Dealing more specifically with energy recovery from Imhoff tanks, as previously disclosed, several works discussed potentials for capturing and burning biogas from Imhoff tanks and producing energy thereby [18,30,31,57,86]. According to some studies, producing energy from Imhoff tank methane represents a good approach for a local population [18] and for others the produced energy could be used to heat up the accumulated sludge in the same system [31,57,86] to achieve a more intensified anaerobic digestion along with a sludge wastage reduction and an increase in Imhoff tank capacity with consequent investment cost reduction [86]. This is beneficial especially in winter seasons where temperatures inside the tanks may not allow for good and stable digestion [84]. Nevertheless, according to [83], energy recovery from Imhoff tanks is inconvenient given the low amount of biogas produced, and heating up the digestion compartment of the same tanks is not convenient either due to the heat loss with the effluent. It must be pointed out that these works were published about one century ago and that more up-to-date research is needed to clarify the actual convenience of burning Imhoff tank biogas and assess its possible exploitation options.

Contrary to the outdated—yet intensive—research on energy recovery from Imhoff tank biogas, essentially no work dealing with energy recovery by burning the CH_4 produced in septic tanks could be found. Nevertheless, for this last technology there is a growing interest in alternative ways of producing energy through electrochemical technologies [60,108–113] or through establishing an enhanced anaerobic digestion process [114].

Electrochemically assisted anaerobic digestion through microbial electrolysis cells (MECs) can be helpful to enhance the produced energy yields: through the application of an electric field, an in situ production of H_2 and O_2 is observed, with higher H_2 concentration in the biogas and/or an improved CH_4 production through hydrogenotrophic homoacetogenic pathways [108]. When comparing the performances of septic tanks with and without MECs, a significant increase in biogas production (up to 5 times) was observed, with a reduced H_2S concentration (2.5 times lower); in addition, while no significant differences in COD removal were observed, total phosphorus in the output of the MEC-assisted septic tank was 39% lower than in the effluent from the septic tank alone [60]. Similarly, another literature study reported a significantly higher total phosphorus removal in MEC-assisted septic tanks (from 12.2% to 77.2–98.7% at 25 °C, from 7.45% to 20.7–93.9% at 15 °C) at a small applied voltage input (0.50–0.88 V, corresponding to an energy consumption of 0.26–37.1 kWh/m^3 treated sewage), along with a complete sulfide removal.

Among the various electrochemical technologies, microbial fuel cells (MFCs) have recently gained interest in the scientific literature thanks to their capability to generate electricity in decentralized areas [109]. MFCs are composed of an anode and a cathode isolated by a membrane: at the anode, exoelectrogenic microorganisms degrade the organic matter, releasing protons, electrons, and CO_2 [110]. The protons diffuse through the membrane, while the electrons flow through an external circuit, generating an electric current; finally, both protons and electrons reach the cathode, where they combine with oxygen, generating water [110]. Recently, microbial isolates from septic tank wastewater (*Cronobacter sakazakii* AATB3 and *Pseudomonas otitidis* AATB4) were used to biodegrade wastewater, showing a high COD removal (79.1%), a maximum coulombic efficiency of 15.5% at pH 7, and producing power and current densities, respectively, of 280 mW m^{-2} and 800 mA m^{-2} when using *P. otitidis*. The capability of microbial isolates from septic tank wastewater to act as catalysts in the degradation of polycyclic aromatic hydrocarbons was demonstrated in [111], when using *Psathyrella candolleana* as a novel basidiomycete fungi at the cathode. As MFCs can be difficult to design and operate, especially in decentralized systems, an easy-to-operate MFC stack, consisting of a common base and multiple pluggable units, was recently proposed in the literature [112]: besides obtaining a power density of 142 mW m^{-2} by connecting three units in parallel, a relatively limited cost of USD 25 per day was highlighted to power a 6 W led light. Excellent performances of septic tanks converted with MFCs were again highlighted in [113], with remarkable removals of COD (93.9%), BOD (92.7%), and TSS (98.6%) and a generation of 3.029 V of electricity, able to power a 2.0 V LED bulb. Similarly, elsewhere multi-stage MFCs equipped with resistors from 50 to 1000 Ω showed remarkable TSS (99.76–99.8%), BOD (69.56–86.4%), and nitrate (68.97–82.8%) removals for simultaneous septic wastewater treatment and electricity production [115]. Finally, an excellent COD removal and a total coulombic efficiency, respectively, of 89.67% and 48.07% were reported in [116], where 15 cartridges of MFCs with a proton exchange membrane and without catalyst were installed in a real septic tank; challenges for system upscale were identified to be the high activation energy, the biofilm in the anode, and the conductivity of the anode and cathode solutions [116].

Another strategy to improve energy recovery from septic tanks is to improve the biodegradability of sewage COD, which is known to be limited. Several pretreatment technologies, including mechanical, thermal, and chemical ones applicable for septic tanks, have been recently investigated to improve COD solubilization and subsequently methane production from sewage sludge [117]. Regarding septic tank accumulated sludge, ultrasonication was proved to be effective in raising CH_4 production potential (from 299 to 410 L kg^{-1} $VS^{-1}{}_{destroyed}$) and methane content in biogas (from 73.15 to 81.83%), showing a net energy gain of 1.67 $Wh \cdot L^{-1}$ [118]. Another possibility to stabilize and improve the performances of septic tanks, leading to a transition to high-rate septic tanks and thus obtaining higher CH_4 production, can be biosolid-derived biochar addition: biochar-amended reactors showed a steady increase in daily methane production (4.3 times higher than the control) by raising the organic loading rate (OLR) from 0.08 to 3 g $COD \cdot L^{-1} \cdot d^{-1}$, while control septic tanks showed disturbances when the OLR was raised over 2 g $COD \cdot L^{-1} \cdot d^{-1}$ due to VFA accumulation [114].

A further alternative to enhance the sustainability of septic tanks can be the integration of solar energy (e.g., through photovoltaic installation), even supporting simple downstream biological treatment solutions (such as rotating bed contactors) for an installed PV area of 25 m^2 and a treated population of 100 inhabitants [119].

To sum up, current literature is focusing on innovative technological solutions to efficiently exploit the methane yield generated from septic tanks, which is hindered by limited sludge biodegradability in traditional configurations; however, the economic profitability of energy generation from the produced biogas strongly depends on the produced volumes, which are often low in decentralized sanitation systems. Further research is needed to assess the actual sustainability of biogas collection, purification, and usage from existing septic and Imhoff tanks, broadly analyzing its dependence over system potentiality.

7. Conclusions

The present work is a critical review about gas production from septic and Imhoff tanks with focus on the carbon footprint and related energy recovery potential. This review led to the following findings:

- a lack of up-to-date research about gas emissions from Imhoff tanks has emerged;
- research about septic tanks should be carried out involving longer periods of time to incorporate the effect of seasonal variations;
- temperature is found to be a dominant parameter strongly promoting methane and biogas production in both septic and Imhoff tanks;
- besides temperature, other important parameters affecting gas production in both types of tank are pH and sludge accumulation;
- operationally speaking, liming has been a common practice in Imhoff tanks to keep pH within its optimal range during their start-up and recovery from a low-temperature period;
- carefully optimizing sludge withdrawal is found to strongly affect biogas production in both septic and Imhoff tanks;
- biogas from both septic and Imhoff tanks can be used for energy production, although research has focused essentially on energy production exclusively from Imhoff tank methane. This energy could be used for human beings' daily needs or to heat up digestion compartments and improve system capacity by reducing sludge accumulation;
- electrochemically assisted anaerobic digestion via microbial electrolysis cells (MECs) can be beneficial to increase the energy yields from septic tanks;
- improving the biodegradability of sewage COD by promoting organic matter solubilization in the sludge through the application of dedicated pretreatment technologies is another way to improve energy recovery from septic tanks;

- another option for stabilizing and improving septic tank performance, leading to a transition to high-rate septic tanks and consequently increasing CH_4 output, is to add biochar generated from biosolids: by increasing the organic loading rate (OLR), biochar-amended reactors were found to produce 4.3 times more methane per day than the control;
- reduction of carbon footprint and improved energy recovery from septic tanks have been achieved through integrated solar energy generation (e.g., through photovoltaic installation).

The current review is limited to the carbon footprint of septic and Imhoff tanks without considering the derived emissions due to the discharge of their variably polluted effluents in either a disposal soil or a secondary treatment such as constructed wetlands. It is worthy of being mentioned that effluents from septic and Imhoff tanks still present a significant content of organic matter and nitrogen assimilable into a primary effluent from conventional WWTPs, that can stimulate reactions producing greenhouse gases either in a disposal soil or in a secondary treatment. This topic needs an ad hoc investigation considering all the possible destinations of septic and Imhoff tank effluents.

Given the widespread application of septic and Imhoff tanks and their potential contribution to the overall carbon footprint of wastewater treatment, more research developing effective strategies for carbon footprint mitigation from these technologies needs to be performed in the future.

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