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Agricultural biogas plants as a hub to foster circular economy and bioenergy: An assessment using substance and energy flow analysis

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ABSTRACT

Today's agro-food system is typically based on linear fluxes (e.g., mineral fertilizers importation) when a circular approach should be privileged. The production of biogas as a renewable energy source and digestate as an organic fertilizer is essential for the circular economy in agriculture. This study investigates the current utilization of biomass in agricultural anaerobic digestion plants in Switzerland in terms of mass, nutrients, and energy flows to assess its contribution to the circular economy and climate change mitigation through the substitution of mineral fertilizers and fossil fuels. We quantify the system and its benefits in detail and examine potential future developments using different scenarios. Today, agricultural anaerobic digestion provides 1300 TJ/a of biogas. Our results demonstrate that the system could be largely expanded and provide ten times more biogas by 2050 while saving significant mineral fertilizer amounts (over 10 kt/a of dry mass nutrients yielding 38 kt/a of CO_2 equivalent).

1. Introduction

Energy from biomass can make significant contributions to reducing global greenhouse gas emissions by servicing multiple sectors, including electricity, heating, and transport fuels. However, the amount of biomass is limited and influenced by competitive uses as well as environmental and economic factors (Popp et al., 2014). Wet biomass can be used to generate energy through anaerobic digestion (AD) plants, in which micro-organisms decompose the organic fraction while producing biogas. Simultaneously, the resulting nutrient-rich digestate serves as a fertilizer for local agriculture. Further positive externalities of AD technology include, e.g., energy independence, soil quality preservation, and job creation (Montpart et al., 2021).

AD from agricultural residues fits into the context of the circular economy (European Commission, 2015). Restorative, it aims to keep the material and its components at their highest utility and value (Fagerström et al., 2018). Today's agro-food system is typically based on linear fluxes (e.g., import of resources, fossil fuel, and mineral fertilizers) when a circular approach should be privileged. To promote the many positive externalities of AD and justify the political support for this technology, it is crucial to investigate its many advantages. In the agricultural sector, the use of digestate instead of unfermented slurry limits water pollution and reduces the use of mineral fertilizers (Baştabak and Koçar, 2020; Holm-Nielsen et al., 2009), which production is based on fossil fuels or exhaustible natural resources (Chojnacka et al., 2019). Therefore, the replacement of fossil-based fertilizers resulting from the production of digestate should also be assessed in terms of avoided greenhouse gas (GHG) emissions and nutrient imports.

Agricultural AD is particularly promising where livestock farming is largely developed (Cantrell et al., 2008; Cuellar & Webber, 2008), which is the case in Switzerland. The manure is estimated to have an exploitable potential of 25 PJ biogas per year. AD of this resource can contribute to the energy transition and the reduction in greenhouse gas emissions. However, compared to some countries, manure is hardly used for energy in Switzerland, and less than 5% of the generated manure is currently used for biogas production (SFOE, 2019).

In 2018, the Swiss renewable energy statistics reported 111 agricultural biogas plants (SFOE, 2019). Agricultural plants use mostly liquid substrate inputs as the fermentation mix's dry matter (DM) input should not exceed 15% (BAFU, 2016). Biogas plants are considered

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“agricultural” when 50% of the treated material originates from farms, accounting for at least 10% of the energy generation (The Swiss Federal Council, 2000). More information about the current situation in Switzerland can be found in the supplementary information (SI).

Being a country with only a few raw material resources, circular economy is part of the sustainable development plan of Switzerland (BAFU, 2016). Similarly to many countries, biomass is also considered important in the country’s energy transition strategy, especially for difficult-to-decarbonize sectors like heavy transport and manufacturing (SFOE, 2020a). The Swiss biomass potential has been examined with regard to sustainability criteria (Burg et al., 2018a; Burg et al., 2019), and wet biomass could supply an additional 30 PJ of primary energy per year, with 26 PJ from animal manure. Furthermore, AD of manure is a promising strategy to reduce greenhouse gas emissions from manure management (Burg et al., 2018b; Chadwick et al., 2011; Moral et al., 2012). So far, however, AD technology has only been used to a limited extent - especially in agriculture - due to the low profitability for the plant operator (Burg et al., 2021b).

To analyze systems’ circularity, Material Flow Analysis (MFA) procures indicators facilitating decision-making (Tanzer and Rechberger, 2019; Virtanen et al., 2019). Tonini et al. (2014) further note that material-, substance-, and energy flow analysis (MFA, SFA, EFA) are useful to assess mass, energy, and substance flows in different urban systems, including waste management and bioenergy. However, MFA/SFA are rarely used in the regional context, as it is challenging to gather regional-level information (Virtanen et al., 2019), and studies with regional or national boundaries often focus on only one or a few nutrients (Binder, 2009; Coppens et al., 2016).

Within this study, we assess the current biomass utilization in agricultural digestion plants based on an MFA, several SFAs, and an EFA to provide a quantitative understanding of the system. We examine whether and to what extent AD can lead to improved resource cycles. For this purpose, the nutrient balance of the current agricultural AD system is assessed at the national level. Possible scenarios and substitution effects (replacement of mineral fertilizers, CO_2 emissions) are analyzed, and the possible economic value of agricultural digestates is estimated. Indeed, possibilities to increase the added value of digestates are important for the viability of biogas installations. Altogether, this provides a reference for future research and a basis for practical optimization and political measures. More specifically, this study has the following objectives:

(1) Show the current utilization of wet biomass in agricultural AD plants in Switzerland in an MFA, an EFA, and several SFAs.
(2) Investigate the mass, nutrient, and energy balance from biomass in agricultural AD installations on a national scale.
(3) Quantify the economic value of digestate, understand the substitution potential of mineral fertilizers with digestate, and examine their contribution to closing the nutrients cycles.
(4) Examine possible future developments of agricultural biogas plants using scenarios.

2. Materials and methods

2.1. System boundaries and model

The system boundaries are limited to the inputs and outputs of Switzerland’s 111 agricultural biogas plants for 2018. Any pre- and post-processing steps that take place on-site are included: storage on site, processing through the fermenter, and sorting/storage after the fermentation. The potential wider impact of the output flows on other sectors, such as crop or livestock production and biogas utilization, is not considered here (see SI)). The model is calculated on the software STAN (Binder, 2009; Cencic and Rechberger, 2008; Coppens et al., 2016; Jensen et al., 2017; Tanzer and Rechberger, 2019).

2.2. Data

Data for material quantities inputs and outputs were collected based on the national monitoring database (CVIS, 2020; FOAG, 2019; Schleiss, 2020) and complemented with direct information from cantonal authorities and the biogas plants. In total, the data of 61 agricultural plants could be used (see SI for more details on the data collection).

Material inputs are weighed and recorded in fresh mass (FM) tonnes, whereas output material is either measured in mass "tonnes" or in volume "m^3". For the conversion of volume to mass, densities of different outputs were collected (supplementary data (SD)). 47 biomass streams were identified and grouped into three main categories to describe the biomass streams and their origins: agricultural residues, industrial biowastes, and green wastes from municipalities and landscape maintenance.

To represent the Switzerland-wide situation, the data obtained from 61 agricultural biogas plants (of a total of 111) was extrapolated by a factor of 1.45 (+45%). This factor was chosen by comparing the total generated biogas according to the collected data (1020 PJ) with the official nationwide value for 2018 (1440 TJ) (SFOE, 2019).

2.3. Nutrients, carbon, and plastic concentrations

Several databases and previous literature provided the values for dry mass (DM), and nutrients (total nitrogen N_{tot}, phosphorous P_2O_5, potassium K_2O, carbon C) for the 47 different substrates fed into biogas plants (see SI). The nutrient concentration in the outputs (solid and liquid digestates and composts) is regularly measured by the biogas plants (CVIS, 2020). Nutrient flows in tonnes of DM were calculated as follows:

$$nutrient\ mass_{(tonne)} = fresh\ mass_{(tonne)} \times DM\ content_{(\%)} \times nutrient\ concentration_{(\%DM)}$$

Plastic contamination is expected to come mainly from municipal green wastes; hence, it is a marginal problem for agricultural biogas plants. Thus, we estimated the expected input and output without STAN, based on the concentration of plastics in municipal green wastes (average 0.1% (±0.1%); (Hüsch, 2018).

2.4. Energy content, biogas production and emissions

Biomass primary energy was calculated based on the lower heating values of the DM. The values were collected from literature for each substrate, as seen in the SD. Data related to secondary energy carriers, including electricity, heat, and biomethane production from biogas processing, was acquired mainly from the national recording database (Schleiss, 2020), and the energy content in biogas was estimated from these values.

Emissions of gases such as vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ammonia (NH_3) take place during storage, anaerobic digestion, and composting. If the biogas installation is operated following the national guidelines (Biomasse Schweiz, 2012), a flat loss factor of a maximum 2% emission of the annual quantity of biogas produced can be expected at the fermenter level and of 3% emission for digestate maturation taking place before it is spread onto the fields (BAFU, 2015). Vapor losses from the fermenter and the storage after fermentation were also considered (Baier, 2022).

2.5. Flows modelling

The MFA, SFAs, and EFA emanate from the material flow model created on STAN 2.6 (Cencic and Rechberger, 2008) using the IMPLE2013 calculation method extension. Following Brunner and Rechberger (2016) approach, flows were quantified by creating of a material flow balance using a static analysis approach. Seven levels were created to analyze each of the following flows separately: FM, DM, N_{tot}, P_2O_5, K_2O, C, and primary energy. The SFA was conducted for the nutrients and carbon levels using their concentration in the feedstock (in % DM).

2.6. Sensitivity analysis

A sensitivity analysis was conducted for some parameters to understand their influence on the flows and the overall results. Liquid cattle manure represents about half of all input, but its DM and nutrient contents vary widely according to literature and farm measurements. Therefore, the sensitivity analysis was based on an uncertainty range of ±3% DM and ±5% nutrient contents.

2.7. Scenario development

Starting from the base model, which relies on data from 2018 (Baseline), various scenarios for the future of agricultural biogas plants were elaborated. For this purpose, interviews were conducted with nine experts from different disciplines using the Wild Card method (SI), which refers to a plausible future event with a low probability, but a high impact should it occur (Barber, 2006). Four key scenarios with distinct characteristics are presented in this paper, and more can be found in the SI, along with all calculated flows.

2.7.1. Scenario 1: continued support

The first scenario was defined to provide a reference scenario for the year 2050 to remain coherent with the Swiss Energy Perspective 2050+ (SFOE, 2020a). Through several interviews (Gisler, 2021; Christian, 2021), it was estimated that a doubling of plants in 10 years is realistic if continued support is granted to promote agricultural biogas such as simplified permit procedures (Christian, 2021). This increase corresponds to a system with approximately 460 agricultural biogas plants in 2050, assuming the average plant size does not change (SFOE, 2020b). Based on 2018 flows model and the expected development until 2050, this doubling was converted into a diffusion rate (460/111 = 4.14). All input flows were increased by this factor, similarly to the extrapolation in the Baseline model.

2.7.2. Scenario 2: sustainable manure potential

This scenario is based on the complete utilization of manure's sustainable energy potential, according to Burg et al. (2018a). This sustainable potential considers the total amount of manure generated in Switzerland. It includes the losses when the animals are in pastures and the techno-economic constraints linked to the spatial distribution (as a minimum amount of locally produced manure is necessary). The co-substrates were also increased by splitting their remaining sustainable potential between industrial and agricultural biogas plants, considering today's share. Indeed, we know from other studies how much biomass is available in Switzerland and which proportion of the biomass is treated today in which type of installations (Burg et al., 2018a). Hence, the amount of industrial biowastes treated in agricultural biogas plants was multiplied by 1.33 (as no more biomass is available), whereas e.g., cattle manure could be multiplied by more than 20 (see all values in SD).

2.7.3. Scenario 3: sustainable food system

As in many European countries, nutrition in Switzerland is likely to change in the future. This could directly influence agricultural production (Christian, 2021) and thus the availability of substrates for agricultural biogas plants. Less meat consumption influences the amount of manure produced, which makes up a large part of the input. Zimmermann et al. (2017) analyzed and compared four nutrition scenarios under different framework conditions, where environmental impacts were reduced. For our study, the Sustainable Food System scenario follows the "FoodWaste" nutrition scenario as it has the lowest environmental impact and is closest to a closed-loop system. This scenario was not associated with the share of manure digested today (Baseline) but with that of scenario 2, which would make sense from a sustainability point of view: society needs both to use the whole available biomass for energy and to reduce the impact of its food consumption.

2.7.4. Scenario 4: technical change separation

Following experts' discussions, improvement in efficiency at different technical levels can be expected. One suggestion was the slurry separation (Christian, 2021; Meier et al., 2016), where the obtained liquid fraction is digested on site in a liquid fermenter while the solid fraction is taken to a solid fermenter processing all inputs with more than 10% DM (see details in SI). This should favor higher exploitation of the manure potential for energy in more efficient solid fermenters. In the modeling, all input flows remain constant compared to the Sustainable Manure Potential scenario to show the impact of manure separation on biomass, energy, carbon, and nutrient flows.

2.8. Uncertainties

Uncertainties were estimated to be 5% for co-substrate input, 10% for agricultural inputs and 15% for output flows (Trachsel, 2021), considering that some mass may be lost during the separation of digestate and the transfer of solid digestate with forklifts. The uncertainties associated with the nutrient, carbon, and energy flows were calculated from the literature ranges (see SD), thus estimating the standard deviation and standard error. The uncertainty values were integrated into the models and adjusted by STAN, considering data reconciliation and error propagation.

2.9. Mineral fertilizers substitution

The estimated quantities of nutrients (N, P_2O_5, K_2O) were used to estimate how much mineral fertilizers could be replaced using digestates. GHG emissions and energy consumption reduction corresponding to the production of mineral fertilizers were calculated using specific factors (see SI)(Amenumey and Capel, 2014; Daniel-Gromke et al., 2015). This was done for the total digestate produced but also considering only nutrients from non-agricultural biomass. Indeed, manure and agricultural by-products would have been brought back to agricultural fields even without the fermentation process.

2.10. Economic value and opportunities of digestates

We estimated the theoretical economic value of agricultural digestates based on their nutrient contents and availabilities, considering the most common digestate products: digestate, liquid separated digestate, and solid separated digestate. To determine their economic value, we evaluated the mineral fertilizer use and their prices in Switzerland in 2018–2021 and determined mineral fertilizer parity prices for the nutrients N, P_2O_5, and K_2O, of the most used fertilizers. We then attributed economic values to the digestates, depending on the levels of available N, P_2O_5, and K_2O. Additionally, we surveyed 22 agricultural biogas plant operators regarding the market value of their digestate. Through interviews with stakeholders and literature research, we derived possibilities to add value to agricultural digestates considering current political and market price developments.

3. Results

3.1. Material flows

Fig. 1 shows the results of the MFA representing the situation of agricultural biogas plants in Switzerland for 2018 (Baseline). Around 1.2 (±6%) megatonnes (Mt) of FM were brought to agricultural biogas

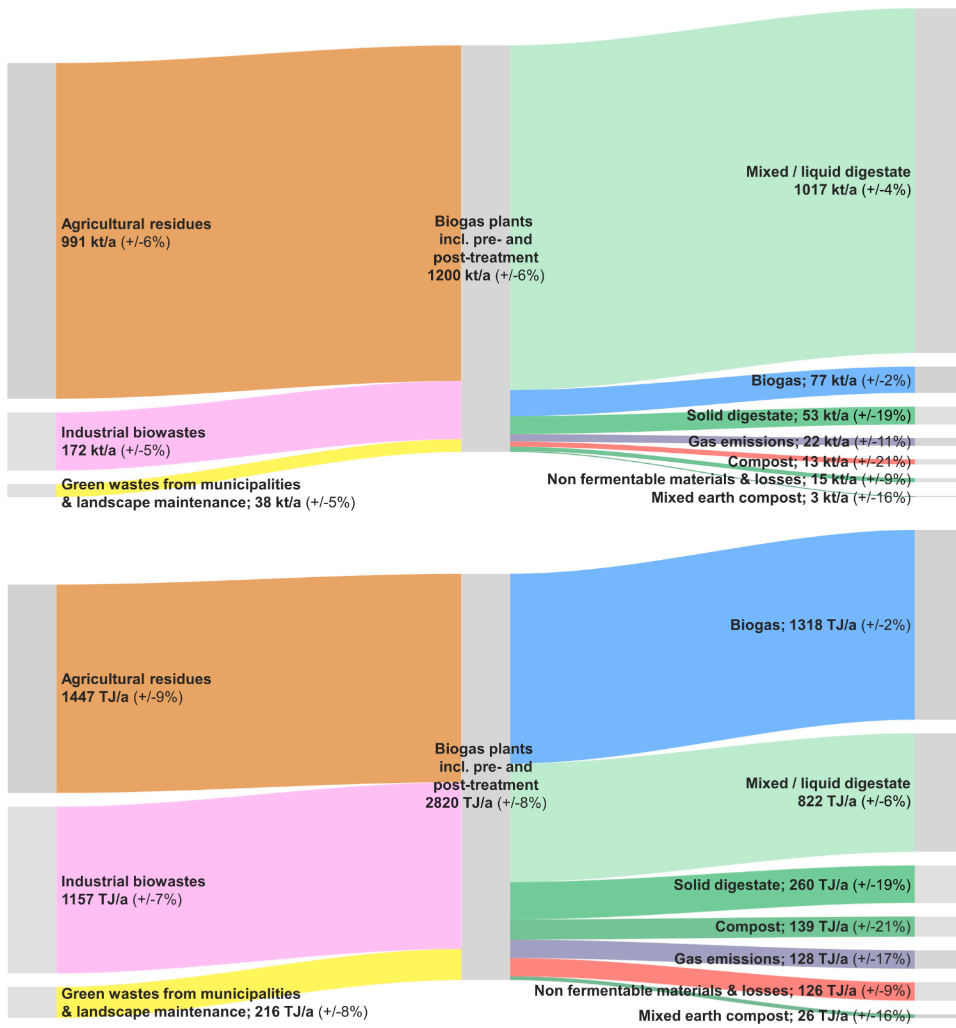

Fig. 1. Sankey diagrams of major material flows (upper diagram, in kilotonnes (kt) per year) and energy flows (below, in terajoule (TJ) per year) through agricultural biogas plants.

plants in Switzerland in 2018. The largest contributing biomass stream came from agricultural residues (83%), mainly from animal manure representing 79% of the total incoming material, followed by industrial biowastes 14%. This resulted in 1.1 (±5%) Mt of liquid and solid digestate.

3.2. Substance flow analysis

The 111 installations process in total 164,034 (±7%) dry tonnes of feedstock. In total, the input material contained 78,880 (±5%) t C, 5318 (±8%) t N_{tot}, 2783 (±10%) t P_2O_5, and 5485 (±9%) t K_2O. As agricultural residues were the most dominant incoming stream, a crucial amount of nutrients came from it (76% for K_2O, 78% for P_2O_5, and 67% for N_{tot}). With regards to the input of industrial biowastes, it represented

Table 1
Mass (tonne) and transfer coefficients in final output from initial input expressed in percent of input toward the four categories.

	Total input	Biogas	Emissions	Fertilizer	Non fermentable materials & residues
Fresh mass (t)	1,200,011	77,172	22,239	1,085,889	14,712
Transfer coefficient		6.4%	1.9%	90.5%	1.2%
Carbon (t)	78,880	38,197	4,019	33,274	3,390
Transfer coefficient		48.4%	5.1%	42.2%	4.3%
Dry Mass (t)	164,034	75,500	7,198	74,529	6,807
Transfer coefficient		46.0%	4.4%	45.4%	4.1%
Energy (GJ)	2,819,623	1,317,599	127,746	1,247,872	126,406
Transfer coefficient		46.7%	4.5%	44.3%	4.5%
Potassium (t)	5,485	0	0	4547	938
Transfer coefficient		0%	0%	82.9%	17.1%
Nitrogen (t)	5,318	750	85	4431	52
Transfer coefficient		14.1%	1.6%	83.3%	1.0%
Phosphorus (t)	2,783	0	0	2417	366
Transfer coefficient		0%	0%	86.8%	13.2%

about 12% for K_2O, 14% for P_2O_5, and 25% for the N_{tot}).

The SFA results showed a high transfer of nutrients. Indeed, transfer coefficients of nutrients to biofertilizers were 83%, 87%, and 83% for N_{tot}, P_2O_5, and K_2O, respectively (Table 1). Moreover, 48% of the carbon is transferred to the biogas and 42% to the fertilizers. Approximately 170 (±6%) tonnes of plastics came into the system in 2018, but we expect this amount to be partly reduced through sorting within the installations.

3.3. Energy flows

The incoming biomass contained 2819 TJ (±8%) primary energy (PE) in 2018 (Table 1; Fig. 1). More than 80% of the fresh biomass comes from agriculture, but only about 51% of this PE was gained from it as most of the input is manure, which has a low energy content. 41% of the PE comes from industrial wastes and 8% from green wastes. Regarding the outputs, the primary energy was distributed largely between biogas (47%) and digestates and composts (44%), representing significant untapped energy.

From the data of the installations themselves, an estimated 69×10^6 m^3 biogas was produced, leading to approximately 137,800 MWh electricity and 59,700 MWh heat sold in 2018. A small part of the biogas was converted into biomethane and injected into the grid. Because the installations sell these energy products and have to report them to authorities, we expect a high level of accuracy, which is then reduced through the up-scaling.

3.4. Sensitivity analysis

The changes in fresh biomass were less than the 5% uncertainty of the model. However, an increase or decrease of 3% of the DM of manure leads to an increase or decrease twice as large for DM and C in the model. Increasing or decreasing by 5% the quantity of nutrients N_{tot}, P_2O_5, K_2O from liquid manure had an effect of less than 5% on the final nutrient's quantities, which was smaller than the variation of the system (between 8 and 10% uncertainty). The detailed sensitivity analysis results can be found in the SD.

3.5. Mineral fertilizers substitution

In the Baseline, co-substrates substitute 3716 tonnes of fertilizers (1769 N, 623 P_2O_5, 1325 K_2O), which is equivalent to saving almost 13,000 t CO_2-eq from mineral fertilizers (see SI). The highest values are found for the Sustainable Manure Potential scenario, which represents more than 15,000 tonnes of fertilizers and around 40,000 t CO_2-eq emission saving. Furthermore, depending on the literature, the nitrogen availability of manure can be increased between 5 and 20% after digestion. This suggests that, in addition to the mineral substitution calculated here for co-substrate only, a maximum of 354 tonnes (Baseline) up to 1026 tonnes (Sustainable Manure Potential) of nitrogen available to the plants coming from non-agricultural inputs could be added.

3.6. Scenarios

3.6.1. Material flow

With continued measures to support the diffusion of agricultural biogas, an expansion is envisioned by 2050, i.e. the operation of a total of approx. 450 biogas plants processing 5.1 (±6%) Mt of FM per year (Continued Support Scenario). Industrial bio-wastes and green wastes from municipalities and landscape maintenance account for 17% of the FM but 52% of the primary energy. The shares of inputs by origin remained constant compared to the Baseline (Fig. 2).

If the entire estimated Sustainable Manure Potential is exploited in Switzerland, 23.5 (±4%) Mt/a of FM can be used, which corresponds to an increase by a factor of 19.6 compared to today. The increase is strongest for agricultural residues, which is mostly manure, from a proportion of 83% (Baseline) of total inputs to 98%.

A change in the food system towards more sustainability and the associated reduced livestock farming and food waste would lead to a 48% decrease in the estimated sustainable biomass potential in Switzerland mainly due to the reduction in manure. This also changes the composition of the substrates.

In the Technical Change Separation scenario, slurry represents 16.1 (±4%) of total 21.9 (±4%) Mt/FM fed into the pressing screw. After separation, the liquid fraction consists of about 14.2 (±3%) Mt/a of thin slurry with a DM content of about 1%, and the solids weigh about 1.8 (±4%) Mt/a with a DM content of about 12%. The solids are subsequently fed into the regional digester, along with the other biomass types. The inputs to the liquid and solid digesters are thus about 57% and 43% of the total fresh biomass inputs.

3.6.2. Substance flows

The composition of the flows is comparable for the Baseline and the scenario Continued Support. The nutrients N_{tot}, P_2O_5, and K_2O remain predominantly in the digestate (83, 87, and 83%, respectively). Carbon accounts for a total of 331,933 (±20%) t/a, representing 7% of the processed FM. 48% of the carbon goes into biogas (160,842 (±2%) t/a) in the form of methane and carbon dioxide, and almost 43% (141,493 (±9%) t/a) goes into the fermentation residues, where carbon can be directly returned to agriculture (see SI).

In the Sustainable Manure Potential scenario and those based on it (Sustainable Food System and Technical Change Separation), the share of the agricultural inputs is much higher for all substances e.g. carbon comes around 95% from agricultural residues compared to about 65% in the Baseline and Continued Support scenario. If all agricultural residues

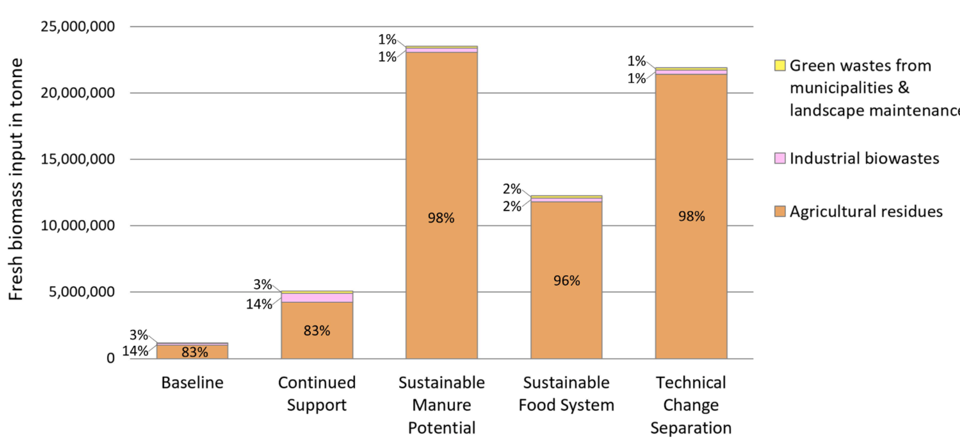

Fig. 2. Fresh biomass inputs (tonnes and composition) for the Baseline compared to the different scenarios.

are added together, they account for more than 90% of the N_{tot}, P_2O_5, and K_2O inputs. If the entire sustainable manure potential in Switzerland is used, there are 74,064 (±7%) t/a of N, 50,475 (±7%) t/a of P_2O_5, and 96,726 (±9%) t/a of K_2O in the digestate annually. Regarding the scenario Sustainable Food System, we obtain 42,747 (±6%) t/a N, 24,123 (±6%) t/a P_2O_5, and 50,436 (±6%) t/a K_2O in the digestate (Fig. 3). Due to the scenario's assumptions of much lower manure quantities and co-substrates, the quantity of nutrients in the system also declines, with a reduction of at least a third compared to the Sustainable Manure Potential. In the Technical Change Separation scenario, the proportion of nutrients in the separated liquid fraction is higher due to the better solubility of nutrients compared to carbon (Christian, 2021). Nevertheless, about two-thirds of the nitrogen and phosphorus and half of the potassium still enter the regional solid digester.

3.6.3. Energy flows

In the Continued Support scenario, the total primary energy content of the inputs reaches 11.6 (±8%) PJ/a) and 5.4 (±5%) PJ/a biogas is produced (Fig. 4). If using the whole Sustainable potential, biogas production increases from 1.3 (±2%) PJ/a today to 15.5 (±8%) PJ/a (factor of 11.8).

For the Sustainable Food scenario, there is a decrease in carbon and primary energy by 35% compared to the Sustainable Manure Potential Scenario, leading to a reduced amount of produced biogas (10.8±7% PJ/a). In the Technical Change Separation scenario, we can observe that due to the higher DM content, the percentage of carbon processed in the solid digesters (85%) is significantly higher, and thus also, the biogas yield (91%) compared to the liquid digester.

3.7. Economic value and opportunities for digestates

The operator survey ($n = 22$) showed that only one biogas plant was able to price their digestate as it is after digestion. More than 20% of the operators either needed to add the process of separation before pricing their digestate or include a service such as transport or spreading of the digestate. Nearly 50% of the operators were not able to put any pricing on their digestates (see SI). The theoretical economic values varied according to the type of digestate (Fig. 5). Digestate had a gross fertilizer value of CHF 8.3–8.7 per m^3 of FM and a net fertilizer value of CHF 5.3–5.7. Taking into account the mineral fertilizer prices applicable at the beginning of 2022, the net fertilizer value of digestate increased to 12.5–13.6 CHF/m^3 FM. For solid separated digestate, the gross fertilizer value of CHF 15 per tonne and a net fertilizer value of CHF 10 per tonne were calculated, and up to CHF 17 net per tonne FM for 2022. Regarding the possibilities to increase the opportunities to commercialize digestates, there are many open fields that need to be explored depending on the regional setting of the biogas plant: improving marketing, including storage costs in the price, increasing both quality and the number of products or expanding the range of services provided with the products (e.g. spreading on the fields). Very effective leverage can be exerted by the mineral fertilizer prices, as could be seen with doubling and tripling prices at the beginning of 2022. As soon as mineral fertilizers become expensive or limited in availability, the local organic fertilizers automatically become interesting, without marketing or additional services from the producers. Without these circumstances, the economic values varied according to the type of digestate (Fig. 5).

4. Discussion

The material flow analysis results allow us to understand better the current agricultural biogas system and possible future development. There are, however, some limitations due to available data being scarce and generally incomplete. This is true for both the quantity and the quality of the input and output feedstock information. Indeed, the measured fresh mass quantities (especially solid manure and compost) can already entail up to 10% inaccuracy propagating in the system. This is amplified by the uncertainty linked to substrate characteristics from literature references from other regions. For example, values for food waste composition have been taken from a German source when eating habits may partly differ from Switzerland. The importance of qualitative, publicly available data cannot be stressed enough.

A large proportion of the energy chemically bound in the input

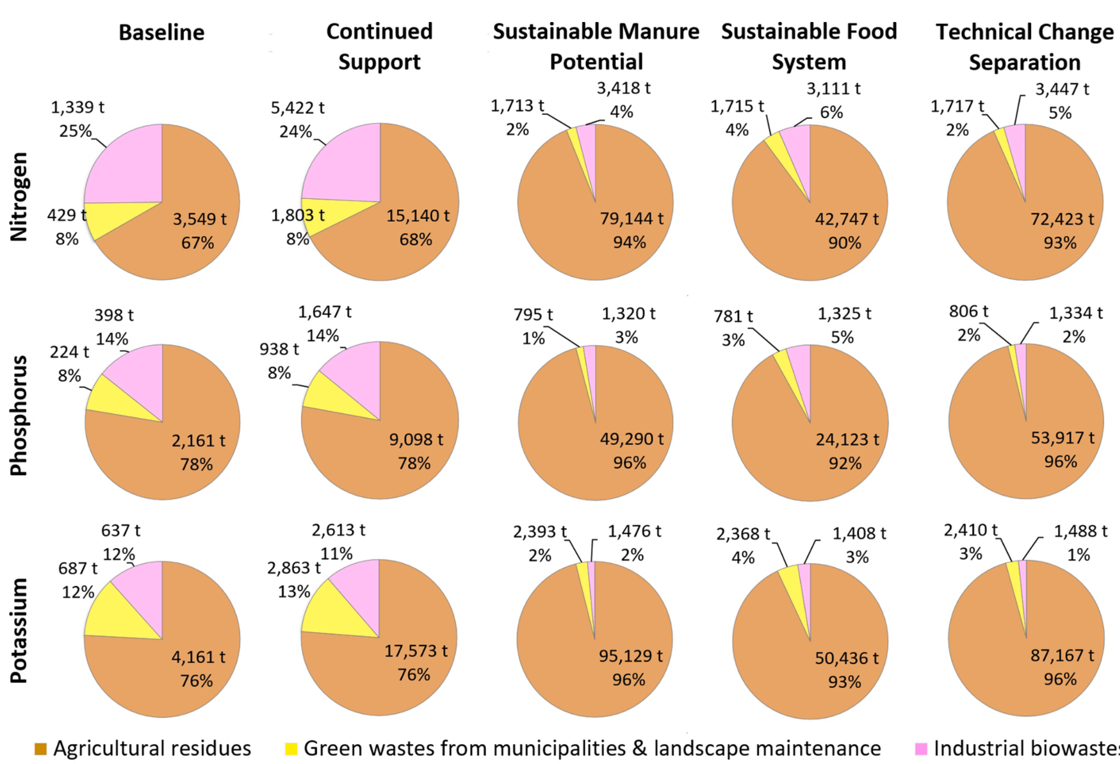

Fig. 3. Nutrients (nitrogen N_{tot}, phosphorus P2O5, potassium K_2O) input in tonne and % per scenario.

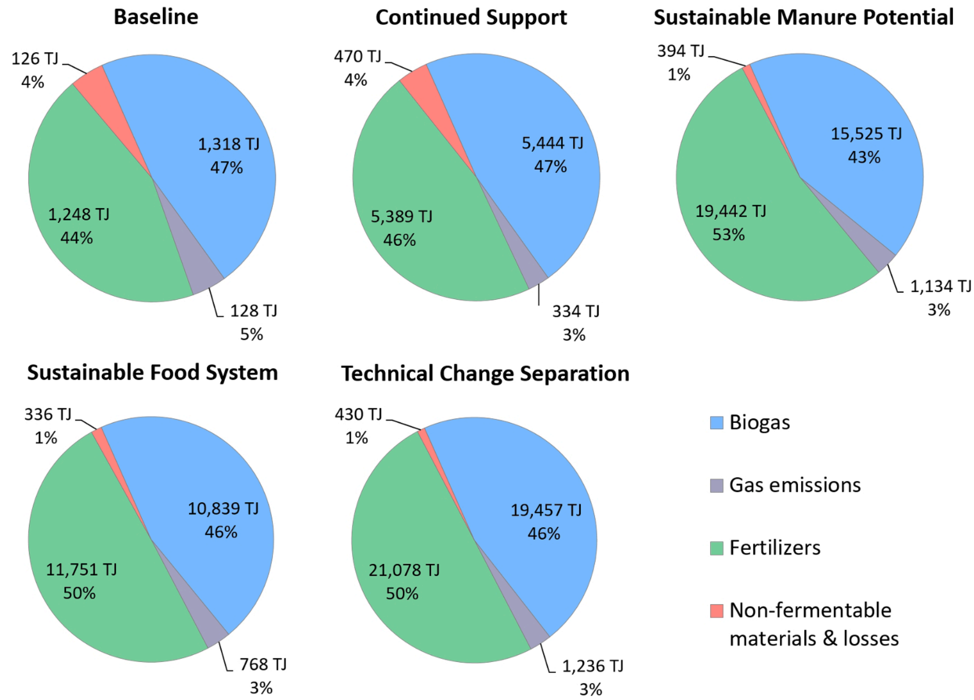

Fig. 4. Primary energy in terajoule (TJ) per output for the different scenarios.

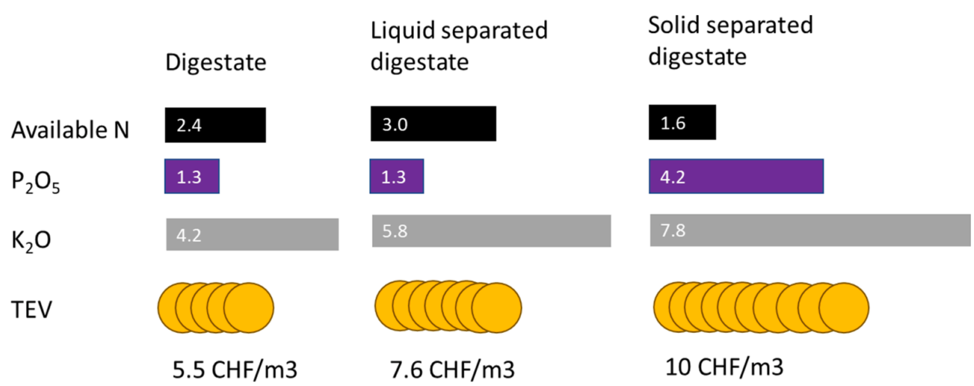

Fig. 5. Nutrient levels in the three typical agricultural digestates investigated and the net theoretical economic value (TEV) calculated. Nutrient levels are indicated in the unit [kg/m3]. Parity prices for the nutrients used were: 1.1–1.3 CHF per kg available N, 1.50 CHF per kg P_2O_5, and 0.90 CHF per kg K_2O.

substrates will not be converted into biogas and is retained in the solid and liquid residues. While the total primary energy contained in the incoming biomass was estimated to be 2819 TJ (±8%) for the year 2018, we found that 47% of the input energy was converted into biogas (1318 TJ (±2%)) and 44% remained in the digestates and composts. This biogas amount is similar to the values from the official statistics, which recorded about 1400 TJ gross biogas production in 2018 (SFOE, 2019).

The calculated emissions from the biogas plants (including pre- and post-treatment) were a bit higher than observed in other studies (Scharfy and Anspach, 2022). However, a high variation has been found in different biogas plants (Calbry-Muzyka et al., 2022) and from the emissions from the post-treatments (Dinkel et al., 2012). Moreover, water inputs and losses throughout the process are also little known and highly dependent on feedstock and pre- and post-treatments (Baier, 2022). This strongly indicates that comprehensive emissions measurements at many sites and at different times are needed to quantify all the precise material and substance flows.

All nutrients considered showed good transfer to the digestates. Although agricultural inputs represent 83% of the material inputs entering the biogas plant, the share of their nutrients (~67% N_{tot}, 78% P_2O_5, 76% K_2O) and even more their share in the energy (~51%) and carbon (~56%) input is much more limited. Nutrients and carbon are already well recycled in agriculture as, even without AD, raw manure is spread onto the fields. However, the nutrients and carbon added by the co-substrates are far from negligible. Indeed, this represents 4% N_{tot}, 7% P_2O_5, and 8% K_2O applied yearly in Swiss agriculture. The substitution benefits are both impacting resource preservation and energy savings, thus also having a positive effect on climate change mitigation. Moreover, the carbon staying in the digestate ensures a high humus value for the fertilizers leading to improved soil quality on agricultural land. However, it should be noted that this substitution does not consider that, in practice, farmers often prefer to use separate fertilizers instead of a combined one to better adapt the amount of each nutrient according to the crop.

The economic value of agricultural digestates depends on how they are considered in terms of quality and quantity. Even though agricultural digestates meet the criteria for a circular economy and there are already some market-ready technologies for their post-treatment, their commercialization is limited and depreciated in Switzerland and other countries. This might change due to the currently rising mineral fertilizer prices and the political pressure to reduce the nitrogen surplus in agriculture (20% less N and P_2O as surplus by 2030 (FOAG, 2022)).

To achieve the climate goals of the Paris Agreement, Switzerland must fully exploit the potential of all renewable energies by 2050, including sustainable biomass (SFOE, 2020a). Therefore, policymakers need to develop a support program for biogas plants that is as comprehensive as possible and goes further than the current support measures. Indeed, although a significant increase in biogas production is already envisaged in the Continued Support scenario, only one-third of the sustainable potential is used in this scenario. Potential restrictions on the use of the more limited co-substrates, as well as possible changes in the food system, e.g., leading to a strong diminution of available manure, must also be considered. However, the margin compared to the current situation is so large that there is, in any case, a great deployment potential for agricultural AD in Switzerland. Technical advancements may also play an important role in future development (Burg et al., 2021a). For example, the Technical Change Separation scenario could imply a higher production of biogas with the same amount of processed biomass through more efficient AD digestion in separated liquid and solid systems. Other technological changes that could increase the efficiency and the economic viability of energy from manure can also be envisaged (Burg et al., 2021a).

The developed methods can be applied elsewhere as long as enough data is available and the uncertainties are part of the analysis. Further studies could include the entire national biomass system. Regarding industrial biogas plants, this is already done in another study (Bowman et al., 2022, Submitted). However, to gain a complete view, it would be necessary to include other biomass types and uses, such as other bioenergy (e.g., municipal waste or wood incinerators) or material usages. The assessment could go up to a detailed national carbon cycle analysis.

Considering wider environmental effects, Tonini et al. (2014) further notified that MFAs, SFAs, and EFAs can also serve as a basis for life-cycle assessments and are, therefore, complementary tools for environmental management strategies. Indeed, we know that manure management can have many other impacts, e.g., on water pollution and soil fertility. An LCA approach at the country level could show other possibilities to improve the environment in a more holistic way.

All in all, the next step should be to validate the present results through the implementation of these opportunities at the business scale. Indeed, the precarious economic viability of agricultural biogas plants is an issue in Switzerland but also in the whole of Europe and beyond. Finding new potential added value to the system of agricultural biogas plants will be key to the diffusion of this technology in the agricultural context.

5. Conclusion

We currently face challenges due to resource overuse, climate change, and energy autonomy in a connected yet volatile world. Promoting biomass digestion in an agricultural setting is one aspect that should be tackled. Our first quantification of the biomass available in Switzerland and its potential for fertilization and climate mitigation provides guidance to decision-makers. Agricultural anaerobic digestion could provide ten times more biogas by 2050 while saving significant amounts of mineral fertilizer and GHG emissions. Increasing the digestates quality is important to improve their sustainable and efficient use as a mineral fertilizer replacement. No country can afford to underuse its domestic resources.

CRediT authorship contribution statement

V. Burg: Conceptualization, Funding acquisition, Formal analysis, Investigation, Methodology, Validation, Visualization, Project administration, Supervision, Writing – review & editing. **C. Rolli:** Methodology, Investigation, Writing – original draft. **V. Schnorf:** Data curation, Methodology, Writing – original draft. **D. Scharfy:** Funding acquisition, Methodology, Validation, Writing – original draft. **V. Anspach:** Funding acquisition, Methodology, Validation, Writing – original draft. **G. Bowman:** Conceptualization, Funding acquisition, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – review & editing.

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.

Data Availability

The authors do not have permission to share data.

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Supplementary materials

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