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Country report

Assessment of a full-scale solid-state anaerobic co-digestion: A multi-component substrate analysis by using ORWARE

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ABSTRACT

Long-term sustainable biogas production requires different raw material alternatives, especially when reducing the most desirable organic substrate, food waste, which has been set as a goal in the 2030 Agenda. In Sweden, horse manure (HM) is generated in large quantities, and due to its physical and chemical characteristics, it has the potential to be used as a raw material to produce biogas through anaerobic digestion (AD). In order to investigate the challenges that HM digestion can impose in terms of methane yield and/or digestate quality, the modified ORganic WAste REsearch (ORWARE) AD model was applied. The aim was to study the effects of different substrates and combinations of these on the AD process during a full-scale solid-state (SS)-AD. In this sense, the model allows for the analysis of the digestion process of multicomponent substrates at the element level. The simulation results suggested that the replacement of green waste (GW) by HM with wood chips as bedding material gave the best improvement in terms of energy turnover; the liquid fraction of the digestate of this mixture of substrates presented the highest concentration in all the nutrients analyzed, specifically in total carbon-biological and phosphorus. The nutrient concentrations in the digestate from the aforementioned scenario are in line with the SPCR120 certification.

1. Introduction

Anaerobic digestion (AD) offers various services such as treatment of organic waste, generation of a digestate rich in nutrients, as well as production of clean energy through biogas. Biogas utilization is expected to play an important role in achieving energy and environmental targets, as it can be used in several ways, such as electricity and heat production, and as a renewable fuel for transportation and industry when upgraded (Budzianowski, 2016; Hijazi et al., 2016). In 2020, biogas production in Europe reached 191 TWh, of which 32 TWh were upgraded while the rest was used to produced local heat and electricity (Alberici et al., 2021). Digestate, on the other hand, is high in nitrogen (N) in addition to phosphorus (P) and potassium (K), and it can therefore be used as organic fertilizer; it is also considered as a sustainable option as its use decreases the environmental impact from conventional fertilizers, also giving a circularity to the process (Głowacka et al., 2020; Salomon and Wivstad, 2014).

Even if AD is flexible in terms of feedstock, the growing interest in the biogas sector should ensure that the feedstock supply is sustainable concerning its potential impacts on the environment (Meyer et al., 2018). In that sense, for a sustainable production process, biogas must reduce greenhouse gas emissions compared to the fossil alternatives, must not displace food and feed production, and should avoid any direct or indirect unwanted land use change while preserving biodiversity and soil quality (van Melle et al., 2018). Furthermore, it is well known that one of the main feedstocks for AD is food waste, rich in components such as fats, proteins, and sugars that usually give good biogas yield, between 117 and 531 m^3 CH_4/tonne VS (Carlos-Pinedo et al., 2019; Komilis et al., 2017). However, as part of the Agenda 2030, a goal was set to halve per capita global food waste at the retail and consumer levels, and to reduce food losses along production and supply chains, including post-harvest losses by 2030 (DESA U.N., 2016). According to a study by ECOFYS (van Melle et al., 2018), considering feedstock availability to ensure sustainable biogas production, only 3% of food waste was assumed for the European Union (EU) by 2050. These, in turn, require finding other feedstock substitutes for AD. For instance, in 2016, horse manure (HM) represented about 10% of the total manure produced by all domesticated animals in Sweden and it amounted to approximately 2.7 million tonnes per year (Svenska Ridsport Förbundet, 2016). This number is significant as for the same year, the collected food and residual waste

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accounted for slightly more than 2.2 million tonnes (Avfall Sverige, 2020).

Large amounts of horse manure (HM) can have negative impacts on the environment if they are not treated (e.g. composted) and/or stored properly (Hadin and Eriksson, 2016). According to Westendorf, (2004), most horse owners do not have sufficient land to dispose the generated HM and with improper management, nutrients might be emitted mainly as ground or surface water pollution due to its N and P content. To reduce emissions, HM is often stored on a cast metal slab or in a watertight container, and in some cases, stored directly or by using stockpiling on the ground (Hadin et al., 2017; Häggblom et al., 2012). Since it contains various macronutrients such as N, P, and K, the most common way to treat it has been by implementing composting as it does not require special tools or structures (Shaji et al., 2021). However, this form of organic waste can also be used for renewable energy generation through AD, while digested manure can serve as an organic fertilizer. Digesting manure generally increases its ammonium content and the total nitrogen concentration, elevates pH values and reduces viscosity (Głowacka et al., 2020; Möller and Müller, 2012); these have been regarded as advantages for the handling of manure through digestion. In addition, digestate contains organic carbon which has a positive effect on the soil's properties, and the absorption of its nutrients by plants seems to be similar compared to mineral fertilizers (Möller and Müller, 2012; Song et al., 2021; Verdi et al., 2019). Moreover, replacing mineral fertilizers with digestate can lower its financial and environmental costs since ammonia manufacturing for the production of such is still energy-intensive (Lukehurst et al., 2010; Riva et al., 2016). P is mainly obtained from phosphate rock, globally 91% of it is used for fertilizer production with a projection of 1.2% increase per year. Although most of the reserves have not been yet developed for production, there are already concerns about its depletion in future years (European Commission, 2020). In some countries, several secondary sources of phosphorus are already being considered to reduce the dependence on phosphate rock (Wang et al., 2020).

Early studies (Hadin et al., 2016; Kusch et al., 2008; Mönch-Tegeder et al., 2014) stated that digestion of HM may impose challenges in terms of lower methane yield and/or digestate quality as compared to food waste digestion. This is because HM generally contains a large portion of bedding material, which is used to create dry and clean spaces for horses and to facilitate its handling. At the same time, that bedding material which consists of a large amount of cellulose and hemicellulose can hamper the digestion process if no pre-degradation has occurred. For instance, some research has been done based on HM and bedding ratios, as well as the type of bedding used. Wartell et al. (2012) investigated different HM:bedding ratios, bedding as fresh and used softwood, and straw, concluding that softwood could have a dilution effect on potential energy production. Böske et al. (2015) studied the digestion of HM with different types of bedding materials such as wheat straw, flax, hemp, and wood chips, showing that straw had the higher biochemical methane potential. In addition, Hadin & Eriksson (2016) simulated different types of bedding materials with HM, stating that methane yield using straw is comparable to wood chips. Mönch-Tegeder et al. (2014) indicated that a pretreatment for HM and bedding material is necessary to achieve a better degradation rate and therefore gas production. It should however be pointed out that this study was conducted by using a pilot CSTR rector that is based on a low solid content within the digester. As compared to other types of manures, HM can have a total solids (TS) content of 20% or higher (Hadin and Eriksson, 2016) and therefore fits perfectly as a feedstock for high solid or solid-state AD (SS-AD) processes, which usually requires a TS of more than 15% (Carlos-Pinedo et al., 2019). Even when a recent study analyzed the environmental impact of different HM treatments like SS-AD under full-scale conditions (Havukainen et al., 2020), to the best of our knowledge, no studies have been performed to examine its digestion when other types and amounts of substrates are also present, and how these mixtures will affect the desired products such as methane and digestate. The aim of this study is, therefore, to investigate how different substrates or combinations of these would influence the production and quality of methane and digestate from a full-scale SS-AD when different feedstocks including HM are co-digested.

It is also important to understand how nutrients from different substrates are balanced when a co-digestion is implemented. The risk for secondary pollution when an excess of nutrients is applied to land should also be taken into account, which is unfortunately not always the case in the literature. Back in 1999, the Swedish Waste Management Association created a voluntary certification system i.e., SPCR120, which gives recommendations and directions for digestate usage in addition to specific requirements for incoming input material (feedstocks), deliverers, collection and transport, and process of treatment (Avfall Sverige, 2007; Risberg, 2015). Towards that end, the modified ORganic WAste REsearch (ORWARE) AD-model (Carlos-Pinedo et al., 2020) which enables analyzing digestion process of multi-component substrate on an element level was applied to study not only the energy performance but also digestate valorization from a full-scale SS-AD plant located in Sweden.

2. The solid-state anaerobic digestion plant

The SS-AD plant under study is located in Gävle, Sweden, and is operated to treat different organic fractions under thermophilic conditions at 55 °C. It should be noted that the digester at this plant is configured as a plug-flow reactor (PFR) with a hydraulic retention time (HRT) of 36 days. The plant is designed with a capacity of treating 25,000 tonnes of feedstock/year. However, to perform an analysis regarding the influence of the types of feedstocks on the production of biogas and digestate in comparison with the original plant operation, the total amount of feedstock was set to be 14,808 t/year in this study being the same as the one in our previous work (Carlos-Pinedo et al., 2020). More specifically, HM and two types of bedding material, wood chips, and straw have been added to the original feedstock mixtures consisting mainly of biowaste (BW) or food waste and green waste (GW) such as garden and parks waste. Likewise, a small fraction of a semi-liquid food slurry/grease sludge (FS/GS), which is considered as a secondary feedstock that helps to adjust the TS to be 27% inside the digester; this value was kept the same for all the mixtures during this investigation. Besides, by utilizing a screw press for dewatering, the SS-AD plant produces a liquid digestate that is used as organic fertilizer as well as a solid digestate used as a soil amendment. More detailed descriptions of the SS-AD plant can be found elsewhere (Carlos-Pinedo et al., 2020).

3. ORWARE anaerobic digestion model

To analyze methane production, digestate quantity and quality, energy and mass balances for this specific SS-AD, the modified ORWARE AD-model which is able to study the SS-AD under PFR configuration was used (Carlos-Pinedo et al., 2020). As explained previously, one of the most important features of the ORWARE model is that different feedstocks are described at an elemental level in terms of the chemical compositions of e.g., carbohydrates, proteins, lipids, as well as other characteristics such as TS and VS, and so on. In the ORWARE model, this information is processed as a dataset of 74 substances and used to describe all substance flows in the model to calculate the turnover of materials, energy, and financial resources. In this study, the methane yield is of particular interest and is evaluated by using Eq. (1) (Carlos-Pinedo et al., 2020), in which the biogas production is related to the amount of organic matter degraded and the fraction of methane from each organic compound, i.e., carbohydrates, lipids, and proteins present in the feedstock, together with the molecular weights of methane and carbon dioxide expressed in their carbon form. In that sense, ORWARE relates the degradation of organics only to the composition of the substrate (Dalemo et al., 1997).

$$B_i = C_i\left(m_i\frac{16}{12} + (1-m_i)\frac{44}{12}\right)D_i \tag{1}$$

where,

$_i$ = different organic compounds in the feedstock such as carbohydrates, fats, and proteins
B_i = biogas production from each organic compound contained in the feedstock (kg/kg input of feedstock)
C_i = amount of each organic compound in the feedstock as their hydrocarbon form (kg/kg input of feedstock)
m_i = fraction of methane from each organic compound
D_i = degradation ratio for each organic compound

The values of degradation ratios, the fraction of methane as well as the categorization of the biodegradable organic compound of a substrate are retrieved from the ORWARE datasets by Dalemo (1996).

On the other hand, the digestate is evaluated by doing a mass flow analysis between what the feedstock has as initial and final TS, water, N, P, K, etc., together with the amount that is left after calculating the biogas production, in addition to the necessary extra fresh water used to adjust the process TS. As for the energy turnover, the used heat and electricity in the production of biogas are subtracted from the final methane yield. More details about the heat and electricity values can be found in Carlos-Pinedo et al. (2020).

3.1. Feedstock

Based on the ORWARE dataset, the chemical and nutrient characteristics of each feedstock used in this study are presented in the supplementary materials in Table S1. Biogas production is then calculated from each organic component where N, P, and K represent the main nutrients to be used as fertilizers.

The proportions of bedding material and horse manure are generally difficult to quantify due to differences in the handling of each stall. For instance, Wartell et al. (2012) estimated a softwood bedding to horse manure ratio in terms of volatile solids (VS) from 1:1 to 2:1. In this particular case, two types of bedding material were analyzed, i.e., wood chips and straw. Wood chips are mostly used in Sweden while straw is more common in other countries (Hadin and Eriksson, 2016; Kusch et al., 2008). For this study, it was assumed that horse manure contains one-third of bedding material, which is consistent with the value reported in the literature (Eriksson et al., 2016; Hadin and Eriksson, 2016).

3.2. Scenarios

To analyze the impact of different feedstocks and their proportions of components in a mixture on AD, four scenarios were constructed. The total amount of waste digested per year was kept at 14,808 tonnes for all scenarios. The studied scenarios are presented in the supplementary materials in Table S2 and are described as follows. Scenario A is the baseline scenario representing the plant operation during the time of this investigation and focused on the digestion of BW and GW as the main feedstock; scenario B is used to study the impacts on the process when GW is substituted by HM + wood chips; bedding material as one influential parameter in the digestion of HW is examined by a comparison of using straw in scenario C; scenario D exemplifies a situation to understand how the digestion of only HM affect the biogas production and the characteristics of the digestate. Scenario D shows a prospective situation regarding the decrease in the generation of food waste as a consequence of future better consumption practices and policies for sustainable development.

According to the characteristics of the feedstocks in the ORWARE dataset, wood chips have a higher VS than that of straw, 76 and 72 %w/w respectively, in that sense, the bedding (VS):manure (VS) ratio was 1.27:1 for scenarios B and D, and 1.2:1 for scenario C. The final characteristics of each scenario are given in Table 1. The operational conditions for all the scenarios are the same as described in section 2.

3.3. Assessment of the digestate

The amount and chemical composition of the digestate will depend on the characteristics and type of feedstock, in addition to the operational conditions and type of AD process (Risberg, 2015). Nutrients in the feedstock, like P and K, are conserved in the AD process but converted to a more organic form like orthophosphorous and reduced basic cations, K^+, (Logan and Visvanathan, 2019). Ammonium nitrogen (NH_4^+-N) content will be linked to the original feedstock total N, however, digestate will usually have higher NH_4^+-N:N ratios (Möller and Müller, 2012). According to regulations in Sweden, the input material for digestion should be from clean source-separated organic waste to avoid unwanted pollution for the process. In addition, a hygienization process needs to be done if the co-digestion includes animal waste such as manure to prevent the spreading of undesired materials when digestate is applied on land (Avfall Sverige, 2007). The SS-AD process works under thermophilic conditions with a high HRT of 36 days, and this can be considered as an in-situ/internal hygienization in the digester (Jorbruksverket, 2016). In that sense, an extra pre-treatment process is avoided.

Digestate was assessed both quantitatively and qualitatively through the model. For instance, the main nutrients, organic carbon (C-tot biological), N, NH_4^+-N, P, and K were analyzed in each scenario. Amounts of digestate and its nutrients can be directly retrieved from the model. This analysis was applied to both liquid and solid fractions of the digestate. The separation of the different compounds in the fractions in ORWARE is done by stoichiometry, either to follow the suspended solids (SS) or the compounds that dissolve in water. The dewatering process focuses on dry matter (DM), VS and SS (Dalemo et al., 1997). It is worth mentioning that the Swedish restrictions (SPCR120) on the use of digestate as organic fertilizer, i.e., 22 kg of P/ha/y counted as a five-year average and 150 kg NH_3/NH_4^+-/ha/y (depending on the type of soil it can be max. 170 kg NH_3/NH_4^+-/ha/y) were taken into account (Avfall Sverige, 2007). When applying digestate as fertilizer, the SPCR120 regulation states that it should not exceed the next values regarding heavy metals (Avfall Sverige, 2007): 1.00E-04 kgPb/kgTS, 1.00E-06 kgCd/kgTS, 1.00E-06 kgHg/kgTS, 6.00E-04 kgCu/kgTS, 1.00E-04 kgCr/kgTS, 5.00E-05 kgNi/kgTS, 8.00E-04 kgZn/kgTS. Since the input feedstock have low concentrations of heavy metals in all scenarios, see Table S3, it should be expected that the final digestate will not exceed the permissible range specified in the regulation.

4. Results and discussion

The results were divided into two main sections. Energy analysis for all scenarios was presented to determine the performances of the co-

Table 1
Characteristics of the scenarios.

Component (% w/w)	A	B	C	D
Total solids, (TS)	28.9	28.2	28.4	37.2
Volatile solids, (VS)	24.8	24.4	24.2	33.4
C-lignin	1.8	1.36	1.43	3.82
C-starch & sugar	2.3	2.0	2.5	0.0
C-fat	2.9	2.9	3.0	0.2
C-protein	1.5	1.4	1.6	0.3
C-cellulose	4.4	4.6	3.7	11.7
Total Nitrogen, N-tot	0.5	0.6	0.6	0.4
Ammonium nitrogen NH_3/NH_4^+-N	0.05	0.06	0.06	0.01
Phosphorus, P-tot	0.09	0.09	0.09	0.03
Potassium, K	0.23	0.21	0.21	0.08

Note: A, B, C and D stands for the four different analyzed scenarios.

digestions in which the substances and their proportions of the feedstock mixtures are varying among the scenarios. Following these, digestate yield from each scenario was shown with an assessment of its use as an organic fertilizer applied to Swedish conditions. In this section, scenarios B, C, and D were compared to scenario A, which represents the baseline case.

4.1. Energy performance

It is known, based on our previous study (Carlos-Pinedo et al., 2020), that the ORWARE AD-model is sensitive to changes in the proportions of different compositions of the feedstock, mainly on heat consumption and methane production. In connection with the energy analysis, the simulation results in Table 2, show that by substituting GW for HM in scenarios B and C, the co-digestion has an increase in methane production as well as energy turnover with negligible changes in electricity and heat consumption. This can be understood, according to the characteristics of the feedstocks in Table 1, that HM would decrease the amount of lignin by 91% and cellulose by 40% compared to GW in which lignin is categorized as slowly degradable organics in ORWARE (Dalemo et al., 1997). However, HM is constituted with bedding material, and wood chips and straw have high amounts of both lignin and cellulose. Despite this, the bedding:manure ratio used in this study was not high enough to have negative effects regarding these components. Note well, Wartell et al. (2012) identified that by increasing the bedding:manure ratio, the methane production potential decreases, which is also related to the origins of the bedding material and its lignocellulosic material content. It is also found in Table 1 that TS of scenarios B and C is similar to that of the baseline scenario A and this gives rise to similar electricity and heat consumptions among those scenarios. The handling of other types of feedstock with altered TS would otherwise increase the heating inside the digester as suggested by scenario D. Increasing the dry organic matter content inside the reactor will, therefore, increase the amount of fresh water needed to adjust the specified TS of the process, and this, in turn, leads to higher consumption of heat required to raise the desired temperature. As a result, the energy turnover of scenarios B and C increases with respect to scenario A. On the other hand, as stated above, biowaste is a nutrient-rich feedstock that is normally associated with high methane yield. Results of scenarios in which biowaste was reduced gradually (results not presented here) showed that as their amounts decrease, biomethane will do so as well. It is then understandable that when going from scenarios A, B, and C, where biowaste is one of the main feedstocks, to scenario D without a presence of biowaste, the decrease in biomethane is even greater.

By comparing scenarios B and C, biomethane and energy turnover experienced a minor change when straw is used instead of wood chips as bedding material. To explain such a change, a detailed analysis of the composition of the feedstocks should be performed, and Eq. (1) presented under section 3 can allow this; in the model, the biodegradable organic composition of a substrate is categorized by consisting of rapidly degradable carbohydrates e.g., sugars, moderately degradable carbohydrates e.g., hemicelluloses/cellulose, slowly degradable carbohydrates e.g., lignin, as well as protein and lipids. As a result, by setting the feedstock's composition in baseline scenario A as the reference, Fig. 1 shows that scenario C contains a little more sugars, fats, and proteins concerning those of the baseline scenario, as 8%, 3%, and 6% respectively. Although both wood chips and straw contain a similar amount of lignin, wood chips have much more cellulose than straw, which is regarded as moderately degradable carbohydrates and can thus still give wood chips + HM better methane yield. Scenario B also reduced the amount of lignin by 24% from the baseline scenario. It should be mentioned that these results have been generated based on chemical characteristics given by the model database where the values for VS and cellulose are higher in wood chips than those of straw while lignin is higher in straw. This suggests that a replacement of wood chips by straw as bedding in scenario D should result in a decrease in biomethane production which follows the same effect of such a replacement of bedding material from scenarios B to C. Even if the literature indicates that methane production is higher when straw is used as bedding (Böske et al., 2015; Kusch et al., 2008; Wartell et al., 2012), it should be noted that those results are expressed in terms of methane/VS substrate while the yields of biomethane in the studied scenarios are presented as per tonne treated waste. A more detailed comparison is difficult to perform since the specific chemical characterization of bedding is not always available in the literature, such as amounts of cellulose, lignin, etc., as what is given for the scenarios in Table S1 and Table S3 (see Fig. 2).

In summary, by analyzing the correlations between scenarios B, C, and D, it is established that the presence of lignin would be limiting an SS-AD process. Lignin is a natural barrier against degradation of lignocellulosic material, and as mentioned in other studies, the hydrolysis of lignocellulose often becomes the rate-limiting step in an SS-AD process (Carlos-Pinedo et al., 2019; Liew et al., 2012; Triolo et al., 2011; Xu et al., 2019). However, it should be pointed out that there are more benefits of substituting GW with HM + bedding material than the increase in biomethane and, therefore, a better energy turnover. The fresh water input for scenarios B and C can decrease to zero since HM has less amount of TS than that of GW. This represents a benefit in terms of having a more sustainable process, by reducing the input resources. Another benefit is, since the input of fresh water is reduced or avoided, the amount of liquid digestate for scenarios B and C is minor. This can be positive as a possible improvement when handling the liquid digestate. Likewise, by avoiding the use of GW, there is also the possibility of reducing heavy metals input, e.g., lead and cadmium, since this waste is usually generated in areas close to vehicular traffic emissions in cities (Kabala et al., 2009; Paradelo et al., 2020). The use of GW in this SS-AD plant was mainly for meeting the production capacity when the proposed substrates mix at the plant was food waste based. If GW is not then treated in an SS-AD process, it can be a suitable feedstock to produce ethanol, bioplastics, or briquetting into a product of higher density for energy recovery (Ballesteros et al., 2010; Bhange et al., 2014; Karimi and Karimi, 2018). Another promising option is to use it for the production of fillers for bio-composites applications (Viretto et al., 2021).

4.2. Digestate valorization

Commonly, the digestate is treated physically by solid-liquid separation. The compositions of these two fractions will be different, the liquid fraction is concentrated in N (Möller and Müller, 2012) while the solid fraction will be more suited as a soil amendment. Moreover, the solid fraction can decrease the excess of nutrients on land due to its low content in comparison to the liquid fraction (Greenberg et al., 2019; Tambone et al., 2017). Regarding the results from the simulations, the total tonnes of nutrients existing in both fractions of the digestate are presented in Table 3. Most of the nutrients are present in the liquid fraction except for the C-tot biological and P, for scenario D, which is mainly allocated in the solid fraction, see also the supplementary materials Figure S1.

Since the quantity of the total digestate from each scenario is different, it is more desirable to appreciate the relative changes between

Table 2
Simulation results from the scenarios.

Parameter	A	B	C	D
Biomethane (MJ/$t_{\text{treated waste}}$)	3,570	3,730	3,677	2,455
Electricity consumption (MJ/$t_{\text{treated waste}}$)	−61	−61	−61	−72
Heat consumption (MJ/$t_{\text{treated waste}}$)	−352	−353	−352	−436
Energy turnover (MJ/$t_{\text{treated waste}}$)	3,156	3,316	3,264	1,947
Recirculation flow (t/year)	1,275	1,372	1,328	1,334
Fresh water for dilution (L/t_{waste})	4.4	0	0	304
Solid fraction of digestate (t/year)	2,736	1,641	2,095	7,035
Liquid fraction of digestate (t/year)	10,021	10,856	10,495	10,494

Note: A, B, C and D stands for the four different analyzed scenarios.

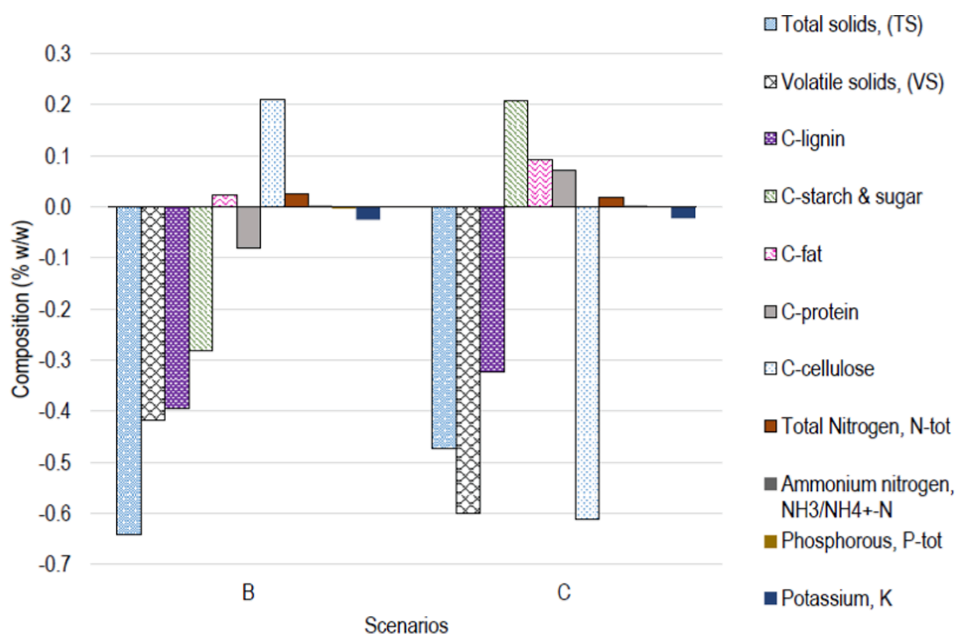

Fig. 1. Representation of the composition of nutrients for scenarios B and C in comparison to scenario A (base scenario). This representation is based on the relative variation with respect to the change according to the original value in Table 1.

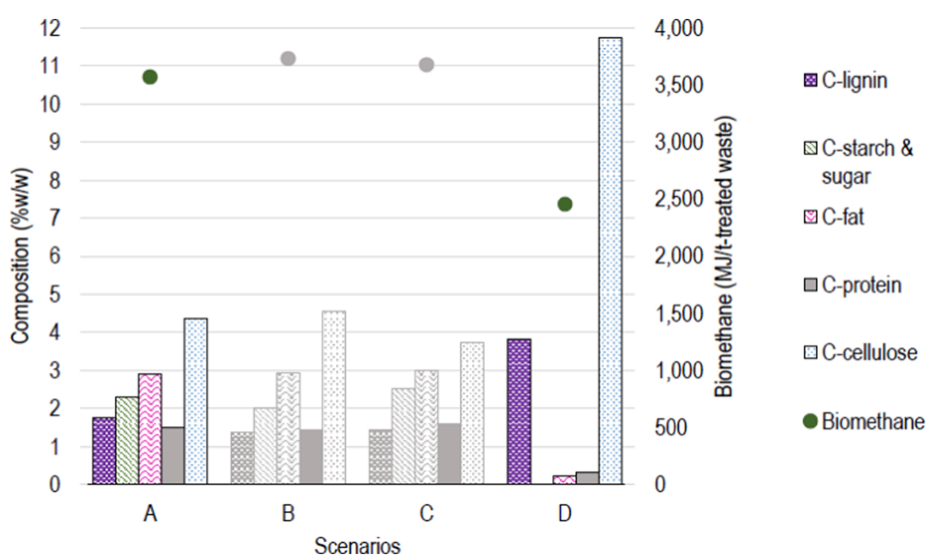

Fig. 2. Comparison of different scenarios having emphasis on scenarios A and D, and presenting only the main carbon-components.

Table 3
Total amount of tonnes of nutrients in the digestate after the simulations.

	Liquid fraction				Solid fraction			
Component (tonnes/year)	A	B	C	D	A	B	C	D
C-tot biological	440	434	418	533	351	192	243	1,041
Total Nitrogen, N-tot	61	71	67	36	18	12	15	25
Ammonium nitrogen NH_3/NH_4^+-N	52	59	56	31	10	7	8	16
Phosphorus, P-tot	7	9	8	1	6	4	5	3
Potassium, K	28	27	27	7	6	3	4	4

scenarios and their digestate fractions. As a result, the variation in the composition of each nutrient for all scenarios is presented in the supplementary materials in Figure S1. These values were calculated based on the amount of nutrients per total wet weight value. Based on this representation, the liquid fraction of scenario B indicated the major contribution in all the analyzed nutrients, specifically in N and K. On the other hand, the main contribution of P is found to be the solid fraction of scenario D, which is comparable with results found in the literature (Möller and Müller, 2012; Tambone et al., 2017; Vanden Nest et al., 2015).

One of the characteristics of digesting manure is the increase of NH_4^+-N due to the mineralization process. Manures may mineralize different amounts of N because of different chemical compositions (Möller and Müller, 2012). In this study, based on Tables 1 and 3, net mineralization of around 70% was found for all the scenarios after digestion. Moreover, farmers might prefer using digested manure because of a faster nitrogen absorption effect than undigested manure (Botheju et al., 2010). In short, the utilization of digestate instead of mineral fertilizers could benefit the increase of the stable soil organic matter since it consists of a high proportion of stable C-biological as suggested by Table 3. Moreover, digestate can contain bioactive substances that have the potential to promote plant growth, reduce stress levels for plants, and in general, increase soil resilience (Głowacka et al., 2020).

By using the specific restricted amount for P and N in the SPCR120 regulation, i.e., 22 kg of P/ha/y and 170 kg NH_3/NH_4^+-/ha/y, results presented in Table 4 were calculated by making a ratio between the amount of N and P for the specific digestate in each scenario. The results presented indicate that for scenarios A and D there could be an excess of N when spreading the liquid fraction. In digestates, ammonia form is abundant due to the usual high pH value; using ammonia as the main or sole source of N is not optimal since it can increase ammonia volatilization and acidification in plant roots (Botheju et al., 2010). This might be improved by a post-treatment like dilution that also results in a decreased P concentration; nitrification provides another possibility. In addition to these, the total amount of tonnes spread on land affects the soil compaction, which is a general problem in crop cultivations due to the heavy equipment used and other field operations, and that is more common when using digestate than mineral fertilizers (Lantz and Börjesson, 2014). The spreading technology is then a crucial factor to reduce or to avoid this problem. On the other hand, if only spreading the solid fraction, the lack of nitrogen might not comply with the wanted requirements. In that sense, its value as an organic fertilizer might not be optimal.

Carrying out a post-treatment to the liquid fraction means the use of energy and/or resources. The most straightforward nutrient recycling method is then the direct application of the digestate. Therefore, if the separation of its fractions were avoided, the baseline scenario A would fit according to the restrictions established as suggested by Table 4; this implies that neither pre- nor post-treatment technology is needed with respect to the regulation. Not using any method for the separation of the fractions of the digestate or any post-treatment should be beneficial in a way that the energy turnover is maintained or increased. This would be valid for scenarios A, B, and C, even when scenarios B and C already fit with the regulations when separating its fractions. As mentioned before, many factors will affect the soil compaction when spreading digestate, however, we can assume that regarding the tonnes of digestate per hectare, the direct application of the total digestate might have a positive effect on soil compaction since the total tonnes/ha would be less, see Table 4. Regarding the energy consumption, as an example, if taking the energy value presented in our previous work (Carlos-Pinedo et al., 2020) for dewatering, 32 MJ/t, it could mean that avoiding the dewatering process for the separation of digestate, the electricity consumption in the digestion process can be decreased by around 50% and, therefore, increasing the energy turnover. One should understand that this 50% electricity reduction represents only a minor part of the total energy produced since this evaluation accounts only for the digestion area of the SS-AD plant, i.e., the pre-treatment of the feedstock (shredding) as well as the dewatering of the digestate, based on design and energy measured at the SS-AD plant. It should be pointed out, however, that even if there are benefits by not separating solid/liquid fractions of the digestate, the technology for digestate spreading must be modified to suit a more semi-solid than liquid digestate (in the case of comparing it only with the spreading of the liquid fraction).

Concerning scenario D, none of the cases for the application of the digestate seems to be optimal; even though the solid fraction can give the necessary nitrogen without a post-treatment, the amount of digestate applied could negatively affect the soil compaction. In this case, other alternatives for its use would be more appropriate. The most common use for the solid fraction of the digestate is as a soil amendment to enhance its physical properties such as water infiltration and holding capacity, and to improve air distribution among others. The solid fraction can also be used as a source of P. For instance, Vanden Nest et al. (2021) suggested that the P availability for crops was higher in digestates than in compost. In addition, biochar can also be produced from the solid fraction, which can be used as a solid fuel or soil amendment with a high carbon sink capacity (Peng et al., 2020). Another use of solid digestate could be as an animal bedding material due to its low moisture content (Sheets et al., 2015).

5. Conclusions

By substituting GW with HM + bedding material, both scenarios B and C suggests an increase in biomethane yield without significant change in heat/electricity consumption as compared to those of baseline scenario A. With the help of a multi-component feedstocks' composition analysis in ORWARE, it can be understood that the amount of lignin and cellulose decreases considerably after the substitution of GW, giving rise to higher energy turnover in scenarios B and C. On the contrary, an increased TS in scenario D requires a large amount of added fresh water which in turn leads to a much higher heat consumption as compared to other scenarios. Meanwhile, the altered feedstock mix in scenario D gives a small presence of sugars, fats, and proteins in relation to those of the baseline scenario. As a result, even if scenario D has the highest cellulose content, the biomethane yield is found to be the lowest among all the scenarios. The quantity, as well as compositions, of both liquid and solid digestate differ among all the scenarios under study. Concerning scenario A, it is shown that the liquid fraction of scenario B

Table 4
Analysis of fractions of digestate according to the Swedish regulations*.

	Liquid fraction			Solid fraction			Total digestate including both fractions		
Scenarios	kg NH_3/NH_4^+-N-/ha/y	Tonnes of digestate/ha/y	ha/y	kg NH_3/NH_4^+-N-/ha/y	Tonnes of digestate/ha/y	ha/y	kg NH_3/NH_4^+-N-/ha/y	Tonnes of digestate/ha/y	ha/y
A	155	30	334	39	10	266	104	21	600
B	146	27	403	37	9	178	113	22	581
C	149	28	377	38	10	220	108	21	597
D[1]	515	172	61	130	59	119	261	97	181

*Based on the restrictions published in the SPCR120 certification (Avfall Sverige, 2007): max. 22 kgP/ha/y and 150 kg NH_3/NH_4^+-N/ha/y (max. 170 kg NH_3/NH_4^+-N/ha/y). Calculation example for the liquid fraction of digestate in scenario A: $\left(\frac{5.17kgNH_3/NH_4^+/t_{digestate}}{0.73kgP/t_{digestate}}\right)(22kgP/ha/y) = 155kg_{NH3/NH4+}/ha/y; \frac{22kgP/ha/y}{0.73kgP/t_{digestate}} = 30t_{digestate}/ha/y; \frac{7,348kgP}{22kgP/ha/y} = 334ha/y$. [1]For scenario D, the N/P ratio is higher than in the SPCR120 restriction (if taking the maximum of 170 kg NH_3/NH_4^+-N/ha/y/ and 22 kgP/ha/y), where N will be higher than P. In that case, N-limit could be also used to calculate how much digestate can be spread without exceeding the N amount: $\left(\frac{0.13kgP/t_{digestate}}{2.99kgNH_3/NH_4^+/t_{digestate}}\right)\left(170kg_{NH3/NH4+}/ha/y\right) = 7.39kgP/ha/y; \frac{170kgNH_3/NH_4^+/ha/y}{2.99kgNH_3/NH_4^+/t_{digestate}} = 57t_{digestate}/ha/y; \frac{31,482kgN}{170kgNH_3/NH_4^+/ha/y} = 185ha/y$. N and P values for digestates can be found in Table 3, together with the total amount of digestate in Table 2.

contributes to the biggest increase in all the analyzed nutrients, specifically in N and K. Using HM + bedding material instead of GW could also give a benefit in terms of N and P quantities when spreading the digestate on arable land. For scenarios A and D, the simulation results suggest that there could be an excess of N if the liquid fraction is spread according to the restrictions in the Swedish SPCR120 certification. It is found that if the solid/liquid separation is avoided, nutrient concentrations in all scenarios, except scenario D, would be in line with the regulation; this also implies that not using fraction separations of the digestate would be beneficial for the process in terms of maintaining or increasing the energy turnover, specifically, it could decrease the electricity consumption in the digestion process at around 50%. However, the appropriate technology for spreading the digestate would have to be modified.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

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