Agronomy Research **19**(S1), 687–697, 2021
https://doi.org/10.15159/AR.21.085

Carbon balance of biogas production from maize in Latvian conditions

K. Bumbiere, A. Gancone, J. Pubule* and D. Blumberga

Riga Technical University, Institute of Energy Systems and Environment, Faculty of Electrical and Environmental Engineering, Azenes 12-K1, LV-1048 Riga, Latvia
*Correspondence: jelena.pubule@rtu.lv

Received: January 31st, 2021; Accepted: March 28th, 2021; Published: May 19th, 2021

Abstract. Production of biogas using bioresources of agricultural origin plays an important role in Europe's energy transition to sustainability. However, many substrates have been denounced in the last years as a result of differences of opinion on its impact on the environment, while finding new resources for renewable energy is a global issue. The aim of the study is to use a carbon balance method to evaluate the real impact on the atmosphere by carrying out a carbon balance to objectively quantify naturally or anthropogenically added or removed carbon dioxide from the atmosphere. This study uses Latvian data to determine the environmental impact of biogas production depending on the choice of substrate, in this case from specially grown maize silage. GHG emissions from specially grown maize use and cultivation (including the use of diesel fuel, crop residue and nitrogen fertilizer incorporation, photosynthesis), biogas production leaks, as well as digestate emissions (including digestate emissions and also saved nitrogen emissions by the use of digestate) are taken into account when compiling the carbon balance of maize. The results showed that biogas production from specially grown maize can save 1.86 kgCO_2eq emissions per 1 m^3 of produced biogas.

Key words: agriculture, bioenergy, biofuels, multicriteria analysis, sustainability.

INTRODUCTION

The European Union is the most progressive global leader on the path to climate change mitigation, therefore The European Commission presented the vision for climate-neutral economy by 2050 to keep global temperature increase below 2 °C above the pre-industrial level (Bereiter et al., 2015), with decarbonising the energy sector as one of the key points (European Council, 2019). Production of biogas using bioresources of agricultural origin plays an important role in Europe's energy transition to sustainability (European Council, 2014; European Council, 2019) due to the possibilities to use it for different purposes - transportation fuel, heat and electricity generation (Meyer et al., 2018).

The biogas production process integrates production (Chen et al., 2015), processing and recycling of degradable by-products (Li et al., 2019). Not only does the biogas produced by anaerobic digestion prevent greenhouse gas emissions and produce renewable energy, but also provides for the production of processed fertilizers, improving nutrient self-sufficiency in the agricultural sector (Timonen et al., 2019). The productivity of a biogas plant depends on different aspects, like the type of biomass (Melvere et al., 2017; Krištof & Gaduš, 2018; Bumbiere et al., 2020), digestion (Meiramkulova et al., 2018; Mano Esteves et al., 2019), availability of biomass, impurities that may harm microorganisms (Mehryar et al., 2017; Muizniece et al., 2019) and lignin content (Lauka et al., 2019).

The most important element of the biogas production system, is the choice of a substrate, because by knowing the composition of biomass, it is possible to predict the yield of biogas and its ratio of methane (Ugwu et al., 2020). Almost any organic material can be used for the biogas production, for example, paper, grass, animal waste, domestic or manufacturing sewage, food waste, agricultural products (Ugwu et al., 2020), but whereas finding new sources of renewable energy production is a global issue (Sauthoff et al., 2016; Siddique & Wahid, 2018) at the same time specially grown substrates are being rejected for the production of biogas (Schulz et al., 2018).

One of the substrates being rejected is the use of maize as a result of differences of opinion on its impact on the environment (Schulz et al., 2018), even though maize biogas yields and characteristics are far superior to other crops for biogas production (Pimentel, 2003; Gowik & Westhoff, 2011). Not only does maize have a high carbon fixation and assimilation capacity (Crafts-Brandner & Salvucci, 2002), but it can also be grown worldwide due to its high photosynthesis and resource utilization (Arodudu et al., 2017), even in conditions of drought, high temperatures and lack of various nutrients (Patzek, 2004). In addition, in the process of anaerobic digestion it is very important to use co-digestion, which allows to increase the productivity of produced biogas from 25 to 400% over mono-digestion (Cavinato et al., 2010; Shah et al., 2015). Co-digestion is often used for the very reason that the optimal carbon-nitrogen ratio on biogas production is in the rage of 20:1 to 30:1, but in general, manure has very low carbon ratio and it is important to mix it with other substrates that are carbon-rich like maize to increase the biogas yield.

Therefore, in this case, a carbon balance was developed and carried out to objectively quantify naturally or anthropogenically added or removed carbon dioxide from the atmosphere in order to determine the environmental impact of biogas production from specially grown substrates, in this case - maize silage.

Although many authors have acknowledged that, when analyzing biomass life cycle analysis, the range of results is quite wide (Murphy et al., 2014) due to the differences in various factors and system boundaries (Muench & Guenther, 2013), it is considered to be the best method for calculating Greenhouse gas (GHG) balance (Cherubini, 2010).

In this study carbon balance was carried out to determine the environmental impact in terms of greenhouse gas emissions by biogas production from specially grown maize.

The methodology was based on life cycle analysis, which included calculations of: emissions from maize silage cultivation due to tillage, mineral nitrogen fertilizers and fuel use in heavy machinery (both in the process of growing maize, in the process of preparing the substrate for biogas production, and in the process of incorporating digestate into the soil); emissions collected due to the photosynthesis process; emission leaks from biogas production process; emissions from the use of maize digestate fertilizer; emissions saved from the mineral fertilizer replacement with digestate.

Although the carbon balance method has been used so far, for example, to model the change of land use (Guo et al., 2017) or of forestry under various effects of forestry (Zubizarreta-Gerendiain et al., 2006), but there are no studies that have developed carbon balances to determine the environmental impact of substrate selection in biogas production.

METHODOLOGY

In order to calculate fuel emissions, data from an agricultural farm in Latvia was collected. It is important to note that the results of the calculations may differ, if a more detailed calculation is made, considering factors such as soil consistency and the technologies used, the efficiency of tractors and other indicators. The more efficient the techniques and methods used, the lower the emissions from maize production process. First, the number of times specific tractor-tillage techniques that use diesel fuel and the tons of diesel fuel consumed per 1 ha of the particular activity by off-road vehicles and other machinery were collected to an indicator of how many tons of diesel needed per hectare and how many tons of diesel fuel are consumed per year to process 1 ha of biogas maize fields. In turn, knowing the area of land that was used to grow the biogas maize substrate in a given year, can provide an indicator of all year's fuel consumption for biogas maize cultivation per ha (Table 1). Data from company producing biogas from maize in was used.

Table 1. Diesel fuel consumption for the production of maize for biogas production

	Times	Fuel needed, t ha^{-1} at a time	Fuel needed, t ha^{-1}	Area, ha	Fuel consumed over the area, t yr^{-1}
Plowing	1	0.025	0.025	5,382	134.335
Shuffle	1	0.008	0.008	5,382	44.778
Cultivation	1	0.007	0.007	5,382	40.300
Sowing	1	0.007	0.007	5,382	35.823
Plant protection + microelements	3	0.006	0.017	5,382	94.034
Shredding	1	0.029	0.029	5,382	156.724
Fertilizer application	3	0.004	0.012	5,382	67.167
Transportation field-farm	1	0.016	0.016	5,382	85.437
Compression	1	0.031	0.031	5,382	167.918
Picking from the pit, pouring, dumping	1	0.017	0.017	5,382	89.556
Incorporation of digestate into soil	1	0.015	0.015	5,382	80.601
In total	-	-	0.185	5,382	996.674

By finding out the lowest combustion heat of diesel fuel, it is possible to obtain consumed energy for field treatment (Intergovernmental Panel on Climate Change, 2006). But, knowing the energy consumed in the process in field cultivation as well as using the emission factors of the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines, it is possible to obtain the result in terms of tons of emissions from the use of fuel (Central Statistic Bureau, 2018). By determining the annual emissions, indicators - emissions from the processing of 1 ha of maize used for biogas production - are calculated.

During the special cultivation of maize, fuel is not the only source of emissions, it is also caused by the incorporation of crop residues into the soil, as well as the use of nitrogen, therefore the Tier 1 methodology from the 2006 IPCC guidelines was used to calculate nitrous oxide emissions from managed soils (IPCC, 2006). For direct nitrous oxide emissions from agricultural soils, the following equation was used.

$$N_2O - N = [(F_{SN} + F_{CR}) \cdot EF], \quad (1)$$

where N_2O – N – N_2O emissions in units of nitrogen (direct N_2O emissions from treated soils, kg N_2O–N yr^{-1});
F_{SN} – the amount of nitrogen in the fertilizer applied to the soil kg N yr^{-1}; F_{CR} – N amount of maize residues entering the soil on an annual basis (above and below ground); EF – N_2O emission factor from N input, kg N_2O–N kg^{-1} N (input = 0.01).
The following equation was used to report kg N_2O–N emissions to N_2O emissions:

$$N_2O = N_2O - N \cdot 44/28 \quad (2)$$

One of the calculation parameters for estimating the direct nitrogen oxide emissions from the use of N in managed soils is the amount of pure nitrogen fertilizers per year. Data on the required inorganic fertilizers used in soils are taken from A. Kārkliņš book 'Calculation methods and standards for the use of soil treatment and fertilizers', which states that a maize yield of 31.8 t ha^{-1} requires 0.1 t ha^{-1} N fertilizer (IPCC, 2006).
Yield N per year is calculated on the Tier 1 methodology of the 2006 IPCC Guidelines:

$$F_{CR} = \text{Yield} \cdot \text{DRY x } Frac_{Renew} \cdot \text{Area x } R_{AG} \cdot N_{AG} \cdot \text{Area} \cdot R_{BG} \cdot N_{BG}, \quad (3)$$

where Yield – harvested maize yield (kg fresh maize yield ha^{-1}); DRY – dry matter part of harvested maize (kg dry matter kg^{-1} fresh matter); $Frac_{Renew}$ – total area of maize; Area – the total part of the area harvested for maize (ha $year^{-1}$); RAG – terrestrial, surface residue solids (AGDM) and maize harvest (Crop), kg dry matter (kg dry matter)$^{-1}$; N_{AG} – N surface plant residue content in maize (kg N kg^{-1} dry matter); R_{BG} – ratio of underground residues to maize yield (kg dry fraction kg^{-1} dry fraction); R_{BG} can be calculated by multiplying RBG-BIO by the total aboveground biomass to cereal yield ratio ($R_{BG} = [(AG_{DM} \cdot 1{,}000 + \text{Crop Crop})^{-1}]$; N_{BG} – the N content of underground residues of maize (kg N kg^{-1} dry matter) (0.007) (Liu et al., 2019).

To calculate the annual production of crop residues F_{CR}, the following calculation is required:

$$R_{AG} = \frac{\text{AGDM} \cdot 1{,}000}{\text{Crop}} \quad (4)$$

as well as an additional equation to estimate terrestrial surface solids AGDM (Mg ha^{-1}):

$$\text{AGDM} = \left(\frac{\text{Crop}}{1{,}000}\right) \cdot \text{slope} + \text{intercept}. \quad (5)$$

And the correction factor for estimating the dry matter yield is determined as:

$$\text{Crop} = \text{Yield Fresh} \cdot \text{DRY}, \quad (6)$$

where Crop – harvested dry yield fraction T, kg dry matter ha^{-1}; yield Fresh – part of fresh harvest T, kg fresh fraction ha^{-1}; DRY – dry matter fraction of harvested crop T, kg dry fraction (kg dry fraction)$^{-1}$ (IPCC, 2006).

Although the use of digestate in field fertilization reduces emissions compared to synthetic fertilizers, digestion of soil with digestate also generates greenhouse gas emissions (Ericsson et al., 2020). The results of analyzes obtained from the farm 'X' producing biogas from maize indicate that the N content of the digestate fertilizer is on average 3.8 kg t^{-1}. By knowing the N content of the digestate and the tons of digestate obtained, digestate fertilization emissions were calculated by the 2006 IPCC guidelines.

When looking at emissions from the biogas production process, it should be considered that although biogas is produced from maize, which is a renewable resource and recovers the carbon emissions that the plant has absorbed during its growth process, emissions from the biogas production process are taken into account. Based on the scientific article emission leakages account for 1% of biogas losses in biogas production, which includes both the 52% methane in it and the remaining 48%, which is assumed to be carbon dioxide (Blumberga et al., 2010).

Although GHG emissions result from field cultivation during maize cultivation, maize growth involves photosynthetic processes that sequester CO_2 from the atmosphere. In order to calculate the amount of CO_2 captured in a year in a certain area of biogas maize, the amount of dry matter is multiplied by the CO_2 sequestration factor (Scarlat et al., 2018).

RESULTS AND DISCUSSIONS

For the analysis of cultivation of maize and GHG emissions related with it, data about amount of total cultivated maize from 2017 were used. It can be seen that in 2017, GHG emissions are generated for the cultivation of maize, which was used as a substrate for biogas production, in total 3.53 kt CO_2eq yr^{-1} to treat it with heavy agricultural machinery, which uses diesel fuel. Knowing that 5,382 ha of biogas maize were managed in 2017, a result is obtained which shows that 0.66 tCO_2eq ha^{-1} per year of GHG emissions are generated in the management of biogas maize fields with agricultural machinery. Table 2 show fuel emission indicators per 1 ha of cultivated maize area used in calculations.

Table 2. Fuel emission indicators per 1 ha of cultivated maize area (based on IPCC, 2006)

	CO_2 emissions, t ha^{-1}	CH_4 emissions, kg ha^{-1}	N_2O emissions, kg ha^{-1}
Plowing	0.079	0.004	0.030
Shuffle	0.026	0.001	0.010
Cultivation	0.024	0.001	0.009
Sowing	0.021	0.001	0.008
Plant protection + microelements	0.055	0.003	0.021
Shredding	0.092	0.005	0.035
Fertilizer application	0.040	0.002	0.015
Transportation field-farm	0.050	0.003	0.019
Compression	0.099	0.006	0.038
Picking from the pit, pouring, dumping	0.053	0.003	0.020
Incorporation of digestate into soil	0.048	0.003	0.018
In total	0.588	0.033	0.225

In order to objectively determine the total greenhouse gas emissions from fuel use, it is necessary to convert them into a single unit of measurement - CO_2 equivalents. As the global warming potential (GWP) of 1 ton of CH_4 equals 25 tons of C_2 and 1 ton to N_2O equals 298 tons of CO_2, these values are used to produce total greenhouse gas emissions (IPCC, 2006). Table 3 shows CO_2eq emission indicators per 1 ha of biogas produced from specially cultivated maize.

Table 3. Fuel CO_2eq emission indicators per 1 ha of biogas produced from specially cultivated maize (based on IPCC, 2006)

	CO_2 emissions, kgCO_2eq ha^{-1}	CH_4 emissions, kgCO_2 eq ha^{-1}	N_2O emissions, kgCO_2 eq ha^{-1}	Total emissions, tCO_2 eq ha^{-1}
Plowing	79.28	0.11	9.04	0.09
Shuffle	26.43	0.04	3.01	0.03
Cultivation	23.78	0.03	2.71	0.03
Sowing	21.14	0.03	2.41	0.02
Plant protection + microelements	55.49	0.08	6.33	0.06
Shredding	92.49	0.13	10.55	0.10
Fertilizer application	39.64	0.06	4.52	0.04
Transportation field-farm	50.42	0.07	5.75	0.06
Compression	99.09	0.14	11.30	0.11
Picking from the pit, pouring, dumping	52.85	0.07	6.03	0.06
Incorporation of digestate into soil	47.57	0.07	5.42	0.05
In total	588.16	0.82	67.06	0.66

The obtained data show that the highest emissions per ha occur per year due to harvesting and shredding to prepare maize for placing in the bioreactor, as well as due to compaction. The lowest emissions occur during sowing. Total indicative emissions from biogas production from specially grown maize per ha shown in Table 4.

Table 4. Total indicative emissions from biogas production from specially grown maize per ha (based on IPCC, 2006)

Indicative emissions	tCO_2eq ha^{-1}
Fuel emissions	0.656
Crop residue emissions	0.443
N fertilizer emissions	0.468
In total	1.567

As a result, it can be seen that the highest emissions per ha are caused by the use of fuel to perform all the necessary treatment operations with heavy machinery, which is almost 0.66 tCO_2eq ha^{-1}. Emissions from tillage with nitrogen fertilizers and crop residue incorporation in soil after harvest are relatively similar, amounting to 0.468 tCO_2 eq ha^{-1} and 0.443 tCO_2 eq ha^{-1}. In total indicative emissions from biogas production from specially grown maize creates 1.567 t CO_2 eq ha^{-1}.

The biogas production process produces a very valuable by-product – digestate. It contains significant amounts of nutrients that are suitable for enriching the soil (Brown et al., 2010; Pereira et al., 2018). The dry weight of digestate from biogas production using only maize is approximately 58.22% (Tambone et al., 2019). Digestion of fields with digestate can indirectly reduce greenhouse gas emissions, for example, digestate from 1 ha of maize green matter with a yield of 30 t ha^{-1} fully provides the required amount of potassium fertilizer and saves 31% phosphorus and 44–45% nitrogen fertilizer (Naglis-Liepa et al., 2014; Slepetiene et al., 2020).

Accordingly, using a maize yield of 31.8 t ha^{-1}, it is possible to provide fertilizer for 1.06 ha of maize. As a total of 25,700 ha of maize was grown in Latvia in 2017, the use of digestate is topical, as well as interviews with farmers conducted within the framework of this study revealed that unfortunately digestate for field fertilization is a shortage product, which is why additional synthetic fertilizers are used (Iocoli et al., 2019; Verdi et al., 2019).

Using digestate fertilizer in tillage, 1.19 ktCO_2eq emissions were saved in 2017, while indicative emissions show a reduction of 0.22 tCO_2eq ha^{-1}.

Although the use of digestate in field fertilization reduces emissions compared to synthetic fertilizers, digestion of soil with digestate also generates GHG emissions. The results of analyzes obtained from a farm producing biogas from maize indicate that the N content of the digestate fertilizer is on average 3.8 kg t^{-1}. Assuming that the maize harvest in 2017 is 171,147.6 tons and that the amount of digestate from the amount of mass fed to the bioreactor usually ranges from 90 to 95%, in 2017 158,311.53 tons of maize digestate were obtained, while knowing the N content of digestate per 1 ton, it is obtained that the total N per 5,382 ha of the whole maize area was 0.60 kt (Central Statistic Bureau, 2021). Based on the level 1 methodology of the 2006 IPCC guidelines, it is estimated that digestate fertilization caused 2.82 ktCO_2eq emissions in 2017 indicating on indicative emissions - 0.0005 tCO_2eq ha^{-1}.

The methane content of biogas produced exclusively from maize silage is known to be 52%, and the biogas yield per ton of maize is 202 cubic meters, which allows to calculate both the total amount of biogas produced from maize harvested in Latvia, which is 34,571,815.2 m^3 from 171,147.6 t maize (Latvia's National Inventory Report, 1990).

At a 1% biogas leak in its production process in 2017, 2.63 ktCO_2 eq GHG emissions were released into the atmosphere.

CONCLUSIONS

The research proves that carrying out carbon balance by the methodology based on life cycle analysis for assessment of the impact of biogas production from maize, it is possible to determine the environmental impact in terms of greenhouse gas emissions on the atmosphere. Despite the consumption of diesel fuel and emissions from the maize production process, maize absorbs much more carbon than is produced during photosynthesis, thus, if 1% of biogas leakage is assumed in its production process, as well as knowing by previous calculations that 34,571,815.2 m^3 of biogas can be obtained from 5,382 ha specially grown maize, its production from specially grown maize can save 1.86 kg CO_2 eq emissions per 1 m^3 of produced biogas (in normal conditions, pressure 760 mm Hg).

The carbon balance can be further improved by reducing emissions from the agricultural process by growing the substrate, for example, using zero-emission electric tractors for soil tillage, could reduce total biogas maize growing emissions by 43%. But there are also processes that would not be desirable to reduce emissions, for example, the tractor driving frequency reduction in the field - the fertilization process can theoretically be carried out immediately and at once, but fertilization is divided into several stages in order to gradually spread the substances for a favorable plant vegetation process, as well as not to promote pollution of water due to drainage that leads to erosion (Oshunsanya et al., 2019). After harvest, 28% of total emissions come from nitrogen emissions from crop residues (above and below ground). Unfortunately, these are emissions that cannot be reduced because, although these residues could theoretically be used for biogas production, the removal of crop residues from maize fields would have a negative impact on the environment and soil quality (Industrial Vehicle Technology International, 2021).

It is essential to combine efficiency in agriculture in order to reduce atmospheric emissions without losing sight of sustainable farming, so as not to have a negative impact on soil, water and the environment as a whole.

Results of this study demonstrates that using the carbon balance methodology developed in this work, it is possible to calculate the impact of biogas production and how the environment is affected as a result of substrate selection. Such calculations can be applied to any country or company in the world and it can be an excellent tool for political decision making, based not on discussion, but on quantitative calculations.

ACKNOWLEDGEMENTS. This research is funded by the Ministry of Economics of the Republic of Latvia, project 'Sustainable and renewable transport policy formulation in Latvia', project No. VPP-EM-2018/AER_2_0003.

REFERENCES

Arodudu, O.T., Helming, K., Voinov, A. & Wiggering, H. 2017. Integrating agronomic factors into energy efficiency assessment of agro-bioenergy production – A case study of ethanol and biogas production from maize feedstock. *Applied Energy* **198**, 426–439. https://doi.org/10.1016/j.apenergy.2017.02.017

Bereiter, B., Eggleston, S., Schmitt, J., Nehrbass-Ahles, C., Stocker, T.F., Fischer, H., Kipfstuhl, S. & Chappellaz, J. 2015. Revision of the EPICA Dome C CO2 record from 800 to 600-kyr before present. *Geophysical Research Letters* **42**, 542–549. https://doi.org/10.1002/2014GL061957

Blumberga, D., Dzene, I., Al Seadi, T., Rutz, D., Prassl, H., Kottner, M., Finsterwalder, T., Volk, S. & Janssen, R. 2010. *Biogas HANDBOOK*. https://docplayer.org/69439281-D-blumberga-i-dzene-t-al-sedi-d-rucs-h-prasls-m-ketners-t-finstervalders-s-folka-r-jansens-biogaze-rokasgramata.html. Accessed 05.01.2021

Brown, S., Beecher, N. & Carpenter, A. 2010. Calculator tool for determining greenhouse gas emissions for biosolids processing and end use. *Environmental Science & Technology* **44**, 9509–9515. https://doi.org/10.1021/es101210k

Bumbiere, K., Gancone, A., Pubule, J., Kirsanovs, V., Vasarevicius, S. & Blumberga, D. 2020. Ranking of Bioresources for Biogas Production. *Environmental and Climate Technologies* **24**(1), 368–377. https://doi.org/10.2478/rtuect-2020-0021

Cavinato, C., Fatone, F., Bolzonella, D. & Pavan, P. 2010. Thermophilic anaerobic co-digestion of cattle manure with agro-wastes and energy cr*ops: Comparison of pilot and full scale experiences.* Bioresource Technology **101**, 545–550. https://doi.org/10.1016/j.biortech.2009.08.043

Central Statistic Bureau, CSB database, (n.d.). https://www.csb.gov.lv/lv/statistika/db. Accessed 05.01.2021.

Central Statistic Bureau, Latvian energy balance in 2017. 2018. https://www.csb.gov.lv/lv/statistika/statistikas-temas/vide-energetika/energetika/meklet-tema/332-energobilance-2017-gada

Chen, X.Y., Vinh-Thang, H., Ramirez, A.A., Rodrigue, D. & Kaliaguine, S. 2015. Membrane gas separation technologies for biogas upgrading. *RSC Advances* **5**, 24399–24448. https://doi.org/10.1039/c5ra00666j

Cherubini, F. 2010. GHG balances of bioenergy systems - Overview of key steps in the production chain and methodological concerns. *Renewable Energy* **35**, 1565–1573. https://doi.org/10.1016/j.renene.2009.11.035

Crafts-Brandner, S.J. & Salvucci, M.E. 2002. Sensitivity of photosynthesis in a C4 plant, maize, to heat stress. *Plant Physiology* **129**, 1773–1780. https://doi.org/10.1104/pp.002170.

European Council | European Commission. 2014. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions. A policy framework for Climate and Energy in the period from 2020 to 2030. https://ec.europa.eu/clima/policies/strategies/2030_en. Accessed 04.01.2021.

European Council, European Commission. 2018. 2050 long-term strategy. Going climate-neutral by 2050. https://ec.europa.eu/clima/policies/strategies/2050_en. Accessed 04.01.2021.

European Council, A European Green Deal | European Commission. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. Accessed 04.01.2021.

Ericsson, N., Nordberg, Å. & Berglund, M. 2020. Biogas plant management decision support - A temperature and time-dependent dynamic methane emission model for digestate storages. *Bioresource Technology Reports* **11**, 100454. https://doi.org/10.1016/j.biteb.2020.100454

Gowik, U.& Westhoff, P. 2011. The Path from C3 to C4 photosynthesis. *Plant Physiology* **155**, 56–63. https://doi.org/10.1104/pp.110.165308

Guo, R., Zhao, Y., Shi, Y., Li, F., Hu, J. & Yang, H. 2017. Low carbon development and local sustainability from a carbon balance perspective. *Resources, Conservation & Recycling* **122**, 270–279. https://doi.org/10.1016/j.resconrec.2017.02.019.

Industrial Vehicle Technology International, John Deere develops fully electric, autonomous tractor, (n.d.). https://www.ivtinternational.com/news/agriculture/john-deere-develops-fully-electric-autonomous-tractor.html. Accessed 05.01.2021.

Iocoli, G.A., Zabaloy, M.C., Pasdevicelli, G. & Gómez, M.A. 2019. Use of biogas digestates obtained by anaerobic digestion and co-digestion as fertilizers: Characterization, soil biological activity and growth dynamic of Lactuca sativa L. *Science of the Total Environment* **647**, 11–19. https://doi.org/10.1016/j.scitotenv.2018.07.444

IPCC - Task Force on National Greenhouse Gas Inventories. 2006. 2. https://www.ipcc-nggip.iges.or.jp/public/2006gl/ Accessed 05.01.2021.

Krištof, K. & Gaduš, J. 2018. Effect of alternative sources of input substrates on biogas production and its quality from anaerobic digestion by using wet fermentation. *Agronomy Research* **16**(3), 769–783. https://doi.org/10.15159/AR.18.146

Latvia's National Inventory Report. 1990. http://www.meteo.lv/. Accessed 05.01.2021.

Lauka, D., Slisane, D., Ievina, L., Muizniece, I. & Blumberga, D. 2019. When Bioeconomy Development Becomes a Biomass Energy Competitor. *Environmental and Climate Technologies* **23**, 347–359. https://doi.org/10.2478/rtuect-2019-0100

Li., Y., Wen, Z., Li, J., Cai, L. & Wang, H. 2019. Feasibility of utilizing by-product biogas in breweries after being decarbonized for refrigeration chiller and related primary energy efficiency analysis. Sustainable *Energy Technologies and Assessments* **31**, 390–400. https://doi.org/10.1016/j.seta.2019.01.001

Liu, Z., Gao, J., Gao, F., Liu, P., Zhao, B. & Zhang, J. 2019. Late harvest improves yield and nitrogen utilization efficiency of summer maize. *Field Crops Research* **232**, 88–94. https://doi.org/10.1016/j.fcr.2018.12.014

Mano Esteves, E.M., Naranjo Herrera, A.M., Pecanha Esteves, V.P. & Vaz Morgado, C.R. 2019. Life cycle assessment of manure biogas production: A review. *Journal of Cleaner Production* **219**, 411–423. https://doi.org/10.1016/j.jclepro.2019.02.091

Meiramkulova, K., Bayanov, A., Ivanova, T., Havrland, B., Kára, J. & Hanzlíková, I. 2018. Effect of different compositions on anaerobic co-digestion of cattle manure and agro-industrial by-products. *Agronomy Research* **16**(1), 176–187. https://doi.org/10.15159/AR.18.008

Melvere, M., Ivanovs, K., Pubule, J. & Blumberga, D. 2017. Use of round goby (Neogobius melanostomus) processing waste in bioeconomy. *Energy Procedia* **128**, 484–490. https://doi.org/10.1016/j.egypro.2017.09.064

Mehryar, E., Ding, W.M., Hemmat, A., Hassan, M., Bi, J.H., Huang, H.Y. & Kafashan, J. 2017. Anaerobic co-digestion of oil refinery wastewater and chicken manure to produce biogas, and kinetic parameters determination in batch reactors. *Agronomy Research* **15**(5), 1983–1996. https://doi.org/10.15159/AR.17.072.

Meyer, A.K.P., Ehimen, E.A. & Holm-Nielsen, J.B. 2018. Future European biogas: Animal manure, straw and grass potentials for a sustainable European biogas production. *Biomass and Bioenergy* **111**, 154–164. https://doi.org/10.1016/j.biombioe.2017.05.013

Muench, S. & Guenther, E. 2013. A systematic review of bioenergy life cycle assessments. *Applied Energy* **112**, 257–273. https://doi.org/10.1016/j.apenergy.2013.06.001.

Muizniece, I., Zihare, L., Pubule, J. & Blumberga, D. 2019. Circular Economy and Bioeconomy Interaction Development as Future for Rural Regions. Case Study of Aizkraukle Region in Latvia. *Environmental and Climate Technologies* **23**, 129–146. https://doi.org/10.2478/rtuect-2019-0084

Murphy, F., Devlin, G. & McDonnell, K. 2014. Forest biomass supply chains in Ireland: A life cycle assessment of GHG emissions and primary energy balances. *Applied Energy* **116**, 1–8. https://doi.org/10.1016/j.apenergy.2013.11.041

Naglis-Liepa, K. & Pelse, M. 2014. Biogas production from agricultural raw materials. https://llufb.llu.lv/conference/economic_science_rural/2014/ESRD_34_2014_Productions-172-179.pdf

Oshunsanya, S.O., Li, Y. & Yu, H. 2019. Vetiver grass hedgerows significantly reduce nitrogen and phosphorus losses from fertilized sloping lands. *Science of the Total Environment* **661**, 86–94. https://doi.org/10.1016/j.scitotenv.2019.01.129

Patzek, T.W. 2004. Thermodynamics of the corn-ethanol biofuel cycle, CRC. Critical Reviews in Plant Sciences **23**, 519–567. https://doi.org/10.1080/07352680490886905.

Pereira Domingues Martinho, V.J. 2018. Interrelationships between renewable energy and agricultural economics: An overview. *Energy Strategy Reviews* **22**, 396–409. https://doi.org/10.1016/j.esr.2018.11.002

Pimentel, D. 2003. Ethanol fuels: Energy balance, economics, and environmental impacts are negative. *Natural Resources Research* **12**, 127–134. https://doi.org/10.1023/A:1024214812527

Sauthoff, S., Musshoff, O., Danne, M. & Anastassiadis, F. 2016. Sugar beet as a biogas substrate? A discrete choice experiment for the design of substrate supply contracts for German farmers. *Biomass and Bioenergy* **90**, 163–172. https://doi.org/10.1016/j.biombioe.2016.04.005

Scarlat, N., Dallemand, J.F. & Fahl, F. 2018. Biogas: Developments and perspectives in Europe. *Renewable Energy* **129**, 457–472. https://doi.org/10.1016/j.renene.2018.03.006

Schulz, V.S., Munz, S., Stolzenburg, K., Hartung, J., Weisenburger, S., Mastel, K., Möller, K., Claupein, W. & Graeff-Hönninger, S. 2018. Biomass and biogas yield of maize (Zea mays l.) grown under artificial shading. *Agriculture* **8**. https://doi.org/10.3390/agriculture8110178

Shah, F.A., Mahmood, Q., Rashid, N., Pervez, A., Raja, I.A. & Shah, M.M. 2015. Co-digestion, pretreatment and digester design for enhanced methanogenesis. *Renewable & Sustainable Energy Reviews* **42**, 627–642. https://doi.org/10.1016/j.rser.2014.10.053

Siddique, M.N.I. & Wahid, Z.A. 2018. Achievements and perspectives of anaerobic co-digestion: A review. *Journal of Cleaner Production* **194**, 359–371. https://doi.org/10.1016/j.jclepro.2018.05.155

Slepetiene, A., Volungevicius, J., Jurgutis, L., Liaudanskiene, I., Amaleviciute-Volunge, K., Slepetys, J. & Ceseviciene, J. 2020. The potential of digestate as a biofertilizer in eroded soils of Lithuania. *Waste Management* **102**, 441–451. https://doi.org/10.1016/j.wasman.2019.11.008.

Tambone, F., Orzi, V., Zilio, M. & Adani, F. 2019. Measuring the organic amendment properties of the liquid fraction of digestate. https://doi.org/10.1016/j.wasman.2019.03.024

Timonen, K., Sinkko, T., Luostarinen, S., Tampio, E. & Joensuu, K. 2019. LCA of anaerobic digestion: Emission allocation for energy and digestate. *Journal of Cleaner Production* **235**, 1567–1579. https://doi.org/10.1016/j.jclepro.2019.06.085

Ugwu, S.N., Biscoff, R.K. & Enweremadu, C.C. 2020. A meta-analysis of iron-based additives on enhancements of biogas yields during anaerobic digestion of organic wastes. *Journal of Cleaner Production* **269**, 122449. https://doi.org/10.1016/j.jclepro.2020.122449

Verdi, L., Kuikman, P.J., Orlandini, S., Mancini, M., Napoli, M. & Dalla Marta, A. 2019. Does the use of digestate to replace mineral fertilizers have less emissions of N_2O and NH 3? *Agricultural and Forest Meteorology* **269–270**, 112–118. https://doi.org/10.1016/j.agrformet.2019.02.004

Zubizarreta-Gerendiain, A., Pukkala, T. & Peltola, H. 2016. Effects of wood harvesting and utilisation policies on the carbon balance of forestry under changing climate: A Finnish case study. *Forest Policy and Economics* **62**, 168–176. https://doi.org/10.1016/j.forpol.2015.08.007