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English version

Anaerobic digestion plants - Feasibility assessment methodology for integrating a Volatile Fatty Acid Platform Technology

EUROPEAN COMMITTEE FOR STANDARDIZATION
COMITÉ EUROPÉEN DE NORMALISATION
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Contents

Page

European foreword

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Introduction

In the light of the climate targets to be achieved, major efforts have been made in recent years in Europe to promote the production of renewable energies[1,2]. In this context, the construction and operation of biogas plants - in particular for energy and heat generation - have received substantial support. Today, around 17,000 biogas plants are in operation in Europe[3].

Although the installation and operation of biogas plants has received such great support over many years, plant operators today are confronted with a number of challenges, some of which represent an extensive threat[4,5]:

1) It is expected that the prices for fossil raw materials and energy sources will remain at a low level within the coming years.

2) There are very large market fluctuations in the renewable energy sector, which can be seen as a major problem in the economic operation of biogas plants.

3) Subsidies for renewable energies have been reduced or phased out in the recent past. However, many biogas plants, especially smaller ones, are currently not economically viable without financial support.

4) In the context of energy and non-energy services, there is often high administrative bureaucracy, which in turn prevents urgently needed investments in biogas plants.

5) Existing uncertainties regarding continuity and legal certainty also prevent larger, long-term investments.

6) Very often there are uncertainties in the evaluation of (new) technologies and products, also from the perspective of immature markets. These ambiguities are usually an additional obstacle to investment.

7) Biogas plant managers encounter difficulties in achieving a stable and affordable supply of biomass to be used as feedstock[6]

Due to the above mentioned persistently low market price for fossil fuels, changing (subsidy) policy requirements and changes in legislation, many biogas plant operators are urgently looking for new value chains (like material use) in order to be able to operate continuously in an economically viable way. At the same time, legal changes associated with ecological grievances and growing ecological awareness are creating new markets for sustainably manufactured products.

Technologies for coupled energetic and material use of biogenic residues and waste materials and the integration of these technologies into already existing biogas plants are increasingly being perceived as

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[1] https://ec.europa.eu/commission/energy-union-and-climate/state-energy-union_en

[2] http://unfccc.int/paris_agreement/items/9485.php

[3] http://european-biogas.eu/biogas/

[4] http://european-biogas.eu/2017/12/14/eba-statistical-report-2017-published-soon/

[5] http://european-biogas.eu/wp-content/uploads/2015/01/EBA-Biogas-Report-2014.pdf

[6] Poeschl M, Ward S, Owende P (2010) Prospects for expanded utilization of biogas in Germany. Renew Sustain Energy Rev 14: 1782–1797. doi:10.1016/j.rser.2010.04.010

a possible alternative application (VOLATILE[7], Optigär[8], URBIOFIN[9]). Recently, a BREF document for waste treatment[10] has been published which describes within the section of anaerobic digestion the conversion of organic waste to carboxylates, carboxylic acids or polymers by fermentation with mixed cultures. Although promising approaches have been developed in this field recently, legal uncertainties and ignorance of existing technologies and their potentials amongst others, prevent urgently needed investments in this area.

Integrating a Volatile Fatty Acid Platform in an existing anaerobic digestion plant allows a company to move its practices in the preferred direction of the responsible waste management hierarchy. Rather than recovering the energy of organic waste in the form of biogas, the organic waste can be recycled into new materials. A move towards recycling and reuse of waste is in line with the European Commission's Circular Economy Action Plan, which wants to ensure less waste and that resources are kept in the economy for as long as possible. Nevertheless, this is a rather new technology and governmental incentives have yet to shift in favourable direction for materials created out of waste.

This high complexity requires uniform, simple guidelines to assess the ecological and economic sense of an upgrading of existing biogas plants for coupled energetic and material use. Therefore, the aim of EvaVOLATILE is to develop a guidance document that allows an evaluation of the integration of a Volatile Fatty Acid Platform (VFAP) technology into existing biogas systems with only a little financial and time expenditures. The innovative VFAP technology could be used for the bioconversion of municipal solid biowaste fractions and sludgy biowaste from other industries into volatile fatty acids. The acids could be recovered continuously applying i.e. membrane technologies and used as feedstock / carbon source for value added fermentation targets like PHA, single cell oil and omega-3 fatty acids.

1 Scope

This CWA provides guidance for biogas plant operators, investors, and municipalities on how to assess whether the changeover of a given biogas plant to a coupled energetic and material use is ecologically and economically reasonable under certain conditions. For this purpose, the CWA uses a simple evaluation methodology.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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[7] http://volatile-h2020.eu/

[8] https://fnr.de?id=11150&fkz=22410212;

https://fnr.de?id=11150&fkz=22400515;

https://fnr.de?id=11150&fkz=22400615

[9] https://cordis.europa.eu/project/id/745785/

[10] Pinasseau, A., Zerger, B., Roth, J., Canova, M., Roudier, S. (2018). Best Available Techniques (BAT) Reference Document for Waste treatment Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control); EUR 29362 EN; Publications Office of the European Union, Luxembourg, 2018; ISBN 978-92-79-94038-5, doi:10.2760/407967, JRC113018

https://eippcb.jrc.ec.europa.eu/reference/wt.html

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
platform chemicals
can be used directly in the chemical industry or as building blocks in chemical or biotechnological synthesis.

3.2
volatile fatty acid platform
technical extension for biogas plants which provides volatile fatty acids as platform chemicals through anaerobic digestion

3.3
volatile fatty acids
short-chain fatty acids, which are produced during anaerobic digestion

SOURCE: ISO 6107-8:1993, 64, modified — ("saturated organic acids" was replaced by "fatty acids" and "mainly" was replaced by "which are")

4 Symbols and abbreviations

ABNT	Brazilian Association of Technical Standards (Associação Brasileira de Normas Técnicas)
AD	Anaerobic digestion
ALA	α-Linolenic acid
BIC	Bio-based Industries Consortium
BREF	Best Available Techniques Reference Document
CAPEX	Capital expenditure
CEN	European Committee for Standardization
CEN/TR	CEN Technical Report
CEN/TS	CEN Technical Specification
CENELEC	European Committee for Electrotechnical Standardization
COD	Chemical oxygen demand
CWA	CEN Workshop Agreement
DHA	Docosahexaenoic acid
DIN	German Institute for Standardization
EC	European Commission
EN	European Standard
EPA	Eicosapentaenoic acid
EU	European Union
evaVOLATILE	Anaerobic digestion plants – Feasibility assessment methodology for integrating a

	Volatile Fatty Acid Platform Technology
FA	Fatty acid
GC	Green Certificate
GHG	Greenhouse gas
HM	Heavy metal
IPR	Intellectual property rights
IRR	Internal rate of return
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
MBT	Mechanical biological treatment
MP	Microbial protein
MSW	Municipal solid waste
MVOC	Microbial volatile organic compounds
NBR	Brazilian National Standards (Norma Brasileira Regulamentadora)
OF-MSW	Organic fraction of municipal solid waste
OPEX	Operational expenditure
PHA	Polyhydroxy alkanoates
PLA	Polylactic acid
PPP	Public Private Partnership
SCO	Single cell oil
SIRA	Strategic innovation & research agenda
SWOT	Strengths, weaknesses, opportunities and threats
UNI	Italian National Unification (Ente Nazionale Italiano di Unificazione)
VDI	Association of German Engineers (Verein Deutscher Ingenieure e.V.)
VDMA	Mechanical Engineering Industry Association (Verband Deutscher Maschinen- und Anlagenbau e. V.)
VFA	Volatile fatty acid
VFAP	Volatile fatty acid platform
VGF	Vegetable, garden and fruit
VOLATILE	Biowaste derived volatile fatty acid platform for biopolymers, bioactive compounds and chemical building blocks /EU-H2020 Project
WWTP	Waste water treatment plant

5 Intention and drivers for establishing a Volatile Fatty Acid Platform (VFAP) technology

Carbon in fossil resources was captured millions of years ago and is released at the fossil-based products' end of life. This release of carbon dioxide (CO_2) contributes to an increase of greenhouse gas (GHG) concentration in the atmosphere, in turn leading to climate change. To stay below the 1.5 – 2 °C target of global warming (cfr. Paris Agreement), 70 % of all coal reserves and at least one third of oil and natural gas reserves need to stay in the ground or at least their CO_2 emissions have to be kept from entering the atmosphere. Using biomass as carbon source for chemicals helps to diminish fossil CO_2 release in principle. However, these effects are increasingly mitigated when more fossil energy is used for agriculture and biorefining processes to produce the bio-based chemicals. Moreover, as the global acreage of arable land is limited, there is a resource conflict (area, water, fertilizer) between crops to be used for food and those that are intended for energy or materials production. Using biomass resources derived from waste streams does not suffer from these drawbacks, as long as the production and purification of the bio-based chemicals is not fossil resource intense. This is especially true for the VFAP technology, because it adds on the well-established biotechnological process of anaerobic digestion and produces platform chemicals which can be separated from the effluent by e.g. membrane technologies. Further ecological drivers for the VFAP technology – in addition to using renewable carbon sources – are:

— No fossil carbon is used to produce bio-based platform chemicals (i.e. volatile fatty acids) which in turn serves as source for many consumer goods.

— No extra fossil carbon is needed for the production of mineral fertilizers to produce the input biomass.

— Landfill capacities are saved because an organic waste stream is processed instead of deposited thereby also reducing landfill gases, which also contribute to GHG emissions.

— Using organic waste streams will save energy and help avoid the irreversible damages caused by using up resources at a rate that exceeds the Earth's capacity to renew them in terms of climate and biodiversity, air, soil and water pollution.

Establishing a VFAP technology is in line with the circular economy strategy of the European Union. The circular economy aims to avoid all waste, instead using materials in a circular fashion where nothing is lost but feeds into new cycles. The European Commission expects that the circular economy boosts the EU's competitiveness by protecting businesses against scarcity of resources and volatile prices; helps to create new business opportunities and innovative, more efficient ways of producing and consuming; and creates local jobs at all skills levels and opportunities for social integration and cohesion.

Waste management plays a crucial role in the circular economy: it determines how the EU waste hierarchy is put into practice. The waste hierarchy establishes a priority order from prevention, preparation for reuse, recycling and energy recovery through to disposal, such as landfilling. The EC is putting forward new legislation on waste to provide a long-term vision for increasing recycling and reducing the landfilling of municipal waste. These amendments also encourage greater use of economic instruments to ensure coherence with the EU waste hierarchy.

To achieve high levels of material recovery, the European Commission has realized that it is essential to send long-term signals to public authorities, businesses and investors, and to establish the right enabling conditions at EU level, including consistent enforcement of existing obligations. All waste should be considered, be it generated by household, businesses, industry and mining, or the construction sector.

To modernise waste management systems in the European Union, a revised waste legislative framework[11] entered into force in July 2018. This includes new ambitious recycling rates (e.g. 65 % of municipal waste should be recycled, while reducing landfilling of municipal waste to 10 % by 2035), a clarified legal status for recycled materials and by-products, reinforced rules and new obligations on separate collection of waste streams, e.g. biowaste.

Recently, the European Green Deal[12] has been published as a *"new growth strategy that aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use."* In this context, an EU wide model for separate collections of waste is announced as well as European funds, including for rural development, which will help rural areas to harness opportunities in the circular and bio-economy.

On the technological side the products of the VFAP (acetic acid (main component: 50 % to 70 %), propionic acid, butyric acid, valeric acid …) are so-called platform chemicals, which are used in the chemical industry to produce many kinds of intermediates and fine chemicals.

Aside from using purified components, some industrial applications may also utilize the VFA mixtures (see chapter 6.1.1.2 below).

Using bio-based acetic acid for chemical and biotechnological synthesis is coherent with the bioeconomy strategy of the EU and the Strategic Innovation & Research Agenda (SIRA) of the Bio-based Industries Consortium. The SIRA identifies research, demonstration and deployment activities to be carried out by the Joint Technology Initiative on Bio-based industries. This public-private partnership between the European Commission and the Bio-based Industries Consortium (BIC), aims to invest € 3.7 billion in bio-based innovation between 2014 and 2020. One goal of the SIRA is to raise the share of bio-based chemicals from 10 % 2016 to 25 % in 2030. This is only possible if sustainable resources for bio-based commodities and platform chemicals can be used.

6 Identification and description of framework to be considered

6.1 Non-Technical aspects

6.1.1 Arguments in favour of a VFA platform

6.1.1.1 General

The techniques developed in the VOLATILE project offer a solid future perspective for managers of anaerobic digestion (AD) plants in general, and those of anaerobic digestion plants treating solid and sludgy biowaste in particular. Several arguments demonstrate the advantages of applying the VFA platform. We divide them into two categories; economic arguments and arguments related to the company's image.

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[11] Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste. http://data.europa.eu/eli/dir/2018/851/oj

[12] Communication From the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions; The European Green Deal. COM/2019/640 final

https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2019:0640:FIN

6.1.1.2 Economic aspects

As indicated before, AD plant managers face multiple economic challenges[13]: prices for fossil resources and other raw materials are expected to remain low; renewable energy prices face large market fluctuations; there is a general tendency to reduce or even phase out subsidies for renewable energies; besides financial uncertainties, there are also large legal uncertainties[14] which prevent further investments; and investments are further hampered by uncertainties in the evaluation of new technologies and products and immature markets. Finally, AD plant managers also have difficulties in obtaining a stable and reliable supply of input biomass. All these challenges push AD plant managers to look for new value chains in order to be able to continue their work in an economically viable way.

The VFA platform answers to these economic challenges faced by the AD plant managers in the following way:

— Producing high value bio-based platform chemicals would allow the AD plant managers to increase their revenue, as their output products could be sold at a higher price.

— Investing in the VFA Platform would mean that besides compost and energy, AD plant managers would also produce VFAs, which can be used as carbon sources for PHA, SCO or omega-3 production, respectively. Investing in the VFAP would give the opportunity to diversify the product range, selling products to different markets at different levels, thereby increasing the company's resilience and reducing the economic risks.

— The VFAs would be sold to the chemical industry, where bio-based VFAs are important, which tends to be a more stable market than the energy market. Valeric acid and propionic acid are already in the VFA mixture and could be used as precursor for PHA fermentations. Currently, the propionic acid used in industry for making a bio-polymer (feeding it as add-on to glucose) is synthetic. Propionic acid from the VOLATILE platform would be bio-based. The final PHA quality depends on the VFA mixture and the fermentation strategy.

— Installing a VFA platform would require relatively limited investments and changes to the current operations of an AD plant. Hence, the technology allows the AD plant managers to take a sensible next step in the treatment of organic waste streams: i.e. converting the organic waste streams into new valuable materials instead of lower value energy and compost or compost-like outputs.

— Installing a VFA platform also boosts the plant's capacity, since the methanogenic step, which is now omitted, is the time limiting step of a conventional biogas plant. This may be of importance on investment decisions if capacity enlargement is planned.

6.1.1.3 Image improvements

Currently, the European Union envisions the establishment of a circular economy, in which different waste streams will be used as much as possible in a circular fashion and we are able to use them in new cycles. By using the VFAP technology AD plant managers will be able to convert their organic waste streams into bio-based platform chemicals, that can then be used as building blocks in the chemical industry to produce a wide range of intermediates and fine chemicals. Additionally, VFA can be

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[13] http://european-biogas.eu/2017/12/14/eba-statistical-report-2017-published-soon/;

http://european-biogas.eu/wp-content/uploads/2015/01/EBA-Biogas-Report-2014.pdf

[14] For example, the governments of both Germany and Italy lowered the feed-in tariffs for biogas plants. Additionally, in 2009, the Flemish government decided that biogas plants could profit from lifetime subsidies for the produced energy. However, this decision was repealed in 2012.

upgraded in biotechnological processes to high value products like PHA, SCO, and omega-3 fatty acids. As such, AD plant managers could make the shift from being processors of solid and sludgy biowaste and producers of energy, towards producers of new materials for the chemical industry, while still treating the waste streams and producing energy. Therefore, implementing the VFA platform technology would allow AD plant managers to become pioneers in the circular economy, giving them the image of being innovative, agile, and showing that the company has a vision.

Furthermore, by implementing the VFA platform technology, AD plant managers could also respond to the consumers' demand and market of more sustainable materials, as they exclude the use of fossil resources, or agricultural commodities (such as sugar, starch or oils), thereby largely reducing costs (carbon sources often represent 50 % of the total costs) and avoiding a food versus bio-based economy debate, as well as avoiding landfilling of valuable organic resources. This would further boost the company's green image.

Finally, by investing in the VFA platform, the company would largely contribute to the local economy by creating local jobs and by transforming local organic waste streams into high-value products that can be either used locally or sold on the world market.

6.1.2 Multi-criteria decision-making tool based on non-technical criteria

6.1.2.1 General

During the H2020 project VOLATILE, a web-based decision support tool is developed. The VOLATILE web-based decision support tool (DST) is specially developed for operators of waste water, municipal solid waste and biowaste treatment facilities to identify the specific local potential of the VOLATILE technology for their plants. Information about the free tool can be found via: http://www.volatile-h2020.eu. Besides economic indicators and technical aspects, the decision support tool also takes into account non-technical criteria for VFAP technology implementation. These non-technical criteria are discussed in the paragraphs below.

6.1.2.2 Rationale behind assessing the non-technical criteria

In order to assess whether or not an investment in a VFA platform is beneficial for a company treating solid and/or sludge organic waste streams, not only technical criteria (e.g. substrate quality or anaerobic degradability of the waste streams) are of importance, as discussed in the next section, or pure economic feasibility criteria, as discussed in Section 7, but also non-technical, more qualitative criteria are of importance. Indeed, when companies make an investment decision, this decision is generally not solely based on economic metrics, including the Internal Rate of Return (IRR) or the Net Present Value, but also on more tacit and social components. This section will describe these non-technical aspects that are of importance when evaluating if a VFA platform is a feasible technology to apply. Every criterion should be rated by the decision makers according to the importance it has on the investment decision, choosing between "very low", "low", "medium low", "fair", "medium high", "high", and "very high". In order to evaluate these non-technical criteria, we apply the methodology developed by Sadr *et al.* (2015)[15], which takes into account both experts' and decision makers' knowledge, being a fuzzy logic based multi-criteria group decision making methodology. With the methodology, we are able to rank several scenarios[16] for the decision maker according to the importance given to the 15 criteria discussed below. All these criteria were evaluated on their impact by the different experts involved in the H2020 project VOLATILE.

[15] Sadr, S.M.K., Saroj, D.P., Kouchaki, S., Ilemobade, A.A., Ouki, S.K. (2015). A group decision-making tool for the application of membrane technologies in different water reuse scenarios. Journal of Environmental Management, 156, pp. 97-108.

[16] (a) Only production of biogas; (b) production of biogas and VFA; (3) production of biogas and PHA; (4) production of biogas and SCO; (5) production of biogas and omega-3, (6) production of VFAs, SCO, PHA and omega-3 without biogas.

6.1.2.3 Justification of the evaluation criteria included

Initially, the non-technical evaluation criteria included were obtained from Sadr et al. (2015), who, in turn, compiled a list of criteria from various literature sources. Subsequently, these criteria have been complemented with input from project partners during brief interviews, more specifically, when asking about which additional factors could be important in their investment decision. After conducting several of these interviews, a point of saturation was reached and the list was finalized. In total 15 criteria are included in the analysis. According to the principal component analysis, as discussed in "Deliverable 9.13 – Third Questionnaire Evaluation Report"[17], these criteria can be split into six dimensions (Table 1). Below, we first discuss each of the six dimensions. Next, we discuss each of the criteria and indicate to which dimension they belong.

Table 1 — Principal component dimensions and their above average contributing criteria<Tbl_--></Tbl_-->

Criterion		Dimension					
		Operational production considerations	External factors contributing to uncertainty	System application considerations	Economic factors	Possible future constraints	Practical considerations
1.	Independence	•				•	
2.	Quality and reliability level	•					
3.	Operational costs	•			•		
4.	Energy consumption	•	•				
5.	Safety	•		•			
6.	Community acceptance	•	•				
7.	Certainty of the market		•	•			
8.	Ease of construction and deployment		•	•			
9.	Complexity level		•				•
10.	Adaptability		•	•		•	
11.	Impact on the environment			•			•
12.	Number of employees			•			•
13.	Capital costs			•	•		•
14.	Payback period				•		•
15.	Land requirement					•	

6.1.2.4 Dimensions

1) Operational production considerations: The criteria in this group are the kind of investment criteria to be considered when making any investment; a way for a company to estimate if the new

[17] https://www.volatile-h2020.eu/Open Access/Public deliverables/D_09_13_Third Questionnaire Evaluation Report.pdf (still not available at https://cordis.europa.eu/search)

technology is feasible. These elements include looking at the supply chain, quality, costs and safety of operating a new technology and producing a new end product.

2) External factors contributing to uncertainty: This dimension consists of criteria related to external factors contributing to uncertainty, meaning that these factors may vary over time and space and potentially have the power to inhibit the profitability or implementation of a new technology.

3) System application considerations: This dimension mainly encompasses criteria that concern the day to day operations and feasibility of the production process, both related to the construction process (e.g. capital expenditures) as well as the daily operations (e.g. number of employees needed to run the operations).

4) Economic factors: This is a dimension that concerns the three cost-related variables in the dataset: payback period, capital cost and operational cost.

5) Possible future constraints: The criteria in this dimension (land requirement, adaptability and independence) could potentially affect the freedom of decision making in the future. For example, land requirement is of course related to land availability and cost, while adaptability and independence from other actors in the supply chain are related to how extensive the changes in the production process, as well as in the supply chain, will be when investing in the technology.

6) Practical considerations: This dimension consists out of criteria related to practical considerations, such as the complexity level of the operations or the number of employees needed to run the operations.

6.1.2.5 Criteria

1) Independence: This criterion refers to the importance attached to being independent from other supply chain actors, for example suppliers of inputs, on the investment decision, but also on customers of your VFA. This criterion belongs to the dimensions “Operational production considerations” and “Possible future constraints”.

2) Quality and reliability level of production: This criterion refers to how important it is to the company that it can produce the end product with a reliable quality and in reliable volumes. This criterion belongs to the dimension “Operational production considerations”.

3) Operational costs: This criterion refers to the importance attached to the operational expenditures. The operational expenditures include the maintenance costs, energy costs, purchase costs, overheads and other related costs. This criterion belongs to the dimensions “Operational production considerations” and “Economic factors”.

4) Energy consumption: The energy consumption criterion refers to the amount of energy required by the new technology. It should be noted that while the energy consumption has implications on the operational costs (see criterion nr. 3)), this criterion refers to the energy consumption as such, and not the implications that it has on the operational costs. This criterion belongs to the dimensions “Operational production considerations” and “External factors contributing to uncertainty”.

5) Safety of the operations: This criterion refers to how important it is to you to be able to run the operations without any safety risk. This criterion belongs to the dimensions “Operational production considerations” and “System application considerations”.

6) Community acceptance: The community acceptance gives an indication of a community’s receptiveness to a given technology. This criterion involves addressing complexities and uncertainties arising from the interests, cultural identities, ideologies and goals of different

stakeholders. This criterion belongs to the dimensions "Operational production considerations" and "External factors contributing to uncertainty".

7) Certainty of the market: This criterion refers to the importance attached to having a reliable market, with a reliable offtake, at a reliable price. This criterion belongs to the dimensions "External factors contributing to uncertainty" and "System application considerations".

8) Ease of construction and deployment: This criterion refers to the ease to install the new technology, and the effort required to get the new technology operational and keep it operational. This criterion belongs to the dimensions "External factors contributing to uncertainty" and "System application considerations".

9) Complexity level of the operations: This criterion refers to the level of expertise required for the operation and management of the new technology, e.g. the number of engineers needed versus the number of technicians needed. This criterion belongs to the dimensions "External factors contributing to uncertainty" and Practical considerations"

10) Adaptability of the new technology towards new innovations: This criterion refers to the flexibility of the technology and the ease of upgrading. In other words, can the technology easily be switched on and off or can it be upgraded to produce different end products or receive different input streams, in order to be able to follow market trends? This criterion belongs to the dimensions "External factors contributing to uncertainty", "System application considerations", and "Possible future constraints".

11) Impact on the environment: This criterion refers to the positive environmental impact the technology has on the environment or being less harmful to the environment compared to the current technologies used. Comparison of the environmental impact of the current technology and the new technology can be done using a life-cycle assessment (LCA). This criterion belongs to the dimensions "System application considerations" and "Practical considerations".

12) Number of employees needed to run the operations: This criterion refers to the number of staff needed on a daily base to run the new technology. This criterion belongs to the dimensions "System application considerations" and "Practical considerations".

13) Capital expenditures: This criterion refers to the importance attached to the capital expenditures. The capital expenditures include the costs for the development of the installation and the equipment costs for various processes, as well as insurance costs and costs for interest. This criterion belongs to the dimensions "System application considerations", "Economic factors" and "Practical considerations".

14) Payback period: The payback period is the time needed to recover the cost of an investment. This criterion belongs to the dimensions "Economic factors" and Practical considerations".

15) Land requirement of the new technology: This criterion refers to how important it is to you that the new technology requires a limited land surface. In other words, does the company has sufficient land available for the placement of the new technology or the opportunity to acquire new land? This criterion belongs to the dimension "Possible future constraints".

6.1.3 Political and regulatory context

6.1.3.1 General

In this section, we describe a number of criteria that are external to the company and the technology, but can nevertheless influence the decision-making process. More details can be found in the public fact sheets in the stakeholder platform of the Volatile project[18].

6.1.3.2 Subsidies

Investment in the VFA platform technology requires an appropriate economic environment, which can be partly created by subsidies. As stated already above, AD to produce energy and compost or compost-like outputs has been stimulated by subsidies over the past decades throughout the EU. However, there is a general tendency to reduce or even phase out subsidies for renewable energy produced from anaerobic digestion.

In Flanders, a novel solution for input from WWTP into AD would be required since this is no longer covered by the biogas support scheme. VGF for biogas is eligible for funding, however only until 2022. Thus, the subsidy policy on biogas and alternatives such as a VFA platform will be decisive for planning the future. In Wallonia, the support scheme is related to green renewable energy production. In this regard, the valorisation of biowaste through AD needs to be organised in future. In the Netherlands, a bio-based economy strategy is established, including a set of financial measures and regional clusters. The anaerobic digestion of biowaste, including agricultural waste plays a considerable role in this region and the funding options detected in this work are both in the scope of materials and energy. This is a good precondition for applications addressing the VFA platform. In Portugal, subsidies are limited to operational support within the context of biogas production. In Romania, some national and local funding instruments for biogas investments and a GC system are (still) under use. However, there is not an immense financial support for this technology. Hence, in this region, it would be interesting to consider the production of higher-value products, including VFAs, PHA, SCO, and/or omega-3, instead of biogas. Also in Spain, the lack of subsidies for the biogas technology can be designated as a driver for VFA platform. In Greece, support for biogas is still significant, which might hamper the interest in investment in the VFA platform technology. However, VFAP could be further taken into account for specific challenges, such as food processing waste recycling.

With regard to specific subsidies for the VFA platform technology, at the moment there are no such subsidies present. In general subsidy policy is often specialized to single sectors such as waste management, generation of energy and production of resources from material. A combination of the former with second or the latter subject can be found in certain cases. A novel approach which integrates all of the three sectors would be requested.

6.1.3.3 Political vision

Whether it is interesting or not to invest in the VFA platform technology will also depend on the political climate, especially when the organic waste treatment plants are either publicly owned or the result of a public-private partnership. Indeed, in such organisational forms, usually, the economic benefits in terms of IRR or payback period are taken into account less strictly when taking investment decisions then in case of a private company. For example, the minimum IRR threshold is lower, and allowed payback periods tend to be longer. However, in these cases, as the final investment decisions are usually taken at the political level, the political vision of the ruling local, regional and national government as well as of the municipal council is of importance.

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[18] https://www.volatile-h2020.eu/platform.php

6.1.3.4 Regulation

At European level, four amending Directives that resulted from the European Circular Economy Package 2015 were published in the Official Journal of the European Union on June 14, 2018[19]. Among these the amending Directive (EU) 2018/850 on the landfill of waste and the amending Directive (EU) 2018/851 on waste will positively affect the competitiveness of the VFAP technology on mid-term view because:

— 55 % of municipal waste must be prepared for re-use and recycling by 2025, 60 % by 2030, and 65 % by 2035.

— The amount of municipal waste landfilled must be reduced to ≤ 10 % of the total amount of municipal waste generated by 2035.

— As of 2030 all waste suitable for recycling or other recovery, in particular in municipal waste, must not be accepted in a landfill, except for waste for which landfilling delivers the best environmental outcome.

— By Dec 31, 2023, Member States must ensure that biowaste is either separated and recycled at source or is collected separately and not mixed with other types of waste.

— Appropriate measures shall be taken by Member States

  — to ensure that waste which has undergone a recycling or other recovery operation is considered to have ceased to be waste if it complies with the ‚end of waste status’ in Article 6 of (EU) 2018/851 and 2008/98/EC.

  — to encourage the recycling, including composting and digestion, of biowaste in a way that fulfils a high level of environment protection and results in output which meets relevant high-quality standards.

  — to promote the use of materials produced from biowaste.

— By Dec 31, 2018, the Commission should have requested the European standardisation organisations to develop European standards for biowaste entering organic recycling processes, for compost and for digestate, based on best available practices.

The current situation differs amongst the different Member States and even in regions, as are discussed separately below for the seven regions and six countries respectively, where the VOLATILE test cases are located.

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[19] Official Journal of the European Union, L 150, 14 June 2018

https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L:2018:150:TOC (last accessed: 2020-01-08)

The European Circular Economy Package includes:

- Directive 2018/849 of May 30, 2018, amending Directives 2000/53/EC on end-of-life vehicles; 2006/66/EC on batteries and accumulators and waste batteries and accumulators; and 2012/19/EU on waste electrical and electronic equipment;
- Directive 2018/850 of May 30, 2018, amending Directive 1999/31/EC on the landfill of waste;
- Directive 2018/851 of May 30, 2018, amending Directive 2008/98/EC on waste;
- Directive 2018/852 of May 30, 2018, amending Directive 94/62/EC on packaging and packaging waste.

In Flanders region of Belgium, there is currently not really a legislation that supports the implementation of a VFA platform. However, the region does promote the separate collection of organic waste fraction, which is beneficial for the VFA platform technology. The transition to a circular economy that is also an important policy issue in Flanders is expected to favour material recovery from organic waste like VFA production, but currently there is no active support or legislation. Contrary to AD and composting plants which are well defined in legislation and where it is known what permits they need and what rules they have to comply with, no such definition is available for VFA production from organic waste streams. Hence, it is expected that a tailor-made solution will be necessary to implement the first plant. However, a "hotline" is established by the Flemish Government to underline the willingness of facilitating these solutions towards a circular economy.

In Wallonia region of Belgium, separate organic waste collection is limited to certain regions and communities, but will be introduced by the Wallonia Waste-Resources Plan 2020. Furthermore, Objective No.19 of this plan favours the material recycling of waste into chemistry and feed. For establishing VFAP, it needs to be fully implemented in the legal framework of biogas plants. The use of sludgy biowaste for VFA production should be legally adapted by means of making it competitive against others (e.g. soil improvement). Decisions for the implementation of a VFA platform might be facilitated by a remuneration system similar to energy supply.

In Greece, measures like taxes for landfill might support the awareness for recycling methods for organic waste streams, but further legal decisions are needed to enhance separate biowaste collection. At the moment, there is no regulatory background for the use of the VFA platform technology. Concerning sludgy biowaste for VFA production, the use of wastewater (including sludge) for irrigation should be critically reviewed and the appropriateness of sludge thoroughly evaluated for VFA production. At present, there is an investment programme available for renewable energy, which would need to be extended to the inclusion of materials production, for example by using the VFA platform technology.

In the Netherlands, a separate organic waste collection system is operational. Waste treatment is regulated in detail with the help of 85 sector plans and their minimum standards. Before investing in the VFA platform technology, some legal adaptations should be taken into account, preferably for the use of municipal waste and sludgy biowastes from WWTP towards recycling. Generating energy through biogas is supported by a premium for electricity or biomethane supply. Investments in the VFA platform technology could be encouraged by granting material recycling in anaerobic digestion, prior to energy use.

In Portugal, there is almost no separate collection of organic fractions of household wastes. Therefore, investments in the VFA platform technology could largely benefit from a change in laws which encourage this separate collection. In the meantime, organic fraction of the unseparated municipal solid waste collected, or agricultural waste streams could already be used as input for the VFA platform technology. Furthermore, laws on treatment of sludgy biowaste using AD should be amended by the novel option of VFA production. Finally, the remuneration system for production of electricity from biogas could be supplemented by a compensation for materials production, including VFA production.

In Romania, legal measures would need to be adapted to allow for the valorisation of the organic fraction of municipal solid waste by using the VFA platform technology. Furthermore, as there is less financial support for biogas production, there is almost no competition in this sense with the VFA platform technology. However, the legal acts touching waste and anaerobic digestion facilities are not oriented at VFAP and thus, would need to be modified in this perspective. WWTP sludge should gain legal attention concerning the VFA platform technology, in order to encourage investments. For the use of digestate/compost in plant nutrition, a legal framework could be created with particular reference to VFAP.

In Spain, the separate collection of the organic fraction of the municipal solid waste, is organised by a limited number of Autonomous Regions. Laws for sludge from WWTP treatment should be modified by encompassing the possibility of valorisation by the VFA platform technology. The lack of support schemes for electricity and heat from biogas might encourage the investment in the VFA platform technology, as there is no competition. However, at the moment, Spanish legislation does not foresee the use of the VFA platform technology.

6.2 Multi-criteria decision-making guide based on technical criteria

6.2.1 General

This chapter will describe technical aspects that are of importance when evaluating if a VFA platform is a feasible technology to apply.

6.2.2 Raw materials

6.2.2.1 General

As the raw materials are the source from which the volatile fatty acids will be produced, this is of course a very important aspect to evaluate (in fact, it is the *conditio sine qua non* to determine if a VFA-project will have any chance of success). In this subchapter, two aspects to determine the substrate suitability are discussed: the substrate characteristics (quality) and the substrate availability (quantity). Also, the substrate cost will impact the overall feasibility, but this is discussed in Chapter 7.4.

6.2.2.2 Substrate quality

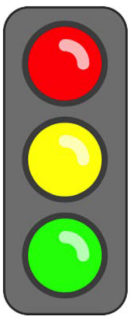
6.2.2.2.1 General

To evaluate the substrate suitability for the VFA platform, the following criteria should be scored:

6.2.2.2.2 Anaerobic degradability

The production of volatile fatty acids takes place in earlier conversion steps during the well-known anaerobic digestion process of organic material to produce biogas (a gas mix mainly consisting of CH_4 and CO_2), where they are considered intermediate reaction products. Hence, a first simplified guideline is that any substrate that is suitable for biogas production in a digester will also be suitable for volatile fatty acid production. This immediately excludes all substrates with high lignin content, as lignin is not biodegraded in the frame of anaerobic digestion. A standardized test to determine the VFA potential of a substrate is being developed in the EU-funded H2020 VOLATILE project.

Recommendations:



Substrate is not anaerobically degradable to VFA
(e.g. wood is not a suitable substrate)

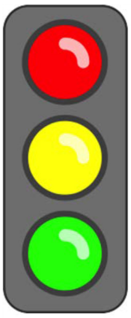
Substrate is moderately anaerobically degradable
(Availability of degradable co-substrates should be checked)

Substrate is highly anaerobically degradable to VFA
(Substrate contains mainly protein, fat, sugar, cellulose)

6.2.2.2.3 Heavy metal content

In anaerobic digestion, heavy metal contamination is of importance in the digestate, and the allowable concentration depends on the final application (e.g. compost, organic fertilizer, landfilling, incineration). As biogas is the only product that leaves the reactor and is always free of heavy metals, the final digestate heavy metal concentration can easily be estimated based on the input concentrations. In the VFA platform, the fate of the heavy metals throughout the process will depend on the chosen technologies (centrifugation, membrane separation, distillation, pertraction …) to separate VFAs from the digestate and on the pH of the reactor which will determine the solubility of the heavy metals. Furthermore, the tolerable contamination in the VFA containing medium will also depend on the final application (e.g. no contamination allowed when targeting food applications).

Recommendations:



Risk of heavy metal contamination
(digestate not allowed in compost and organic fertilizer)

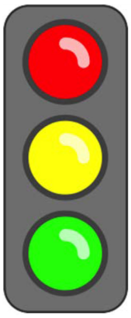
Risk of heavy metal contamination
(dig. possibly allowed in landfilling or incineration; consider VFA separation strategy)

No risk of heavy metal contamination

6.2.2.2.4 Organic pollutant content

Organic pollutants can impact the suitability of a substrate on two levels. First of all, these components can have an inhibiting effect on the conversion process to volatile fatty acids (e.g. terpenes, phenols…), making it unfit for VFA production, or necessitating a prior purification step to remove the inhibiting compounds. Secondly, if the organic pollutants are not inhibiting the process but remain undegraded, they can limit the final application of the VFAs. Similar to the heavy metals, the chosen separation technologies will determine the fate of these pollutants.

Recommendations:



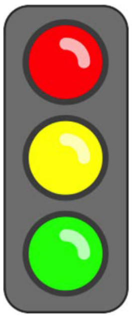
Risk of organic pollutant contamination
(organics may inhibit VFA process, undegraded pollutants need to be separated)

No risk of organic pollutant contamination

6.2.2.2.5 Physical impurities (importance depends on pre-treatment steps)

The presence of physical impurities (plastics, sand, stones, metals …) will mainly impact the pre-treatment needs of a given substrate. As such, these impurities are usually inert and will hence not influence the conversion of the organic fraction to volatile fatty acids or have a negative effect on the quality, but these impurities could damage pumps, mixers or have an abrasive effect on piping and equipment, leading to higher operation and maintenance costs.

Recommendations:



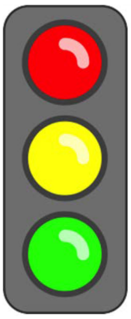
High share of physical impurities
(leads to higher pre-treatment costs)

No physical impurities

6.2.2.2.6 Variability

Some organic substrates may have a consistent composition all year round, whereas other substrates can show seasonal fluctuations. As the input composition of an organic residue influences both the VFA production potential and the composition of the VFA spectrum, fluctuating input characteristics can complicate the VFA production process (e.g. more strict process control, necessitate the addition of co-substrates to maintain output quality).

Recommendations:



Substrates show strong seasonal fluctuations
(no issue as co-substrate. As main substrate, it will negatively impact business case)

Substrates have year-round stable characteristics

6.2.2.3 Substrate categories for anaerobic digestion

6.2.2.3.1 General

Below, a short, non-limiting overview is given on typical substrate categories for anaerobic digestion and their estimated application potential in a VFA platform.

6.2.2.3.2 Source separated food (processing) waste

Definition: Organic residues that originate during the processing of food waste, either industrially (e.g. solid residues from vegetable processing, spent bleaching earth from clarifiers, whey from cheese production), retail (spoiled vegetables from markets, processed food beyond its due-date …) and catering (residues from food preparation, left-overs from canteens and restaurants …), and that are separately collected at source.

Estimated application potential: As the definition comprises a broad range of products, the individual characteristics can differ widely between individual substrates within this category and a case-to-case evaluation should be performed. Nevertheless, as all these substrates originate during food production, a common characteristic is the relatively high purity, meaning there is low contamination with non-organic material (e.g. sand, stones, plastics), heavy metals or organic pollutants. Furthermore, they have typically very low lignocellulosics content, and as such are easily degradable under anaerobic conditions. Finally-, the input characteristics are typically very stable throughout the year. As a result, substrates falling within this category have a large potential to be applied in the production of volatile fatty acids.

6.2.2.3.3 Source separated household biowaste

Definition: Organic residues that originate in households and that are separated at the level of the households. Depending on local legislation, source separated household biowaste consists mostly out of food waste (processed or unprocessed, with or without animal by-products), soiled paper (used napkins, paper plates, pizza boxes …), and small garden waste (grass clippings, weeds, trimmings …).

Estimated application potential: As the legal definition of what is allowed in source separated household biowaste differs from country to country and even between regions in a country, the composition of this substrate category can differ substantially. Especially the amount of small garden waste fraction within this substrate category will influence the overall anaerobic degradability to VFAs (the lower the share of garden waste, the higher the VFA potential). This share not only depends on the legal definition, but also between collection area (urban areas have usually smaller gardens but need to dispose all garden waste through this waste fraction; rural areas produce more garden waste but are also more likely to have a home composting system), and also seasonal variation (more woody garden waste in spring and autumn, more grassy garden waste during summer and hardly any garden waste during winter). As this waste category is source separated, theoretically this should be characterised by a low degree of contamination. Practice however shows that physical contamination is still present and needs to be removed prior to biochemical conversion. Heavy metal and organic pollutants on the other hand are typically very low in this substrate category. All in all, this substrate category shows a relatively high potential to be used as input material in a VFA platform.

6.2.2.3.4 Source separated garden waste

Definition: Organic residues that originate at households or through professional gardeners and landscapers. This fraction mostly contains woody trimmings and grass clippings.

Estimated application potential: As this fraction is characterised by a high share of lignin-rich material, the first evaluation criterion (anaerobic degradability) already scores very poorly (low VFA potential). Furthermore, the substantial variability in composition throughout the year and the likely contamination with sand makes this substrate category less suited as input in a VFA platform.

6.2.2.3.5 Organic fraction of municipal solid waste (OF-MSW)

Definition: The organic fraction obtained through mechanical pre-treatment of the mixed household waste. The exact composition of the mixed household waste again differs from country to country, and typically contains all waste material that is not collected separately for recycling. In many European countries, this fraction still contains up to 50% organic material, which can be partly recovered through the mechanical pre-treatment to remove all inorganic fractions (plastic, metals, stone…).

Estimated application potential: As most European regions have a separate collection of garden waste, the organic fraction that ends up in the mixed household waste is typically well degradable under anaerobic conditions (food left-overs, soiled paper …). Furthermore, the composition is also very constant throughout the year. But due to the mixing with other waste fractions, the OF-MSW usually still contains a relatively high share of physical contaminants, even after the mechanical pre-treatment (e.g. sand, small plastic particles). As the origin of the mixed waste is very diverse, there is also a higher risk for heavy metal and organic pollutant contamination. Depending on the fate of these contaminants (research still ongoing), the OF-MSW could be a substrate with a moderate to high potential as input for a VFA platform.

6.2.2.3.6 Primary sludge from Wastewater treatment plants (WWTP)

Definition: The settleable and/or floating organics that result from primary sewage treatment (clarifiers).

Estimated application potential: As the organics contained in the primary sludge have not yet been converted aerobically, this material has a relatively high biogas potential and hence a higher VFA potential is expected accordingly. Due to the origin of this material and the pre-treatment, no or little physical impurities are expected, but the heavy metal content and potential organic pollutant risk is elevated (especially potentially faecal pathogens), limiting the valorisation routes of VFAs derived from this material. The quality is expected to be rather constant throughout the year, although some minor fluctuations are possible. All in all, this product has an intrinsic good potential to be used in a VFA platform, but much will depend on the fate of heavy metals and potential pathogens throughout the process chain. Research in this field is still ongoing.

6.2.2.3.7 Activated sludge (or secondary sludge) from WWTP

Definition: Sludge originating in the secondary clarifier after an aerobic wastewater treatment phase.

Estimated application potential: As the organics in this material have undergone an aerobic conversion, a substantial amount of the energy from the wastewater has already disappeared and hence the biogas potential and associated VFA potential of this material is moderate. Due to the previous treatment steps, no physical impurities are expected in this material, but contamination with heavy metals, pathogens and/or organic pollutants is possible and could limit the application of the VFAs. The sludge quality is expected to be rather constant throughout the year, although some minor fluctuations are possible (e.g. higher sand content after heavy rainfall). The moderate VFA potential and the potential contamination of the sludge could limit the feasibility of this product in a VFA platform. Much will depend on the fate of heavy metals and potential pathogens throughout the process chain. Research in this field is still ongoing.

6.2.2.3.8 Digested sewage sludge from WWTP

Definition: Sludge originating after anaerobic digestion of activated sludge.

Estimated application potential: This is the WWTP sludge with the lowest VFA potential, as this has already undergone both an aerobic and anaerobic treatment. The high share of methanogenic bacteria in this sludge will also complicate process control (methanogens must be suppressed during VFA production). Only a pre-treatment that kills off the methanogens and breaks open the sludge structure (e.g. drying, temperature/pressure treatment) could improve the VFA potential and suppress methanogens. No physical impurities are expected, but heavy metal content could be higher than in the previous described sludge types (due to concentration effects in the previous treatments). As the digested sludge has undergone both aerobic and anaerobic treatment, the risk for pathogens and organic pollutants is smaller (due to kill-off and degradation in previous steps) but cannot be completely excluded. Variability is expected to be rather low. In conclusion: unless the digested sludge has undergone a severe pre-treatment to kill off methanogens and break open the sludge structure, this material shows a too low VFA potential to allow for a feasible VFA platform.

6.2.2.3.9 Agricultural residues

Definition: Organic substrates that originate in agriculture. It is the non-usable plant parts that are not harvested or are removed post-harvest (on the farm).

Estimated application potential: This is a very diverse category and therefore it is difficult to set uniform characteristics, especially concerning the VFA production potential. E.g. straw has a high lignin content and consequentially will have a low VFA potential. Harvest residues from the vegetable production on the other hand will typically show a high conversion of the organic matter to VFA. In most cases, physical impurities are not present, although in some crops this could be the case (e.g. plastic ropes or clips in tomato stalk residues, or sand when the residues have been in contact with the soil). As the material originates during agricultural production, the risk for heavy metal or organic pollutant contamination is very low. A specific residue also usually has a rather constant quality and once a substrate has been thoroughly characterised, little additional monitoring of the product quality will be needed. Depending on the lignin content, agricultural residues can show a very high potential to be used in a VFA platform.

6.2.2.3.10 Energy crops

Definition: An energy crop is a crop that is grown with the purpose of producing energy from it. In anaerobic digestion, the most popular substrates are whole crop maize silage, whole crop cereal silage, grass and (sugar) beets.

Estimated application potential: Energy crops which are used in anaerobic digestion will be very suitable to be used for VFA production as well. As this considers agricultural crops, contamination with physical impurities, heavy metals or organic pollutants is considered absent or very low, and quality is usually very consistent throughout the years. Based on these characteristics, it can be concluded that energy crops are a very interesting substrate to be used in a VFA platform.

6.2.2.3.11 Manure

Definition: The organic matter derived from animal husbandry, and typically consisting of animal faeces and bedding material.

Estimated application potential: As manure is a combination from already digested material (in the intestinal tract of the animals) and bedding material with typically high lignin content, the VFA potential is estimated to be rather low for this type of substrate. In manure from ruminants, there is also a higher risk that methanogens are present, making it harder to suppress methane production during VFA production. Physical contamination is usually very low, but elevated concentrations of heavy metals can be present (especially Cu and Zn), and also organic pollutants (e.g. antibiotics, disinfectants) can be present, be it exceptionally. The manure characteristics are typically very constant throughout the year. All in all, the usually low VFA potential will limit the feasibility of this substrate category in a VFA platform, although it could be used as co-substrate (e.g. to dilute dry energy crops or agricultural residues).

6.2.2.4 Substrate quantity (OWS)

6.2.2.4.1 General

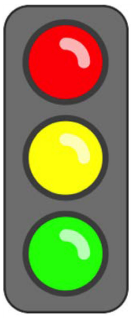
The substrate quantity plays an important role and can be scored on three criteria.

6.2.2.4.2 Annual amount

The annual amount of a substrate (or a combination of substrates) is important as a critical mass will be necessary to make the VFA platform feasible. This critical mass depends on several parameters such as the VFA potential of the substrate, the substrate cost, pre-treatment costs, chosen VFA production technology (CAPEX/OPEX) and local market conditions (e.g. final application process for the VFAs). If no sufficient amount is available, it will be necessary to search for additional input substrates nearby[20]. Local/regional governments can often assist in making a connection between organic waste suppliers and the operator of a VFA production facility. Special attention should also go to potential non-technical limitations when sourcing new input substrates (e.g. other permits needed for treating municipal waste, agricultural residues, manure, animal by-products, sludge, and others).

[20] This is largely dependent on the kind of waste treated (density, …), the location (easy to access,…), and the infrastructure (roads suited for large trucks, …)

Recommendations:



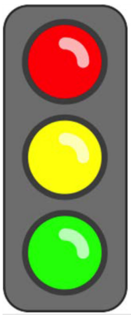
Low supply within reasonable distance[20] of the plant
(negative impact on business case is expected)

Large supply within reasonable distance of the plant

6.2.2.4.3 Availability

Similar to the anaerobic digestion process, VFA production is a biological process and hence needs to be operated on a continuous basis (avoid stop/start as much as possible), although based on the experience gained in the VOLATILE project, the VFA production is more flexible due to the relatively short residence time compared to anaerobic digestion. So, especially in the case where VFA production is combined with anaerobic digestion, a continuous substrate supply is very important to maintain process stability. The availability will also impact the need for temporary storage. Especially in the case of agricultural residues which are usually produced in a relatively short timeframe, the storage will entail additional costs.

Recommendations:



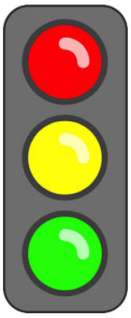
Peak substrate availability due to limited production season throughout the year
(negative impact on business case is expected)

Continuous substrate availability throughout the year

6.2.2.4.4 Logistics

A third criterion linked to the substrate quantity is the logistics or supply chain that is associated with it. Questions that need to be answered are: 'Is the substrate part of an existing supply chain or will a completely new chain need to be set up?', 'What is the maximum distance that will need to be covered to obtain sufficient input material?', 'What is the forecast of availability in the next 5-10 years?' … If the project concerns the conversion of an existing plant (e.g. composting or AD plant), the available amounts are well known and a supply chain will already be in place.

Recommendations:



No existing supply chain/large distances expected/no long-term contracts
(negative impact on business case is expected)

Supply chain exists and long-term supply possible
(e.g. an existing AD plant will be converted)

6.2.3 Impact of and on current anaerobic digestion plant

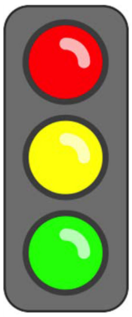
6.2.3.1 General

Combining VFA production with biogas production seems a logical choice for several reasons.

6.2.3.2 Microbiological process

First of all, both processes, VFA production and biogas production show large similarities from a biochemical viewpoint. In fact, ‘only’ the final methanogenesis step from the AD process needs to be eliminated to produce VFAs (which will bring about a more thorough process control compared to AD), and for operators the similarities between the two processes will speed up the implementation and practical operations. If the operator of the AD plant is well acquainted with the ins and outs of the biological process, this knowledge can be put to use in the VFA platform as well, and ultimately reduce the risk of process failure, although an additional training will be necessary to become acquainted with the new process parameters for an optimal VFA production process.

Recommendations:



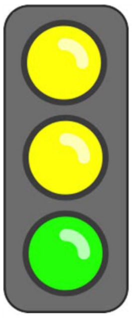
Operator has no experience with microbiological part of AD process
(training of operator is necessary)

Operator has extensive skills on the microbiological part of AD process

6.2.3.3 Biogas recovery

Secondly, it is theoretically impossible to recover all COD that could be produced in the form of biogas as VFAs. During the conversion processes, some of the COD is released in the form of H_2 gas together with CO_2, which during methanogenesis are converted to CH_4. This COD cannot be recovered as VFA, and as the hydrolysis gas contains H_2, it cannot be evacuated to the air and needs to be flared off if no other valorisation is available. Furthermore, the residence time during VFA production is substantially lower (order of magnitude 2-6 days) compared to anaerobic digestion (order of magnitude 18-50 days). This means that slowly degradable organics will not have released their full potential during VFA production. By combining VFA production with biogas production, both the H_2 gas and the remaining, more recalcitrant organic matter can be valorised energetically. Nevertheless, due to the altered pre-treatment, it might be possible that the VFA platform will impact the AD process leading to biogas. E.g. the dry matter content of the input for AD can increase because mainly the more recalcitrant organics will remain. As some of the biomass is removed from the AD input, the existing reactor might be oversized to treat the remaining organics. This will by itself not negatively impact the process, but the reduced biogas production should be taken into account and weighed against the additional revenues from VFA production. Alternatively, the total input to the plant could be increased and the VFA platform designed to treat larger amounts of input.

Recommendations (no red light):



No AD reactor or existing reactor cannot treat remaining organics and H_2 gas
(substantial extra investments are expected)

Existing AD reactor needs modifications to treat remaining organics and H_2 gas
(minor investments are expected)

Existing AD reactor can be fully recovered to treat remain. organics and H_2 gas
(only low or negligible investments are expected)

6.2.3.4 Existing pre-treatment

In many cases, especially when handling solid and heterogeneous substrates, a pre-treatment will be unavoidable before VFAs can be produced. Any existing pre-treatment equipment that could be re-used or converted to make the raw inputs suitable for VFA production can substantially decrease the initial investment costs associated with starting a VFA platform. Examples of pre-treatment equipment that could also be used for a VFA platform are:

— Shredder (to reduce the size of the incoming organic waste)

— Rotating drum (to homogenize and reduce the size of the incoming organic waste)

— Pulper (to reduce size and remove unwanted material)

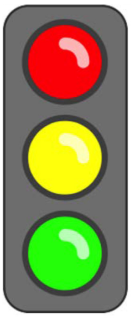
— Ballistic separator (to remove light and heavy impurities)

— Sieve (to remove waste fractions with low VFA/biogas potential)

For VFA production, only the easily degradable organics are targeted, and hence some modifications or extensions to the existing pre-treatment might be necessary (strongly dependent on input substrate).

Some AD plants also have a hydrolysis tank which is in many cases used as a buffer tank for the incoming substrates, and where already some (mostly uncontrolled) acidification takes place. Depending on the design and size of this hydrolysis tank, it might be possible to reconvert this tank (e.g. heating, monitoring equipment, process control…) to a VFA production tank.

Recommendations:



No existing pre-treatment equipment or equipment not reusable
(high investment costs are expected)

Existing pre-treatment equipment completely reusable
(only low or negligible investment costs are expected)

Finally, connecting a novel technology (VFA platform) to a mature technology (AD) could reduce the financial and technical risk of implementing a novel technology, and allow the VFA platform to be further optimized with biogas production as a safe back-up technology.

6.2.4 Available VFA conversion technology

VFA conversion technology is still in development (TRL5-7) and to our knowledge there are currently no commercially available systems on the market. Nevertheless, many international players are active in developing processes to convert biowaste to VFA, e.g. through EU funded projects (VOLATILE, RES URBIS, URBIOFIN, AFTERLIFE …). Similar to anaerobic digestion, it is expected that several different process technologies will develop, each optimized for a specific input substrate or advantageous process design. As with anaerobic digestion, the best technology will strongly depend on the characteristics of the input substrates.

A pre-treatment step is expected to be needed for most organic substrates with either a high dry matter content, high heterogeneity or which contain impurities (such as plastics, metals…). The pre-treatment step is necessary to reduce the particle size (speed up the VFA production process), eliminate large impurities (avoid damage to equipment) and create an easily pumpable and miscible process stream. The extension of the pre-treatment step is also determined by the layout of the VFA reactor. In case of a CSTR reactor, the pre-treatment step will be more advanced than in case of a garage box reactor. Vice versa, the VFA reactor will depend on the available pre-treatment: the more extensive the pre-treatment, the higher the reactor efficiency should be; more basic pre-treatment will lead to lower reactor efficiency.

Post-treatment will mainly consist of two parts. A first part deals with the VFA reactor effluent containing the VFAs in solution. This effluent will need to be purified and concentrated in order to produce a VFA mixture that can be easily transported and used in further fermentation processes. In the VOLATILE project, a membrane cascade approach is developed to obtain this target: microfiltration – ultrafiltration – nanofiltration – reverse osmosis. The second post-treatment step needs to deal with the remaining biowaste which is not converted to VFA. Research performed in the VOLATILE project has learned that this waste fraction can be treated in state-of-the-art composting or (dry) anaerobic digestion facilities.

A final consideration to take into account is the necessary surface that is required to implement the VFA conversion. Thanks to the relatively short residence time required in VFA production (4-10 days, depending on substrate characteristics, pre-treatment and reactor design) the area needed for the reactor is expected to be relatively small in comparison with an conventional AD plant and especially a composting plant. In existing AD/composting plants, it is expected that the existing pre-treatment process can be largely copied, and only some modifications will be necessary, again limiting the extra area requirements. Post-treatment of the residual biowaste can take place in existing AD/composting equipment and requires no additional area. Finally, the purification and concentration of the VFA rich effluent can also be designed in a surface efficient way. Based on the experience obtained in the VOLATILE project, adding a VFA recovery unit to an existing AD/composting plant treating urban biowaste should only require an expansion with 10-20% of the area already in use for most AD/composting plants.

6.2.5 Application of produced VFA

6.2.5.1 General

In most cases, the VFAs will not be the final product in the circular value chain, but will serve as a platform chemical that can be applied in a plethora of biorefinery concepts. Below, a non-limitative list is provided based on ongoing research, but it is expected many more applications will be developed in the next years.

6.2.5.2 Direct application

VFAs or short chain carboxylic acids have a direct application in many chemical processes. The main use of acetic acid is in the production of vinyl acetate (which in turn can be polymerized into polyvinyl acetate, a typical component in paints and adhesives), but also the production of esters (ethyl acetate, n-butyl acetate, propyl acetate…), acetic anhydride or direct use as a solvent are known markets for acetic acid. Today, most of these chemical pathways use fossil-based acetic acid. Only in food production (vinegar), the acetic acid originates from a biological process.

Propionic acid is mainly (± 50% of world use) applied as a preservative in food and feed application due to its mould and bacteria suppressing properties, and in cattle feed to improve feed conversion. Other commercial applications are the production cellulose-acetate-propionate (a thermoplastic), vinyl propionate, and in the production of pesticides and pharmaceuticals.

Butyric acid is mainly used for the production of butyrate esters to be used as food and perfume additives due to their pleasant aromas or taste.

Most of these applications nevertheless require either large volumes of the respective VFAs, or a high purity (or both). As the VFAs are derived from locally available biowaste, both requirements will be difficult to obtain, or will necessitate a costly purification step.

6.2.5.3 PHA fermentation

VFAs can be used as main carbon source by PHA-accumulating microorganisms. Currently the PHAs on the market are short chain length PHAs (scl-PHAs) produced from sugars and medium chain length PHAs produced from oils. VFAs can be incorporated as monomers in short chain length scl-PHAs. The commercially available scl-PHAs are polyhydroxybutyrate (PHB) homopolymer and poly(hydroxybutyrate-hydroxyvalerate (PHBV). PHB and PHBV are currently produced using the same microbial strains using sugar as main raw material and adding a precursor such as pure propionic acid to obtain PHBV. Processing and cost constraints have limited the PHBV to co-polymers with very low incorporation of hydroxyvalerate (around 3%), which has limited significantly the range of mechanical properties of the polymer and originated to date highly brittle materials, with narrow processing windows and limited application potential. The use of low-cost VFA mixes will allow the production of polymers with a more diverse monomeric composition (ex. hydroxyvalerate from propionic and valeric acid, hydroxy-hexanoate from caproic acid) which will provide materials with a much wider range of properties, including elastomeric products. The AD process will need to be controlled to an extent that the VFA composition will allow to oscillate within pre-defined ranges, so as to allow producing a PHA product with stable specifications.

The scale of production of PHA in each AD plant will most likely be too low to allow becoming a player in the broader plastics market. As such, local circular economy concepts should be envisaged, for example, using the PHA to produce biodegradable and compostable garbage bags to be distributed in the community, or to produce mulch films that biodegrade and fertilise the soil without requiring the manpower for their removal, etc. Alternatively, opportunities may arise from lower scale demand of higher value materials, taking advantage of the differentiated mechanical properties of the co-polymers produced through the conversion of VFA mixes, ex. filaments for 3D printing applications.

Integration opportunities may be exploited to reduce the cost of production of the PHA, for example energy integration (using heat available in AD plants to pre-warm water for the production of steam required in the sterilization of the fermenters). Further, the possibility to use locally the VFA mixes will avoid extensive purification costs of VFAs for external use and their transportation.

6.2.5.4 SCO fermentation

To establish a circular bioeconomy, applied research approaches focus on the possibility of using different type of biowastes not only to lower ecological impact but especially to valorise residual substrates into added value compounds such as single cell oil for various applications. Due to their productivity and fast growth rates, oleaginous microorganisms have a huge potential compared to other type of lipid rich biomass. However, to tackle economic requirements cheap carbon sources need to be used to develop applications for specialty or commodity products.

Volatile fatty acids, intermediates from anaerobic digestion or dark fermentation, represent an economical alternative carbon source for single cell oil production. Oleaginous yeast strains can accumulate lipids in high amount, characterized by a metabolism able to convert certain volatile fatty acids directly to acetyl-CoA, which is used in fatty acid synthesis. Fontanille et al. (2012)[21] as well as Kolouchova et al. (2015)[22] demonstrated the feasibility to valorise volatile fatty acids into single cell oil. The resulting SCO can be used for diverse applications depending on its fatty acid profile.

Chemical products obtained from triacylglycerols of plant or animal origin are usually defined as oleochemicals. However, also single cell oil from microbial sources must be considered as starting material. Fatty acids, fatty alcohols and methyl esters derived from triacylglycerols are basic oleochemicals and especially wax esters, an ester between a fatty acid and a fatty alcohol, can be used in different industry segments such as to produce soaps, detergents, cosmetic additives or flavours. Further application sectors are personal care products, paints and coatings, paper recycling and plastics, printing or rubber production, as well as in electronics or industrial lubricants[23].

6.2.5.5 Omega-3 Fatty Acid Fermentation

Polyunsaturated Omega-3 fatty acids play an important role in human diet and physiology. They are characterized by minimum three double bounds in their chemical structure whereby the first double bound is located three atoms away from the terminal methyl group. Since epidemiological studies revealed that Inuit’s from Greenland had substantially reduced rates of acute myocardial infarction compared with Western control subjects, the interest for this health promoting fatty acids is increasing.[24] The main constituents of this class, important for human physiology, are α-linolenic acid (ALA), found in plant oils, and eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), both commonly found in marine oils. EPA and DHA can be produced endogenously by humans out of ALA.

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[21] Fontanille, P., Kumar, V., Christophe, G., Nouaille, R., Larroche, C. (2012). Bioconversion of volatile fatty acids into lipids by the oleaginous yeast *Yarrowia lipolytica*. Bioresource Technology, 114: 443-449. https://doi.org/10.1016/j.biortech.2012.02.091

[22] Kolouchova, I., Schreiberova, O., Sigler, K., Masak, J., Rezanka, T. (2015). Biotransformation of volatile fatty acids by oleaginous and non-oleaginous yeast species. FEMS Yeast Research, 15: fov076

[23] APAG (2017). The European Oleochemical Industry at a Glance - Traditional and Innovative Products from Sustainable Sources.

https://www.apag.org/images/Documents/APAG_A4_website.pdf

[24] O'Keefe Jr, J.H.; Harris, W.S. (2000). Review - From Inuit to Implementation: Omega-3 Fatty Acids Come of Age. Mayo Clinic Proceedings, 75(6): 607-614. https://doi.org/10.4065/75.6.607

Nevertheless, as the corresponding enzyme system is also used by Omega-6 fatty acid transformation, the biosynthesis can be considered as insufficient to meet physiological demands. Normally, seafood can be considered as the best way to consume these fatty acids (EPA, DHA). However, there exist an increasing gap between supply and demand on traditional sources (fish oil, fish meal) to satisfy the demand of aquaculture and human nutritional requirements especially considering growing human population[25]. Based on FAO-OECD Agricultural Outlook data[26] fish oil and fish meal prices increased significantly since year 2000 in relation to growing aquacultural fish production. Therefore, a focus on primary producers, such as microalgae, is needed to develop new supply chains. Several photosynthetic microalgae (e.g. *Nannochloropsis*, *Monodus subterraneus*, *Phaeodactylum tricornutum*, *Odontella aurita*, *Pophyridium cruentum*) are able to accumulate high levels of EPA[27]. However, to produce DHA mainly heterotrophic microalgae are needed. As traditional carbon sources contribute significantly to the cost structure of heterotrophic fermentation approaches, new unconventional sources such as volatile fatty acids (VFA) coming from dark fermentation and waste valorisation are needed, to provide the growing market for Omega-3 fatty acids.

Chalima et al. (2017)[28] provides a comprehensive inside on the metabolism of VFA as carbon source for the production of various added value compounds by heterotrophic microalgae. *Crypthecodinium cohnii* or *Schizochytrium limnacium* are known to accumulate high amounts of DHA and can use VFA as carbon source. *C. cohnii* assimilates, for example, the major VFAs, such as acetate, butyrate and propionate contained in dark fermentation effluents[29]. Therefore, VFA's from anaerobic or dark fermentation represent an interesting carbon source for heterotrophic microalgae and to produce Omega-3 fatty acids.

6.2.5.6 Chain elongation

The high water solubility of short chain VFAs (with 2-5 carbons) necessitates a complex downstream processing to recover them in high purity and concentrations. Medium chain VFAs (with a carbon length of 6-12) on the other hand tend to be highly hydrophobic in their acid form (e.g. solubility of C6 (caproic acid) is 11 g/L, C7 is 1 g/L), making their downstream processing more straightforward[30]. Two promising pathways are known to microbially produce C6-C8 carboxylic acids from short chain carboxylic acids (C2-C4). A first route uses ethanol as electron donor to convert acetic acid to mainly C6 (and some C8)[30]. In this process, butyric acid is produced as an intermediate, so C2/C4 VFA mixtures from the VFA platform are a suitable carbon source for the microbial chain elongation to C6-C8. Yet, the economic feasibility is strongly dependent on the availability of a cheap ethanol source. Recently, a

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[25] Tocher, D.R., Betancor, M.B., Sprague, M., Olsen, R.E., Napier, J.A. (2019). Review - Omega-3 Long-Chain Polyunsaturated Fatty Acids, EPA and DHA: Bridging the Gap between Supply and Demand. Nutrients, 11: 89. doi:10.3390/nu11010089

[26] see: http://www.agri-outlook.org/data/

[27] Hamilton, M.L., Powers, S., Napier, J.A., Sayanova, O. (2016). Heterotrophic Production of Omega-3 Long-Chain Polyunsaturated Fatty Acids by Trophically Converted Marine Diatom *Phaeodactylum tricornutum*. Marine Drugs, 14(3): 53. https://doi.org/10.3390/md14030053

[28] Chalima, A., Oliver, L., Fernández de Castro, L., Karnaouri, A., Dietrich, T., Topakas, E. (2017). Utilization of Volatile Fatty Acids from Microalgae for the Production of High Added Value Compounds. Fermentation, 3: 54. doi:10.3390/fermentation3040054

[29] Chalima, A., Hatzidaki, A., Karnaouria, A., Topakas, E. (2019). Integration of a dark fermentation effluent in a microalgal-based biorefinery for the production of high-added value omega-3 fatty acids. Applied Energy, 241: 130–138

[30] Angenent, L., Richter, H., Buckel, W. (2016). Chain Elongation with Reactor Microbiomes: open-culture biotechnology to produce biochemicals. Env. Sci. Tech, 50(6): 2796-2810

second, novel route has been discovered to convert lactic acid (which can act both as electron donor and acceptor) to C6-C8, again with acetic and butyric acid as intermediates[31,32]. Lactic acid, also a short chain carboxylic acid, can be produced in a VFA platform, and opens opportunities to convert mixtures of lactic, acetic and butyric acid to medium chain carboxylic acids, without the need of an external electron donor. At this moment, the lactic acid route is still at a lower TRL level (research phase), whereas the ethanol route is shorter to market introduction, with some pilot plants already being constructed.

The application potential of C6-C8 is mainly in niche markets as additives in food (artificial flavours), although due to the biowaste origin this valorisation route will be limited to C6-C8 derived from well-defined biowaste streams from the food industry), feed additives or as a building block in the chemical industry. The scale of C6-C8 production expected in a single biowaste treatment plant (coupled with AD) will most likely to be too low to support an individual business case. Nevertheless, as C6-C8 VFAs mainly target a low volume market, the combined production of 2-3 plants is expected to be sufficient to support an economically feasible value chain.

6.2.5.7 Microbial protein

Developed in the 1970s, the production of microbial protein (MP) has recently gained new attention following increased protein prices and the awareness of the importance of sustainable protein production. Current commercial MP products are pure cultures, using one specific strain of bacteria as end product, rendering cultivation conditions challenging and virtually exclude their use for biowaste derived VFAs. Nevertheless, a promising mixed culture approach has proven to be successful to convert high strength wastewater from food industry, and also biowaste derived VFAs are a promising feedstock for MP production, especially because the VFA broth also contains N and P which are necessary for microbial protein production. Due to legislative restrictions, the MP from mixed culture production can currently only be applied in slow release organic fertilizers, but in future also feed and food applications are within reach.

7 Assessment Methodology

7.1 General

The information provided under this chapter is intended to be used to determine if the integration of a VFAP technology into an existing or new biogas plant is economically viable as well as environmentally sound. The assessment methodology is relying beside others on the reference document on Economics and Cross-Media Effects published by the EC in July 2006 in the context of integrated pollution prevention and control[33].

7.2 SWOT Analysis

The following SWOT analysis template offers a methodology to evaluate the positive and negative factors regarding the VFAP technology either by integration into existing biogas plants as well as newly developed plants with municipal wastes as feedstock. These factors are commonly divided in internally

[31] Andersen, S., Candry, P., Basadre, T. (2015). Electrolytic extraction drives volatile fatty acid chain elongation through lactic acid and replaces chemical pH control in thin stillage fermentation. Biotechnol Biofuels 8:221

[32] Zhu, X., Tao, Y., Liang, C. (2015). The synthesis of n-caproate from lactate: a new efficient process for medium-chain carboxylates production. Sci Rep 5, 14360

[33] European Commission (2006). Integrated Pollution Prevention and Control – Reference Document on Economics and Cross-Media Effects. July 2006

related (Strengths and Weaknesses) as well as externally related factors (Opportunities and Threats). Since VFAP is based on anaerobic digestion of municipal waste SWOT analysis have to be considered for

— the municipal waste collection system which delivers the substrate

— the anaerobic digestion technology as the underlying process

— the VFAP technology itself

In VOLATILE project deliverable D1.1 (2018)[34] it is outlined that bio waste is currently collected in fourteen EU countries (AT, BE, CZ, DE, FI, EE, IT, HU, LU, NL, SI, SE, IE, UK) by single stream door-to-door collection (separate collection), which is very effective. A bring-point and civic amenity site system is sometimes applied and appears to be rather effective and is mainly used for the collection of green waste. The SWOT analysis for the single stream door-to-door waste collection method is listed in Table 2.[34]

Table 2 — SWOT analysis of single stream door-to-door waste collection[34]

	Strengths	Weaknesses
Internal factors	**— Clean, high quality waste streams** **— Large positive effect on recycling numbers** **— Lower capital costs for further purification** **— Higher awareness of waste production/removal**	**— Expensive collection method (separate or special trucks for each fraction)** **— Waste bins take up space: less suitable for urban areas** **— Waste bins can produce a 'bad' odour** **— Depends on voluntary contribution**
	Opportunities	**Threats**
External factors	**— Collection of many different types of waste is possible** **— Increasing recycling numbers to higher levels**	**— Public opinion and convenience are important** **— Increased CO2-production of transport vehicles** **— Contamination by other waste streams in the single stream (lower purities)** **— Failure due to ignorance**

Industrial digesters are used to degrade the organic fraction of municipal solid waste (separately collected or obtained in MBT plants), and sewage sludge digesters are degrading the sludge resulting from waste water treatment. During degradation, the organic matter is converted to biogas (mainly CH_4 and CO_2) and digestate, which contains the undegraded organics, biomass and nutrients. In VOLATILE

[34] VOLATILE (2017) Deliverable D1.1 – State-of-the-Art of bio waste valorisation in the test regions and beyond, May 2017.

https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5b3b72875&appId=PPGMS

project deliverable D1.1 (2018)[34] a SWOT analysis for anaerobic digestion is provided (Table 3). The SWOT analysis of the VFA-technology is shown in Table 4.

Table 3 — SWOT analysis of anaerobic digestion [34]

	Strengths	Weaknesses
Internal factors	— Combined production of energy and fertiliser/soil improver — Suitable for heterogeneous waste — Proven technology for organic waste treatment — Limited odour emissions due to closed reactor vessels	— Process stability strongly dependent on input characteristics (e.g. nitrogen content) — Digestate is less stable than compost so additional need for aerobic post-treatment — Complex process (pre-treatment and post-treatment)
	Opportunities	**Threats**
External factors	— Easily integrated in existing composting facilities to improve sustainability — Increased awareness of intrinsic value of recycled nutrients in digestate — Growing market for renewable energy from waste biomass — Co-digestion — Easily integrated into new biorefinery concepts to improve sustainability	— Higher investment cost compared to composting — Competing technologies who aim at higher value products from the same waste material — Variable legislation between countries — More expensive technology for renewable electricity production compared to wind and solar — Often needs subsidies to be profitable

Table 4 — SWOT analysis of VFA technology

	Strengths	Weaknesses
Internal factors	— Valorisation of bio-based platform chemicals will make AD more cost efficient — Digesting process is faster thereby enhancing treatment capacities — Biogas and digestate are still produced in parallel to VFA	— Due to faster digestion the organic fraction which is only slow degradable will enrich in the compost — Composition of VFAs may vary in the product stream and is dependent on waste composition — Production process is more complicated than conventional anaerobic digestion
	Opportunities	**Threats**
External factors	— VFA can be sold to the chemical industry as building blocks — Biotechnological upgrading to PHA, omega 3 fatty acids and single cell protein can extend the business model	— Additional equipment is needed that leads to higher investment cost — A distributing system and clients for the products must be established — The legal status of the products derived from waste must be cleared. — Legislation and standardisation might change short term (< 5 years)

7.3 Life Cycle Assessment

ISO 14040[35] describes an internationally standardised methodology to quantify environmental impact of a product or process considering the full life cycle. As an example in VOLATILE, a LCA study has been performed[36], based on the methodology for LCA, as specified in the standardized documents of ISO 14044, ISO 14040 and ILCD Handbook for eight business cases for the current situation of treatment of municipal solid biowaste and sludgy biowaste by anaerobic digestion. Due to the early stage of the project VFA production data could not be included in the study. Nevertheless, a state-of-the-art analysis about LCA analysis of bio products of interest (PHA, omega 3 fatty acids, SCO) is available.

An LCA is carried out in four steps:

1) Definition of the Goal & Scope of the LCA

The LCA study is performed on appropriate LCA software (openLCA, GaBi. SimaPro, etc.). The objective of an LCA study is to analyse the environmental impacts of specific products / processes. The goal depends on the reason for carrying out an LCA study and the intended applications and audience for the result from the study.

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[35] ISO 14040:2006. Environmental management – Life cycle assessment – Principles and framework. https://www.iso.org/standard/37456.html

[36] https://www.volatile-h2020.eu/Open%20Access/Public%20deliverables/D_08_02_Initial%20Situation%20analysis%20of%20Municipal%20Solid%20&%20Sludgy%20Biowaste%20treatment,%20valorization%20and%20bioproducts.pdf (still not available at https://cordis.europa.eu/search)

When defining the scope of the study the following aspects should be considered:

— The studied system

— The functional unit

— The system Boundaries

— The environmental impact assessment methodology and types of impacts, and interpretation to be performed

— Assumptions and limitations

— Data requirements

2) Life Cycle Inventory Analysis (LCI)

In the inventory analysis, all inputs and outputs of the systems under study have to be reported. All materials and energy inputs, as well as all emissions to air, water and soil are taken into account in an LCA study. The data can be obtained by directly measured data when implementing the process, data from simulation tools, literature data, calculations, databases, etc.

3) Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment identifies and evaluates the amount and significance of the potential environmental impacts arising from the LCI. The choice of the impact categories depends on the process and on the scope of the study. The following impact categories should be considered and assessed when implementing an LCA study for biowaste treatment:

— Acidification

— Global warming

— Ecotoxicity

— Eutrophication

— Human toxicity

— Ozone depletion

— Particulate matter

— Photochemical Ozone Creation Potential

— Freshwater Consumption

— Energy demand

4) Life cycle interpretation

Interpretation and comparison of the results achieved and ranking of the alternative options according to highest level of environmental protection.

7.4 Cost Analyses/ Economic Feasibility Study

7.4.1 Definition of Cost Components

7.4.1.1 General

This section provides a costing methodology which allows stakeholders, users and decision-makers to establish and present the costs of implementing a Volatile Fatty Acid Platform compared to other techniques in a transparent way. The methodology is based on the reference document on Economics and Cross Media Effects of the European Commission[33].

In order to ensure proper data comparison, the cost components included in the analysis should be clearly stated in the assessment report.

The following cost categories should be considered and assessed in relation to other alternatives:

7.4.1.2 Investment expenditure

- Total investment expenditure for implementing VFAP
  - Costs for definition, design and planning of the project for VFAP implementation
  - Purchase of land
  - General site preparation
  - Civil works and buildings (including foundations / supports, erection, electrical, piping, insulation, painting etc.)
  - Engineering, construction and field expenses
  - Equipment costs, auxiliary equipment and instrumentation
  - Costs and fees for contractor selection
  - Performance testing
  - Costs for start-up
  - Working capital costs
  - Costs for decommissioning
  - Contingency allowance for expenses that cannot be estimated precisely
  - Security and privacy equipment
  - Software and licenses
  - Vehicles

If applicable:

  - costs for loss of production during a certain time frame due to implementation of VFAP in existing facility

7.4.1.3 Operating / maintenance costs

- Total annual operating / maintenance costs
  - Energy costs (unit price + overall cost)
    - Electricity
    - Natural gas
    - Petroleum products
    - Coal or other solid fuels
    - Biogas
    - ...
  - Materials and service costs
    - Replacement parts
    - Auxiliaries such as water, chemicals, etc
    - Environmental services such as waste treatment or disposal services
  - Labour costs
    - Operating costs
    - Supervisory costs
    - Maintenance staff
    - Costs for training of staff
    - Travel
  - Fixed operating / maintenance costs
    - Insurance costs
    - Fees for licences
    - Provisions for emergencies
    - Other general overheads (e.g. administration)

If applicable:

- Subsequent costs

  The implementation of the VFAP can lead to changes in the existing AD process – biogas output – which might lead to increasing costs, due to for example a drop-in system effectiveness or inferior biogas, digestate or compost quality

7.4.1.4 Benefits / revenues / avoided costs

- Total annual benefits / revenues / avoided costs
    - Revenues
        - Waste treatment fees paid by biowaste producer (gate fee)
        - Sales of treated effluent (digestate) as fertilizer
        - Sales of biogas – natural gas grid
        - Sales compost
        - Sales of generated electricity
        - Sales of Volatile Fatty Acids
    - Avoided costs (in amount energy saved, number of man-hours saved, quantity of added value product recovered and sold)
        - Savings on raw materials
        - Savings on energy use
        - Savings on auxiliaries
        - Savings on disposal costs
        - …

If applicable:

- Subsequent benefits

  The implementation of the VFAP can for example lead to changes in the existing AD process – biogas output – which might lead to lower costs, due to for example a rise in system effectiveness or improved biogas, digestate or compost quality

Reference values for waste treatment costs as unit costs (€/ton) for composting, anaerobic digestion, incineration and landfilling can be found in VOLATILE – Deliverable 8.1 (2018)[37]

[37] VOLATILE (2018) Deliverable D8.1 – Initial Cost Situation Analysis on Municipal Solid & Sludgy Biowaste Treatment, June 2018.

https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5bbd05f22&appId=PPGMS

7.4.2 Methodology and financial equations

7.4.2.1 Financial equations

1) Total Annual Cost Balance (TACB):

$$TACB = TAR - TAC \tag{1}$$

TAR: Total Annual Revenues
TAC: Total Annual Costs

2) Total Annual Cost (TAC)

TAC considers total investment expenditures as well as total annual operating / maintenance costs.

$$TAC = \sum C_{equipment} + C_{operational} \tag{2}$$

3) Total Investment Expenditures ($C_{equipment}$)

Total Investment Expenditures ($C_{equipment}$) consider discounted costs (depreciation) for equipment purchase as well as costs for building, construction, consulting etc. The equipment costs depend on the lifetime (n_{life}) of the equipment/plant, the Lang factor (LF) which is set at 3.5 and the interest rate (i) to consider the time value of money (i = 0.06 which corresponds to 6 %).

$$C_{equipment} = LF \times C_{invest} \times \frac{i \times (1+i)^{n_{life}}}{(1+i)^{n_{life}} - 1} \tag{3}$$

C_{invest}: Purchase costs of equipment / plant

LF: Lang factor (see text)

In case the equipment is depreciated, C_{invest} is zero. Thus, in this case $C_{equipment}$ is also zero.

Furthermore, C_{invest} depends on the dimension and capacity. In case no real investment data are available, the equipment investment costs (C_{invest}) for a specific capacity (A_{eq}) can be estimated from a standard equipment (A_{ref}) with given dimensions/capacity by using the process scale factor equation:

$$C_{invest} = C_{ref} \times \left(\frac{A_{eq}}{A_{ref}} \right)^{n_{eq}} \tag{4}$$

C_{ref}: the costs for a reference installation with dimension / capacity A_{ref}

n_{ref}: the scaling factor for the equipment (0.6 – 1)

It is recommended that the C_{ref} is expressed on an equivalent price basis, i.e. in the prices of a common year. The procedure for expressing the C_{ref} in the prices of a selected year is given in the reference document on Economics and Cross Media Effects of the European Commission[33].

4) Total Annual Operating / Maintenance costs ($C_{operational}$)

$$C_{operational} = \sum C_{energy} + \sum C_{\frac{material}{service}} + \sum C_{labour} + \sum C_{fixed \frac{operating}{maintenance}} \tag{5}$$

7.4.2.2 Process and prepare cost data / cost adjustments

To compare different technology options equitably, gathered cost information must be adjusted to handle aspects such as effects of inflation or exchange rates. Other aspects to be considered are different operational lifetime of technologies, interest rates or costs of loan repayment. Several options how to make these costs adjustments are described in the Technical Report № 27 (EEA, 1999)[38]. If cost adjustments are done, the steps involved, and the used methodologies should be stated to ensure transparency in the calculations. Information on reference exchange rates, price indices or inflation rates can be found at Eurostat[39] or at European Central Bank[40].

7.4.3 Economic Feasibility Assessment & Interpretation

Calculate the total annual cost balance of every option considered. Interpret and compare the results achieved and rank the alternative options according to highest annual cost balance. Only options with a positive TACB are considered.

7.5 Process – Modelling

7.5.1 Gather data on biowaste type & availability vs distance to treatment location

The first aspect to be analysed is the availability of different type of biomass/biowaste around the year for the treatment in the Volatile Fatty Acid Platform. Also, distance to the planned treatment facility must be assessed carefully as transport costs have a significant impact on the whole cost structure. According to Giuntoli et al. (2017)[41], the distance for municipal organic waste transport can be assumed with for example 20 km.

Furthermore, other treatment facilities competing on the biomass source in a specific region must be considered.

1) Type & Amount of Biomass / Biowaste [ton/year] + [ton/month]

2) Distribution of biowaste in the catchment area of the VFAP

3) Collection scheme / Transport costs

In order to establish baseline indicators, the **biogas potential** of the different biomass sources should be estimated, or biogas potential should be analysed according to standardised methodology:

— High Solid Load - Anaerobic Digestion:

  — Plastics – Determination of the ultimate anaerobic biodegradation and disintegration under high-solids anaerobic-digestion conditions - Method by analysis of released biogas (ISO 15985: 2014)

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[38] EEA (1999) European Environment Agency – Technical Report № 27 – Guidelines for defining and documenting data on costs of possible environmental protection measures

https://www.eea.europa.eu/publications/TEC27

[39] https://ec.europa.eu/eurostat/data/database

[40] https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/

[41] Giuntoli J, Agostini A, Edwards R, Marelli L, Solid and gaseous bioenergy pathways: input values and GHG emissions. Calculated according to the methodology set in COM(2016) 767, EUR 27215 EN, doi:10.2790/27486.

— Standard Test Method for Determining Anaerobic Biodegradation of Plastic Materials Under High-Solids Anaerobic-Digestion Conditions (ASTM D5511: 2012)

— Wet Anaerobic Digestion:

— Fermentation of organic materials - Characterization of the substrate, sampling, collection of material data, fermentation tests (VDI 4630: 2016)

— Determination of the GB21 according to the 'Verordnung über die umweltverträgliche Ablagerung von Siedlungsabfällen und über biologische Abfallbehandlungsanlagen (AbfAblV, 2001) (Annex 2 No. 5).

Afterwards, the **Volatile Fatty Acid Potential** can be estimated according to the Factsheet: "Volatile Fatty Acid Production" of the European funded research project VOLATILE (see Annex A).

Table 5 — Volatile Fatty Acid Production Potential of different biomass / biowaste sources[11]

Biomass / Biowaste	**Volatile Fatty Acid Production Potential** g COD / kg VS[a]
VGF waste	448 ± 152
Organic Fraction MSW	384 ± 91
Food waste	627 ± 226
WWTP sludge before AD	179 ± 100
[a] COD – Chemical Oxygen Demand; VS – Organic matter	

7.5.2 Scope and identify the alternative options for biowaste treatment

Several biomass/biowaste valorisation options exist and should be carefully analysed test case specific. Only valorisation options towards a circular bioeconomy should be considered and compared to the Volatile Fatty Acid Platform Technology. Beside others the following technologies are listed in Pinasseau et al. (2018)[10] and should be analysed test case specific.

Table 6 — Valorisation options (Pinasseau et al., 2018)[10]

Valorisation Technology	**Added-value Product**
Composting	Compost / Fertilizer
Anaerobic digestion	Energy, Biogas/Methane, Digestate (Fertilizer)
AD with integrated VFAP	Energy, Biogas/Methane, Digestate (Fertilizer), Volatile Fatty Acids

Chapter 5 of Economics and Cross Media Effects (EC, 2006)[33] provides a general guideline to select a technology. Especially market structure of the local regional market, resilience as well as speed of implementation should be assessed.

7.5.3 Emissions inventory & Gather and validate cost data

Inventory on emissions and resource use are needed to perform a life cycle assessment and to analyse the environmental performance of the foreseen valorisation plant. Information on emissions can be found in the document Pinasseau et al. (2018)[10] as well as Giuntoll et al. (2017)[41]. General cost data on anaerobic digestion are compiled in Tsiropoulos et al. (2018)[42]. Chapter 4 of Economics and Cross Media Effects[33] provides an approach to determine cost effectiveness of each option identified and how some reference points or benchmark related to environmental benefits can be used in decision making towards the Best Available Technology.

8 Summary

An upgrade of anaerobic digestion plants for coupled energetic and material use of biogenic residues and waste materials offers for many biogas plant operators the opportunity to operate continuously in an economically viable way. One possible application could be the integration of a Volatile Fatty Acid Platform (VFAP) Technology into already existing biogas plant.

The separation of volatile fatty acids (VFA: acetic acid among others) from the biogas process is currently object of research and innovation and demonstration in many European funded projects and derived technological applications are now on the threshold of commercialisation. This CEN/CENELEC Workshop Agreement (CWA) is a technical agreement, developed and approved by an open, independent workshop structure within the framework of the CEN-CENELEC system. Responsible for the content are the registered participants, who are mainly actors of the entire value chain of municipal biowaste treatment by anaerobic digestion and related scientific research disciplines.

The framework considered is been described for managers of anaerobic digestion plants in general, and those treating solid and sludgy biowaste in particular. It is divided into a non-technical and a technical part for the introduction of criteria and dimensions necessary for the evaluation of feasibility and accompanied by a section of assessment methodology.

Economic arguments and arguments related to a company's image are discussed and set in relation to more complex non-technical aspects like the more tacit and social components of the assessment. Contextual factors like subsidies, the political vision and the regulatory framework in the EU and some Member States are also addressed.

For assessing the technical criteria, a multi-criteria decision-making guide has been developed. First, bio-based raw materials of the municipal waste streams suitable for anaerobic degradation are discussed with regard to quality requirements, the different substrate categories and substrate availability criteria. Second, the impact of the integration of a Volatile Fatty Acid Platform Technology of and on current anaerobic digestion plants is assessed focussing on the underlying microbial processes and biogas recovery and taking into account possible existing pre-treatment technologies. Third, the available VFA conversion technologies are presented from direct application to different fermentation routes with VFA as substrates as well as chemical conversion routes.

Whether the integration of a VFAP technology into an existing or new biogas plant is economically viable as well as environmentally sound can be assessed with several well-established methods. The discussed methods of SWOT analysis, Life Cycle Assessment and the principles of Cost Analyses and Economic Feasibility Studies are tailored to the objective of integrating a (VFAP) Technology into an already existing biogas plant.

In conclusion, this CWA provides a simple evaluation methodology for biogas plant operators, investors, and municipalities on how to assess whether the changeover of a given biogas plant to a coupled energetic and material use is ecologically and economically reasonable under certain conditions.

[42] Tsiropoulos I, Tarvydas, D, Zucker, A, (2018). Cost development of low carbon energy technologies - Scenario-based cost trajectories to 2050, 2017 Edition, EUR 29034 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-77479-9, doi:10.2760/490059, JRC109894

Annex A
(informative)

Fact sheet of the VOLATILE project

A laboratory test method (Volatile Fatty Acid Production Potential Test) was developed that yields, in a relatively short time interval (typically 11 days) information about the maximum VFA potential, VFA conversion rate, VFA spectrum and the gas production (CO_2/H_2). The method is based on existing protocols to determine the maximum biogas potential of a substrate, but is altered to suppress methanogenic activity and instead favour acidification and acetogenesis. The test method was developed and optimized with > 60 samples of urban biowaste and WWTP sludge, collected during two sampling campaigns from VOLATILE project partners. The ultimate goal is to further develop this test protocol into an international recognized standard test, similar to e.g. ISO 15985 and VDI 4630 for anaerobic degradation tests.

Within the VOLATILE project, six types of waste streams were identified and evaluated:

— VGF waste (source separated organic household waste, mainly kitchen waste incl. animal by-products if allowed in that region and to a lesser extent small garden waste)

— OF-MSW (the organic fraction contained in residual, non-source separated household waste, usually obtained after a mechanical pre-treatment to remove the non-organic fractions)

— Food waste (source separated organic waste from the food and catering industry)

— Roadside grass (grass obtained from mowing the roadside verges and removing the freshly mown grass as a measure to improve biodiversity in these roadside verges)

— WWTP sludge before AD (secondary sludge or a mix of primary and secondary sludge obtained after wastewater treatment of municipal solid waste)

— WWTP sludge after AD (sludge obtained after anaerobic digestion of secondary WWTP sludge)

The tests revealed that food waste showed the highest VFA potential, followed by VGF waste and OFMSW, and secondary WWTP sludge with the lower potential. Digested WWTP sludge and roadside grass showed a low VFA potential and are deemed unfeasible at the moment to be integrated in a VFA platform (Figure A.1).

In a next step, the lab batch tests were translated into process designs to produce VFAs on a continuous basis. A pre-treatment step was developed and tested to separate the heterogeneous biowaste streams in a fraction for VFA recovery and a residual fraction to be used for biogas production, integrating material and energy recovery. The optimized pre-treatment process was able to retain 93 % of the maximum VFA potential in an easy treatable matrix and a secondary stream which still contained 48 % of the biogas potential compared to the untreated waste (Figure A.2).

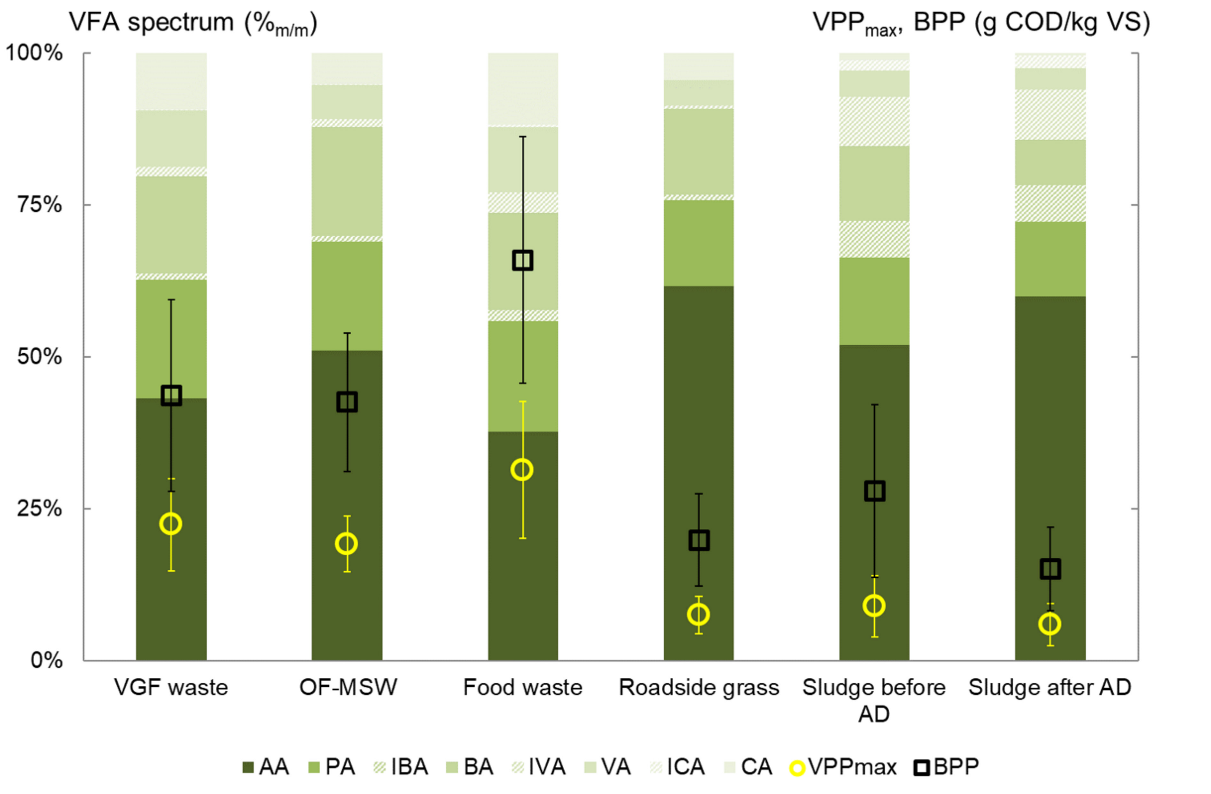

Figure A.1 — Average VPP max (green circle), average BPP (red square) and VFA spectrum composition for the six waste stream categories

As a final step, several process designs were evaluated at lab scale, and will provide the necessary info for the design and construction of a TRL5 pilot reactor at the facilities of a VOLATILE partner, where VFA production will be integrated with an existing 150 m^3 AD reactor during the final VOLATILE project year.

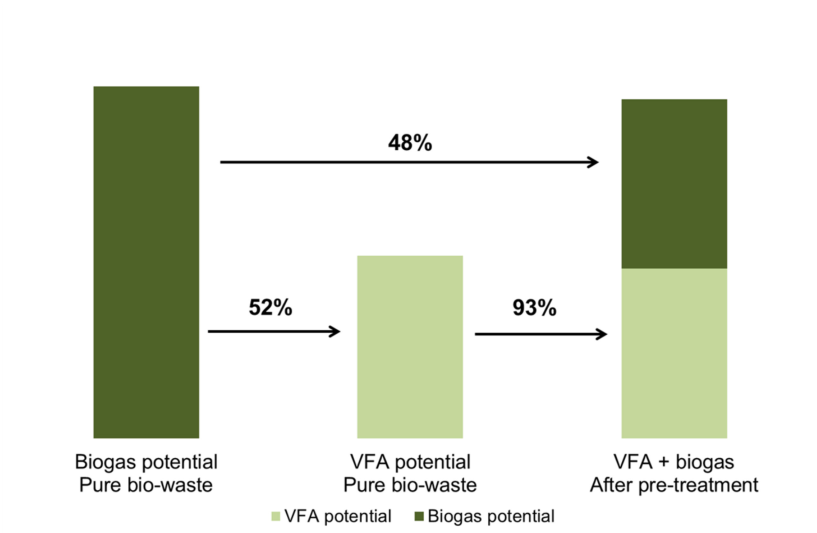

Figure A.2 — VFA and biogas potential after pre-treatment of biowaste

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<std>[1] ISO 20675, *Biogas - Biogas production, conditioning, upgrading and utilization - Terms, definitions and classification scheme*</std>

<unknown>[2] VDMA 4330, Biogasanlagen - Hinweise für Planung, Ausführung und Betrieb</unknown>

<std>[3] ISO 13641-1, *Water quality - Determination of inhibition of gas production of anaerobic bacteria - Part 1: General test*</std>

<std>[4] ISO 13641-2, *Water quality - Determination of inhibition of gas production of anaerobic bacteria - Part 2: Test at low biomass concentrations*</std>

<std>[5] VDI 4630, *Fermentation of organic materials - Characterization of the substrate, sampling, collection of material data, fermentation tests*</std>

<unknown>[6] ABNT NBR 16562, Biogas and bio-methane - Determination of volatile organic compounds by gas chromatography and sampling with thermal desorption tube</unknown>

<std>[7] DIN 11622-2, *Silage and liquid manure containers, containers in biogas plants, bunker silos and trench silos - Part 2: Silage and liquid manure containers and containers in biogas plants made of concrete*</std>

<std>[8] EN 1473, *Installation and equipment for liquefied natural gas - Design of onshore installations*</std>

<std>[9] EN 16723-1, *Natural gas and biomethane for use in transport and biomethane for injection in the natural gas network - Part 1: Specifications for biomethane for injection in the natural gas network*</std>

<std>[10] EN 16723-2, *Natural gas and biomethane for use in transport and biomethane for injection in the natural gas network - Part 2: Automotive fuels specification*</std>

<std>[11] UNI 10458:2011, *Biogas plants for the production and the use of biogas, based on anaerobic digestion processes - Classification, essential requirements, guidelines for construction, trade offer, final order, acceptance tests of the plants*</std>

<std>[12] VDI 3475 *Blatt 1, Emission control - Biological waste treatment facilities - Composting and anaerobic digestion; Plant capacities more than approx. 6000 Mg/a*</std>

<std>[13] VDI 3475 *Blatt 2, Emission control - Facilities for biological waste - Composting an anaerobic (co-)digestion - Plant capacities up to approx. 6000 Mg/a*</std>

<std>[14] VDI 3475 *Blatt 3, Emission control - Mechanical-biological treatment facilities for municipal solid waste*</std>

<std>[15] VDI 3475 *Blatt 4, Emission control - Agricultural biogas facilities - Digestion of energy crops and manure*</std>

<std>[16] VDI 3475 *Blatt 5, Emission control - Biological waste treatment facilities - Anaerobic digestion and post-treatment*</std>

<std>[17] VDI 4631, *Quality criteria for biogas plants*</std>

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<std>[21] EN 16214-4, *Sustainability criteria for the production of biofuels and bioliquids for energy applications - Principles, criteria, indicators and verifiers - Part 4: Calculation methods of the greenhouse gas emission balance using a life cycle analysis approach*</std>

<std>[22] ISO 11734, *Water quality - Evaluation of the "ultimate" anaerobic biodegradability of organic compounds in digested sludge - Method by measurement of the biogas production*</std>

<std>[23] CEN/TR 17238, *Proposed limit values for contaminants in biomethane based on health assessment criteria*</std>

<std>[24] VDI 4254 *Blatt 1, Bioaerosols and biological agents - Measurement of metabolites of microorganisms - Measurement of MVOC in ambient air*</std>