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Development and Assessment of Carbon Farming Solutions

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***Abstract* – In the light of the Green Deal and its 'Farm to Fork' and 'Biodiversity' strategies, the EU aims to find new ways to decrease GHG emissions through the EU Carbon Farming initiative stating that farming practices that remove CO_2 from the atmosphere should be rewarded in line with the development of new EU business models. The Carbon farming initiative is a new approach and concludes that carbon farming can significantly contribute to climate change mitigation. As European Commission acknowledges that carbon farming is in its infancy and there is a lot to be addressed, in the years towards 2030, result-based carbon farming plots and schemes should be settled by the Member States and local governments; therefore, the existing solutions for reducing emissions through improved farming practices should be defined for each region. The research identifies carbon farming solutions in the agriculture sector – minimal/zero tillage, carbon sequestration in soils, biogas and biomethane production, perennial plant growing, and agroforestry and described.**

***Keywords* – Agriculture emission mitigation; biodiversity; biogas production; biomethane; carbon farming methods; CO_2 sequestration; minimal tillage; perennial plants; soils; solutions; zero tillage**

1. INTRODUCTION

Carbon is the atom of life and not only by carbon-based fossil fuels our vehicles, homes, and factories are powered, but it is also used in chemicals, plastics, advanced materials, steel of our cities involves processing carbon, half of the food is carbon, and it is even in human DNA [1]. However, the concentration of carbon dioxide in the atmosphere has increased significantly, mainly due to the combustion of fossil fuels in industrial processes [2] and the activities of various other sectors [3], [4].

Carbon dioxide (CO_2) is a renewable [5], inexpensive [6], safe gas with a balanced geographic distribution [7], mainly known as a greenhouse gas that significantly contributes to global warming [8]. Although CO_2 is a relatively low energy and inert molecule, its involvement consumes much energy and not enough developed processes [7]. Therefore, it is essential to identify the directions with the most significant potential for the sustainable and efficient use of CO_2 in production rather than negatively impacting the economy and the environment.

Although negatively impacting utilisation will not significantly reduce global warming [9], more and more research has come up with different solutions for using CO_2 in various industries' production processes, replacing fossil fuels, for example, in chemistry [10],

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transport [11], food production and processing [12], in the production of various daily necessities [13], [14], thereby promoting sustainable development and reducing greenhouse gas emissions in the atmosphere.

In the light of the Green Deal and its 'Farm to Fork' and 'Biodiversity' strategies, the EU aims to find new ways to decrease GHG emissions through the EU Carbon Farming initiative stating that farming practices that remove CO_2 from the atmosphere should be rewarded in line with the development of new EU business models [15].

The Carbon farming initiative is a new approach for Europe. Its main objective is to create direct incentives to encourage the agriculture and forestry sectors to deliver on climate and biodiversity action and contribute to the European Green Deal. The initiative [15] concludes that carbon farming can significantly contribute to climate change mitigation, and European Commission acknowledges that carbon farming is in its infancy. There is a lot to be addressed. The European Commission highlights that carbon farming can be promoted via EU and national policies and private initiatives. In the years towards 2030, result-based carbon farming pilots and, eventually, schemes should be settled by Member States and local governments. Therefore, solutions for reducing emissions through improved farming practices should be defined for each region [16].

Climate change is included as one of the specific objectives of the current common agricultural policy, promoting the implementation of technical measures for both mitigation and adaptation at the farm level. The agriculture sector keeps an essential role in Latvia's economy. The most significant part of the population lives in rural areas, approximately 84 % of the total area. The agricultural sector is responsible for 28.5 % of Latvia's total non-EU ETS GHG emissions in Latvia. Latvia reduced GHG emissions from agriculture between 1990 and 2018 by 53 %; however, in the latest years and projections show a rising trend most significant part of emissions is related to agricultural soils (59.3 %) and enteric fermentation 32.6 % (mainly dairy and beef cattle). The GHG emission trend of recent years shows a gradual and steady increase in GHG emissions; for example, between 2005 and 2018 + 12.5 %, and during the period 2013–2018, emissions increased by 2.12 %. According to Latvia's National Energy and Climate Plan 2021–2030, total GHG emissions in the agricultural sector are expected to increase from 2020 to 2030, mainly in the enteric fermentation and agricultural soil categories. To achieve determined targets for Latvia's non-EU ETS sector in 2030 and be on track to reach climate neutrality in 2050, the agriculture sector must contribute to GHG emission mitigation. Improved food security and climate-smart activities will be necessary for the agriculture sector to achieve GHG emission reduction.

The European Green Deal is planned to improve people's well-being and make Europe climate-neutral, including decreasing emissions while creating jobs [17]. To move on with these ambitions, EC proposes to revise relevant climate policies, for example, targets to reduce emissions in sectors outside the EU ETS. Reaching these ambitions will require action by all sectors of the economy, including agriculture; nevertheless, it is not easily achieved. One of the main challenges facing the agricultural industry is to provide food for the increasing population while reducing its influence on the climate and environment.

Carbon farming mainly aims to trap carbon in soil and vegetation because of the co-benefits of fertility and productivity boost [18].

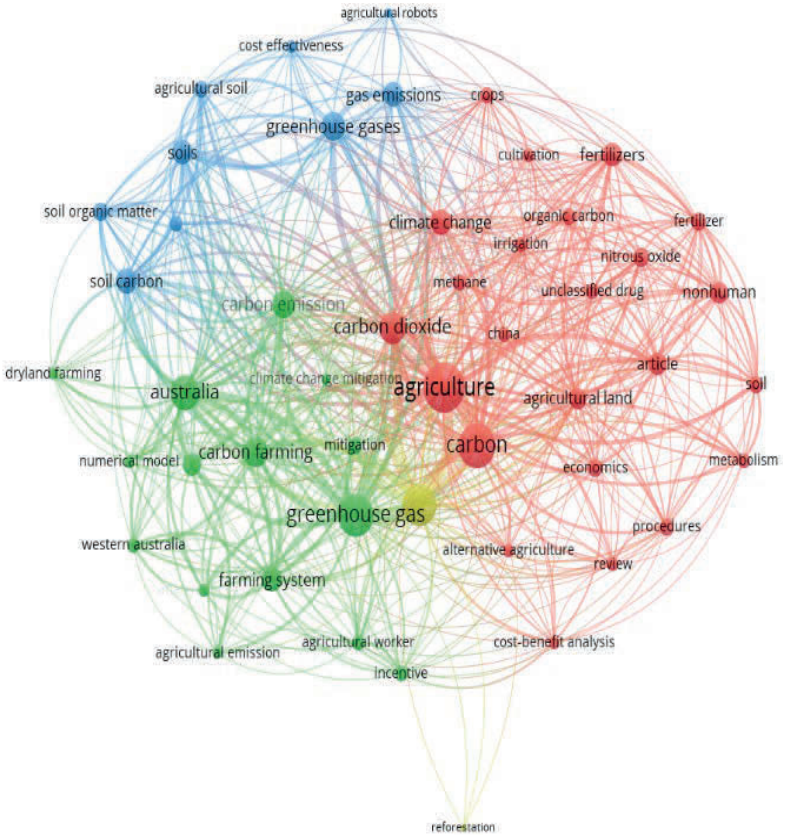
As an increasing number of private carbon initiatives have emerged, where land managers sell carbon credits on voluntary carbon markets, it is the right moment to improve high-quality supply in the EU [1]. The best practice would be to prevent a large-scale lift-off and ensure adequate reward for the carbon credits, but on the supply side, carbon farming credits should

become an additional 'product' for sale [1]. It would be a new source of income for land managers [1].

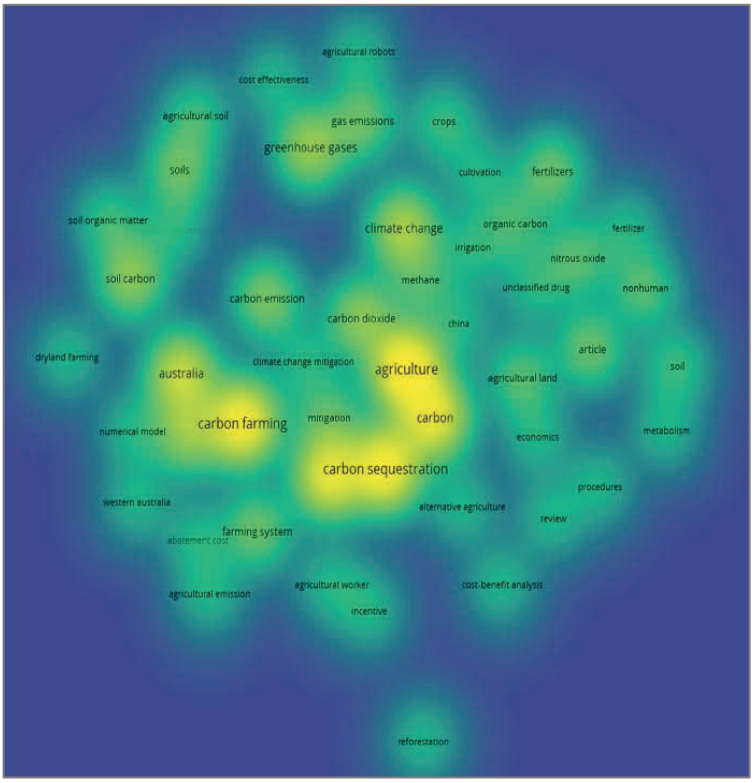
Carbon farming solutions for Latvian conditions will be identified in the research, and their importance in reducing GHG emissions will be determined and evaluated.

2. LITERATURE ANALYSIS

To evaluate the current state of carbon farming and how it is connected to other topicalities and the leading technologies used to achieve it, a bibliometric analysis using *VOSviewer*© was conducted. Scientific publications on the Scopus database with the keywords 'carbon farming' and 'agriculture' were searched. Fifty-three publications were found with these two terms with 50 keywords when a co-occurrence constraint of at least five co-occurrences is considered. This means the bibliometric network presented in Fig. 1(a) displays those keywords that appear at least five times within the publications. The links displayed between items represent a co-occurrence in a source, each connection with a strength score; the higher the value, the stronger the association. Such a strength score represents the number of publications in which both keywords appear together (co-occurrence) [19].



(a)



(b)

Fig. 1. (a) Network visualization; (b) Density visualization.

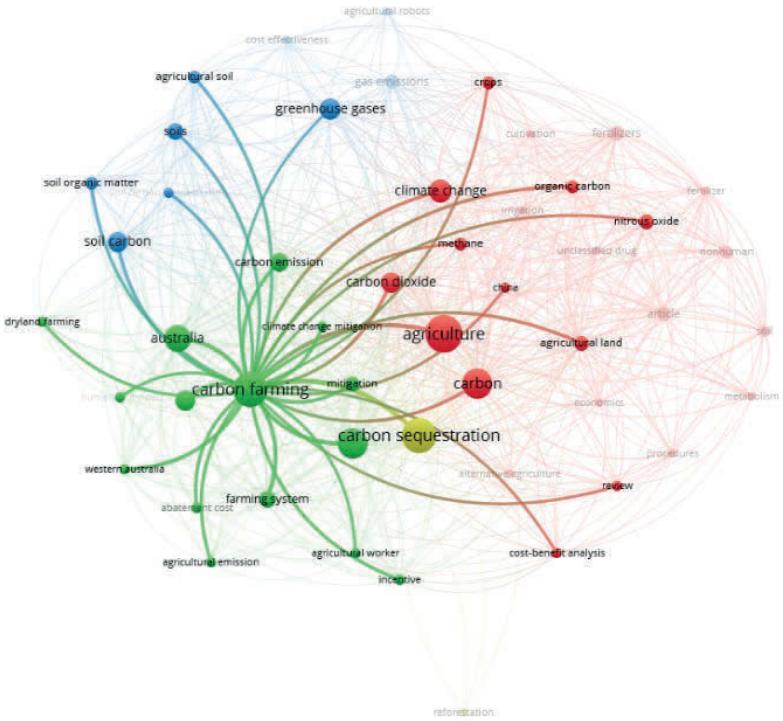
Fig. 1(b) shows the occurrences density visualization of each keyword for the network, with 'carbon sequestration', 'carbon farming', agriculture', 'carbon', and 'Australia' being the most common items. When the 'carbon farming' keyword is analysed within the network (see Fig. 2(a), the main topics connected to it are shown, some of them of importance to this work as some techniques are observed. The yellow cluster for instance (see Fig. 2(b)), displays two current technologies, carbon sequestration with occurrences in 18 out of 50 publications and 46 links, and reforestation with only three occurrences and four links.

Another interesting analysis from the network is the fact that the link between 'carbon farming' and 'agriculture' does not have considerable strength in the network with a score of 5, with the stronger links to exists among 'carbon', 'agriculture', and 'carbon sequestration' showing scores between 9 and 13. When it comes to deep research on carbon farming techniques, the lack of related keywords in this network is noticeable, with most studies focusing on types of crops, economic evaluations, and GHG emissions.

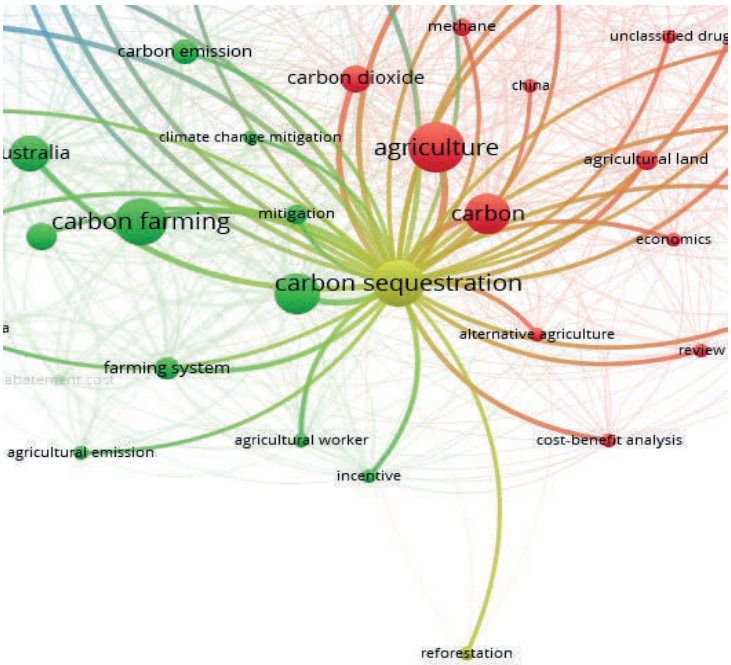
To achieve the goal of this research – to identify carbon farming solutions for Latvian conditions and determine their importance in reducing GHG emissions, a literature review has been conducted, mainly analysing reports, legislation, scientific articles that were identified as a relevant material to provide an understanding of some of the possible solutions for carbon farming in the Latvian agriculture sector. The search was performed mainly using Google, ScienceDirect, Web of Science, and Google Scholar. The review was done based on the agricultural situation of Latvia, but it can be used for other countries too.

In 2018, only 1 % of the approximately one billion tons of biogenic (45 %) and fossil (54 %) carbon was recycled [1]. Fossil carbon should be replaced by carbon derived from waste, the atmosphere, and sustainably harvested biomass, to produce such products as plastics, synthetic fuels, rubber, and various value-added materials and chemicals [1]. Biogenic carbon will play an essential role in construction, providing substitutes for conventional building materials with alternative materials that can store carbon long [1].

It can already be seen that by 2030, the Innovation Fund will provide financial support of 25 billion EUR (at a carbon price of 50 EUR/t CO_2) for companies to invest in clean technologies, CCU, CCS, and carbon sequestration [1]. To achieve climate neutrality, by 2050, each CO_2 eq. ton emitted into the atmosphere will have to be balanced by a ton of CO_2 captured in the atmosphere. It means significantly reducing emissions and increasing carbon sequestration as an input to the production of various products.



(a)



(b)

Fig. 2. Carbon farming links and relationships.

2.1. Zero/Minimal tillage

In 2018, 59.3 % of all emissions in the Latvian agricultural sector were caused by tillage, and 57.2 % of the arable land and these lands are occupied by cereals, which makes it a priority for the necessary change [20]. It is important to note that the treatment of agricultural soils includes emissions from the use of tractors and the use of fertilizers and post-harvest residues, which are later incorporated into the soil [21], [22].

The Strategic Plan of Latvia's Common Agricultural Policy also attaches great importance to reducing GHG emissions from agricultural land management by promoting more sustainable practices. The main aim of the activity is to encourage the use of sustainable agricultural production methods in the management of agricultural lands. It includes precise, well-thought-out fertilizers and plant protection, the cultivation of a single crop in a defined area for a maximum of 3 consecutive years, and the provision of green cover during part of the perennial planting area the growth season.

Reducing emissions from post-harvest residues is unfortunately not possible, as although, in theory, these residues could be collected and used in biogas or biofuel production with a 28 % reduction of GHG emissions, this is by no means acceptable, as it would have a negative impact not only on soil quality but also on the environment as a whole [23]. Even if crop residues are harvested below 25 %, it can lead to segment losses during the rain. Therefore studies show that only a minimal proportion can be removed, but it would be neither economically justified nor rational [24]. It means that the emphasis must be on reducing emissions from fuels and fertilizers; in addition, studies have shown that fuels and fertilizers are responsible for most of the GHG emissions from the agricultural tillage [25], [26].

Although high hopes are for electric tractor development, it is essential to look for solutions today. One solution is a sustainable agriculture technology based on reduced tillage to preserve soil structure and organic matter – minimal or even zero tillage [27].

In Europe, minimum and zero tillage methods have been used for decades. Still, in Latvia, 91.2 % of soils are cultivated with conventional tillage, while the energy consumption of this technology is 26 % higher than at minimal tillage and 41 % higher than at zero tillage [28].

To achieve sustainable agriculture and save emissions, various activities must be carried out in several stages, one stage lasting at least two years and consisting of 4 steps:

1. Minimum treatment methods are introduced (ploughing is stopped);
2. Under the influence of organic matter, the soil is improved due to the decomposition of crop residues, but the number of pests increases, which must be controlled with the help of chemicals;
3. The common system is stabilized, and the diversification of cultivation systems is introduced with intercultural cultivation;
4. The new farming system strikes a balance that can improve productivity compared to conventional farming and reduce the need for fertilizers and plant protection products [27].

Although the introduction of such a system takes an average of 6 years and yields during those six years can be significantly reduced, GHG emissions would be saved considerably and eliminated by reducing the amount of diesel and labour used, as well as fertilizers and plant protection products, in addition, the potential income from carbon farming would make such shift more motivating for farmers [29], [30]. Faster results can be achieved with the most modern seed drills without ploughing technology, where the seeds are pressed directly into the ground with a particular disc. Because direct sowing does not require many processes, the cost of working hours, fuel, spare parts, and repairs, and operating costs are reduced when productivity is not reduced [30], [31]. When choosing this technology, it is most important to pay attention to the sown interculture because it is the intercropping that provides the necessary minerals to the soil and creates micro-reclamation with plant roofs, preventing the soil from drying out or leaching fertilizer [31]. Choosing the right intercultures makes it possible to control weeds and various diseases, resulting in a significant reduction in the need for plant protection products [31].

2.2. Biogas production

The importance of renewable energy development for the decarbonization of the energy sector is already recognized [32], and biogas production is particularly suitable for Latvia because agriculture in Latvia accounts for 24.6 % of total GHGs, ranking as the 2nd largest GHG emitting sector [33]. Biogas is produced by anaerobic fermentation – it is an environmental technology [34] that has been used for a very long time and is entirely developed [35]. Biogas produced by anaerobic digestion prevent greenhouse gas emissions and produce renewable energy from waste and provide for the production of processed fertilizers, improving nutrient self-sufficiency in the agricultural sector [36].

After biogas extraction, it has mainly two options for further use – its combustion to provide heat and electricity at cogeneration plants or to upgrade to biomethane to use it as a road fuel [37]–[39]. Both in Europe and Latvia, the industrial use of biogas is based on power generation through combined heat and power units [40], [41].

The productivity of a biogas plant depends on different aspects, like the type of biomass [42], digestion [43], availability of biomass, impurities that may harm microorganisms [44], and lignin content [45]. Almost any organic material can be used for biomass production, for example, paper, grass, animal waste, domestic or manufacturing sewage, food waste,

agricultural products, etc. [46]. However, some substrates can be problematic with their various applications; for example, the use of agricultural crops to produce biogas represents an increase in competition for land use to make animal or human food [47]. Unlike the competition for land use in the agricultural crop sector, manure needs to be treated to avoid GHG emissions in the air. Studies indicate that the addition of manure is necessary to ensure a sufficient level of micronutrients for the digestion process [47].

Biomass pre-treatment is essential to evaluate and purify it to a state where the fermentation process is not disturbed. The inorganic additions and biomass, which contain too much lignin and are inappropriate, are removed [48]. In addition, in anaerobic digestion, it is essential to use co-digestion, which increases the productivity of produced biogas from 25 to 400 % over mono-digestion [49],[50]. To conclude, manure is the most suitable material for the biogas production [32], but it has a meagre carbon ratio. It is essential to mix it with other substrates; for example, in Latvian conditions, the best solution would be manure and straws combined [51]. It is important to note that fields with untreated manure may only be treated after at least eight months of holding because, during that period, pathogenic microorganisms die [52]. It is one more reason why it is so essential to develop biogas production and reduce not only emissions but also reduce environmental pollution risks – it is one of the most critical co-benefits of the carbon farming [53].

2.3. Biomethane

Decarbonization and gasification of the transport sector is currently the most topical topic for the Latvian policymakers because Latvia, along with the other EU Member States, must ensure that the share of renewable energy in the final energy consumption in 2030 reaches 14 % (the target for this in 2020 is a 10 % share). Still, only 4.7 % were achieved in 2018 [54]. Renewable energy production will increase with a particular focus on solar panels, collectors, and wind energy. However, it will not be technologically possible due to storage issues [55]. Given that around 6 million tons of agricultural waste are produced yearly. The pathways and strategic priorities for the transition to a net-zero GHG emission economy provide a promising future for the development of biogas production, especially for upgraded biogas to biomethane, which is flexible both in use and storage and because its production from agricultural, industrial waste and sewage sludge protects soil, air, and water from the pollution [56], [57]. Suppose the annual biomethane production from anaerobic digestion in the European Union was 2.3 billion m^3. In that case, it is estimated that it could reach 64.2 billion m^3 by 2050 in the case of an optimized gas scenario [32].

The biogas sector is already well developed, and huge investments have been made. Still, the industry is currently highly financially dependent on state aid, and biomethane (product with higher added value) production seems to be a way to reach financial independence and profitability [32].

Biogas can be processed to biomethane and used as a road fuel or for sale on the natural gas network. Unlike natural gas, which is a fossil fuel, biomethane is a renewable fuel, which is emission neutral or even negative [58]. There are different methods for biogas upgrades, but the main aim is to separate methane from carbon dioxide to be used for heating, electricity, and fuel [59].

Since the raw gas contains approximately 65 % methane and 35 % carbon dioxide in the volume, the acquisition of biomethane is measurable on average at 63 % [60]. Therefore, it is possible to produce hydrogen from the carbon dioxide separated from biogas and used it as a transportation fuel and electricity [61], [62]. The practical efficiency of carbon dioxide conversion is 47.7 % with a hybrid Na-CO_2 cell [62].

According to the Central Statistical Bureau, 11 million m^3 of biogas was produced in 2018. If all this biogas were used for methane production, 6.93 million m^3 of biomethane would be made with 63 % efficiency. In contrast, an additional methane yield would be produced during the hydrogen methanation process from the rest of the biogas, which contains 35 % carbon dioxide. Biological hydrogen methanation could increase the biomethane yield and lower the costs for biogas upgrading to natural gas quality [63]. The efficiency of the process in a cogeneration plant right after the methanation is 30–45 % (37.5 % on average) [63], which means that if 4.07 million m^3 carbon dioxide is produced, then with biological hydrogen methanation digesters, it is possible to maintain 1.83 million m^3 of methane. Knowing that 1 litre of diesel equals 1 m^3 of biomethane, which is 10 kWh in the energy [64], the potential impact on the environment would be 1.83 million l of saved diesel fuel.

2.4. Capture by soils

Carbon sequestration comprises several techniques that aim to reduce CO_2 emissions and CO_2 concentration in the air [54]. Such methods are also called Direct Air Capture (DAC), Direct air carbon dioxide capture and storage (DACCS), and Carbon dioxide removal (CDR). Carbon sequestration by using these techniques is of vital importance. It has been reported in the AR6 IPCC [55] that without them, it is impossible to limit global warming to 1.5 °C in the Shared Socioeconomic Pathways (SSPs), where sustainable development and international cooperation are ground rocks.

Carbon sequestration by agricultural-related products and techniques is under the umbrella of biological CDR methods [55]. They aim to increase carbon storage on land by boosting primary productivity while reducing CO_2 in the atmosphere. Within CDR methods, some forest-based ones (such as afforestation and reforestation) are not risk-free [56] and are susceptible to droughts, fires, plagues, diseases, and others [57]. Therefore, the IPCC has placed a high confidence level in other alternatives for carbon sequestration, such as secondary forest regrowth, non-forest ecosystems restoration, and improved practices in agriculture and grasslands [58]–[61].

Furthermore, improving agricultural management practices can offset soil carbon losses by fixing a large share of the historically lost carbon back in the soil [62]. Some of the most effective enhanced agricultural methods to increase soil carbon content are the crop rotation cycles and the use of crop cover to avoid periods of bare soil [58], [63], [64], residue management and grazing optimization [65], [66], agroforestry, reducing grassland conversion, recycling of crop's nutrients and the use of irrigation [67]–[69]. These methods can also improve soil fertility and minimize nitrogen emissions unless an increase in fertilizers is employed [67], [70].

Still, many other methods can be classified as carbon sequestration but are not necessarily linked to agricultural practices. These can include using biochar to improve soil quality and crop yield [71], [72] and enhance the water holding capacity. Peatland restoration is another technique for increasing the land area of CO_2 sinks. However, it increases methane emissions from the created anoxic conditions [73]–[75]. Finally, bioenergy with carbon capture and storage (BECCS) is a technique counting on the carbon neutrality of energy production. It relies on the idea of bioenergy production, where the amount of CO_2 emitted during the combustion is as much as the carbon fixed in the growing biomass used as feedstock [76], [77]. BECCS claims more importance if such emissions are also captured and stored, creating a net negative emission effect in the atmosphere [78].

Overall, there are many CDR methods for carbon sequestration, with a broad spectrum of effects on the soil and water quality that might affect crop yield and biodiversity.

Nevertheless, many of these methods have proven to bring further benefits to natural ecosystems while promoting harmful emissions.

2.5. Perennial plants

Perennial plants make most of the planet's plant species, yet those grain crops for human consumption are not. Annual plants die each year and must be replanted, shortening the carbon cycle time in those areas where they are grown. However, there exist options to grow grain from perennial crops, as is the case for some oilseeds and cereals able to grow in deserts shrubs or seawater [79].

The main advantage that perennial crops bring over annuals is their capacity to distribute more resources underground than in the seeds [80], making these plants a perfect candidate for soil carbon sequestration. Moreover, some perennials can also grow sizeable underground, providing additional ecosystem services such as erosion reduction and a decrease in water and nutrient losses [80]. Thus, a shift to perennial grain crops has been encouraged in the last two decades as part of sustainable agriculture practices [81], [82].

But perennial crops for grains are not the only alternative for carbon sequestration in agriculture. Perennial grasses can also be used in multifunctional agriculture. Those additional non-conventional products can provide ecosystem functionalities and renewable energy production and promote sustainable development in rural areas [83]. The main setback of these crops is the early stage of domestication and development, which means an unexploited potential for carbon sequestration.

Also, perennial grasses can be used to enrich the soil by the conversion of croplands to permanent pastures, which inevitably results in higher carbon fixation in the grounds. Additionally, perennial grasses can reduce soil organic carbon via erosion cover if compared to annual grasses [84]. Also, perennial grasses and crops are more resistant to unfavourable climate conditions thanks to more robust storage structures like roots and rhizomes, making them an excellent alternative to improve agriculture resilience and food security [84], [85].

In conclusion, perennials are a promising alternative to boost carbon sequestration and agriculture multifunctionality while delivering additional ecosystem services.

2.6. Agroforestry

Agroforestry is a practice where perennial tree and shrub planting is combined with crops and/or animals in the same unit of land [65]. Although the term 'agroforestry' is relatively new, the practice is ancient and should return to farmers' daily practices today [66].

It is one of the ways to ensure the self-sufficiency of agriculture by reducing the consumption of fossil resources and increasing the extraction of various products. As globally agroforestry is practiced mainly by smallholder farms [67], it could be a solution in Latvia's case because 26 % of agricultural lands are owned by smallholder farms [22] that might not be able to invest in new technologies. In contrast, it would be possible to enhance income generation and security with an agroforestry system.

It is considered a dynamic and ecologically based system that diversifies production and increases social, economic, and environmental benefits [66]. It has been proved to reduce soil erosion and improve soil condition, increase resilience to weather changes [69], and increase biodiversity and carbon capture by trees and soils [68]. When tree species are deliberately planted, such a system can not only provide many benefits for crop cultivation but also improve agriculture productivity by providing additional products, like fruits, berries, and nuts, also fuelwood, which allows reducing dependency on local forests and if livestock is involved in the system, it provides fodder [69]. In livestock agroforestry systems, trees can

serve as a shelter from winds and heat, which is especially important for dairy cattle to increase milk yields; also, depending on the tree species, it can provide additional feed full of minerals and protein [70].

But as agroforestry leads to a generation of an ample amount of agroforestry waste, biorefinery must be considered for effective management of residues in products with higher added value as biofuels, fertilizers, and biochar and industrial chemicals [71].

3. METHODOLOGY

To achieve the goal of this research – identify carbon farming solutions for Latvian conditions and determine their importance in reducing GHG emissions, multi-criteria analysis method TOPSIS was used. The TOPSIS method is one of the methods that allows determining the exact value of criteria to compare different units with great success. As mentioned above, this paper compares 6 carbon farming options and 5 different parameters were considered – 1 for economic feasibility, 2 for environmental friendliness and 2 for technological aspects – opportunities for the amplitude of methods implementation in real life, and they were weighted equally. To evaluate, which parameter is the most important in the selection of raw materials, industry experts voted and determined the percentage of each parameter. The TOPSIS method is based on 7 main steps:

- Demonstrate a performance matrix,
- Normalize the decision matrix,
- Calculate the weighted normalized decision matrix,
- Determine the positive ideal and negative ideal solutions,
- Calculate the separation measures,
- Calculate the relative closeness to the ideal solution,
- Rank the preference order [72].

The TOPSIS method used in this work to make a decision was 'The classical TOPSIS method for a single decision maker' [73]. During the first step of the research, data collection and analysis, including systemic review of scientific literature were obtained. During the second step, technical, economic and environmental data were used for multicriteria decision making process. Then values of indicators were set and after the normalization and weighting of indicators, rating and evaluation of carbon farming practices in Latvia was conducted. The methodological algorithm of the research is shown in Fig. 3 [74].

The methodological algorithm was applied on case study of Latvia, but it can be used for a variety of studies that need to find the best solution, depending on these criteria [74].

As one of the criteria for the TOPSIS analysis, the area allocated for this process already in Latvia without making any improvements or expansions was accepted. Also, the potential area is determined in order to find out the possible potential of the carbon farming methods not only in existing territories for these processes, but in the future, expanding the management of wider territories with sustainable practices. Since agricultural data in Latvia is relatively rarely updated, the used areas of 2016, indicated in the statistical databases, were accepted. Since the data on the extent of capture by soils application in the territory in Latvia is not known, the area allocated for it is currently accepted as the entire area used for farming, since the scope of application of this practice is very wide, but it has a huge potential for improvement at the same time. The areas required to produce biogas and biomethane were calculated if biogas was 100 % produced from the manure of agricultural animals currently present in Latvia, considering the area needed for pastures, as well as the area needed to produce the necessary food for these animals. Expansion of biogas and biomethane areas is not accepted because biogas and biomethane are products produced from a waste product and

not as a primary product, therefore the development of this method will not be a determining factor to increase the number of farm animals in enterprises. In order to roughly determine the currently used area for biogas/biomethane production, the amount of energy produced in 2016 from biogas obtained in Latvia was determined [80] and taking into account how much yield can be obtained from 1 ton of the respective type of manure [51], it was calculated that only 16.2 % of the manure resource available in Latvia is used. Accordingly, the currently theoretically used territory has been equated to the amount of biogas production. The potential expansion site for such practices as agroforestry and perennial plants is assumed to be the unmanaged Latvian scrubland.

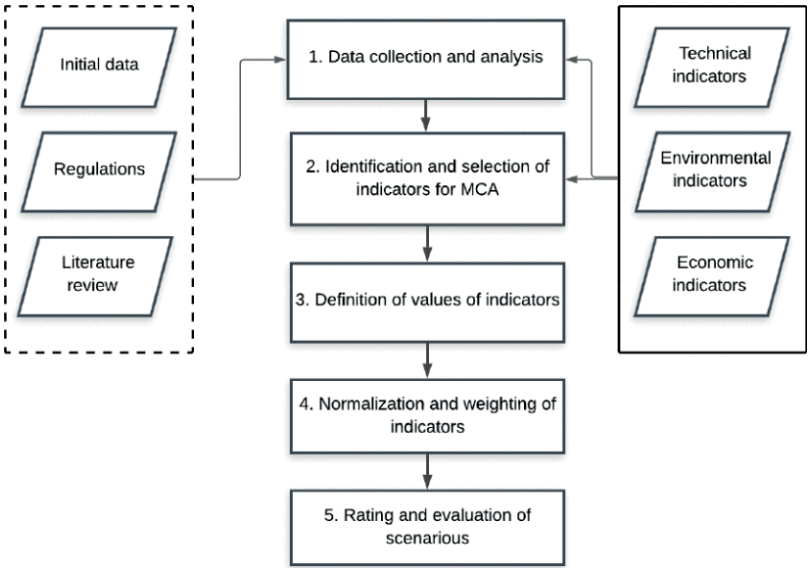


Fig. 3. Concept of the methodology [74].

One of the most important criteria for the development of these methods is the ability to attract the budget, because in practice, the introduction of new methods very often leads to financial losses for the farmer in the first years of transition, which is a possible determining factor why farmers choose to work with the previous methods, fearing to accept the risk. Therefore, to determine the available budget, the information was taken from Latvian Common Agriculture Policy (CAP) Strategic Plan 2023–2027 and information of Cohesion funds for Biomethane development.

As another important criterion, the amount of GHG emission sequestration in kilotons within one year of each method in the currently allocated areas was adopted. Since there is no exact data on how much emission occurs in these processes/sectors, the calculations were made based on assumptions from scientific publications. By improving and obtaining more accurate data on the agricultural sector of Latvia, this calculation should be improved by replacing assumption calculations with real data.

TABLE 1. VALUES FOR TOPSIS INDICATORS

Carbon Farming method	**Area, year 2020, ha**	**Potential area, ha**	**Budget, EUR**	**GHG emission sequestration in the existing areas allocated for this measure, $ktCO_2eq$/year**	**Potential GHG emission sequestration, $ktCO_2eq$/year**
Zero tillage	12 818 [75]	370 000	5 550 000 [76]	8.2	595.0
Minimal tillage	68 388 [75]	370 000	5 550 000 [76]	27.9	377.3
Biogas	180 216.1	1 112 445	0	61.6	380.1
Capture by soils	2 285 477 [77]	2 285 477	16 688 447.8 [76]	119.2	119.2
Perennial plants	28 827 [77]	103 829	15 520 000 [76]	103.8	373.8
Biomethane	180 216.1	1 112 445	61 000 000 [78], [79]	61.6	380.1
Agroforestry	0	103 829 [77]	4 055 000 [76]	0	37.4

Since zero tillage predicts a 41 % emission reduction, while minimal tillage 26 % compared to conventional [28], data from conventional maize cultivation were used to calculate the estimated annual CO_2eq reduction [81]. The current potential of biogas and biomethane is calculated by considering IPCC Default GHG emission factors and average N excretion per head of animal per year. However, it should be taken into account that the real emission reduction would be much higher, because this calculation takes into account only those emissions that are prevented by managing agricultural animal manure, while if the calculation were done differently – not according to the usable area, where the reduction of GHG emissions depends in the most direct way on the territory to be used, but on the possible consumption of biogas/biomethane in Latvia, if the use of natural gas and fossils were completely replaced by biogas and/or biomethane (according to the potential amount that can be obtained, it is possible to make sure that this is a realistically achievable goal in the case of Latvia). Using Central Statistical Bureau data, which indicates that in 2016, natural gas consumption was 1371 m^3 [82], and EPA calculator [83], it is calculated that in 2016, 29 397 tons of CO_2eq were generated due to the consumption of natural gas, which means that if biogas were used, emissions would not only be prevented by 100 %, but they would still be negative, as the use of biogas achieves a 240 % reduction in emissions compared to fossil resources [84] and 64 % compared to the natural gas in energy [85], while for biomethane 202 % to fossil fuel use in transport [84].

Accepting the application of willow biochar in the entire area of agricultural arable land in the current territories, as well as knowing that Willow biochar could compensate 7.7 % of annual agricultural greenhouse gas emissions [86], however, in 2018, soil cultivation in Latvia generated 1547.4 kt CO_2eq emissions [87], which was the largest sub-sector of GHG emissions in the agricultural sector in terms of emissions. It can be seen that the possibilities of sequestration could be as much as 119 kt CO_2eq per year, but it should be noted that this calculation is idealized without in-depth research on those areas where such application of willow biochar would not be desirable. However, taking into account the wide range of capture by soil methods, we accept it as an example calculation for all agricultural lands,

which would be possible to achieve in the entire territory. Perennial plants can sequester about 3.6 tCO_2/ha/y [88] and knowing the currently used territory, the positive impact of the perennial plant on the environment can be calculated.

By calculating how much it would be possible to potentially sequester GHG emissions using all the resources available for the specific method, it is possible to see how big the opportunities for reducing emissions are provided by the implementation of positive agricultural practices. In this calculation, only those emissions that can be prevented as a result of manure management are taken into account in the biogas and biomethane potential. It does not include the emission reductions that would result from using digestate as fertilizer, so it should be noted that the true benefit would be much higher.

4. RESULTS

During the analysis of the literature, six possible carbon farming methods were selected, which could be applied to Latvian conditions and would be in accordance with Latvia's National Energy and Climate Plan. The choice was based on the European Commission Report about Sustainable Carbon Cycles and Latvia's Common Agriculture Politics (CAP) Strategic Plan. These methods can also be used in other countries with different levels of agricultural development.

In this article zero and minimal tillage was mentioned as one of the solutions, as it would mainly work as a method to reduce emissions due to significantly reduced diesel consumption and mineral fertilizers. Carbon sequestration with soils was considered and perennial plant cultivation in order not only to capture carbon but also store it. Whereas biogas production is already existing, but an effective method of preventing agricultural waste emissions and producing a valuable and safe fertilizer. However, biogas development into biomethane is essential to maximize added value and prevent also other sectors (such as transport) emissions. The agroforestry sector is suitable for smallholder farms to increase carbon sequestration and storing in both soils and trees, reduce resource consumption and thereby emissions, and increase income, however, it must be in line with the foundations of biorefineries and focus on the efficient use of resources to achieve environmental, economic, and social goals. These methods are theoretically proving to be sustainable farming methods, which could possibly be introduced with funding for carbon farming, to ensure not only environmentally sustainable management in the future, but also the economy, to reduce costs and maximize local agriculture sector competitiveness.

The TOPSIS analysis results confirm that by current area, budget, and environmental effectiveness, the biggest potential is for such Carbon Farming methods as capture by soils, biomethane, and perennial plants.

TABLE 2. FINAL RANK FOR CARBON FARMING METHOD POTENTIAL

Final Rank	Carbon Farming Method
1	Capture by soils
2	Biomethane
3	Perennial plants
4	Biogas
5	Zero tillage
6	Minimal tillage
7	Agroforestry

5. CONCLUSIONS

Although only six of all possible solutions were analysed, the obtained information proves that these methods have a high potential in moving towards sustainable and emission-neutral agriculture.

The TOPSIS analysis results confirm that by current area, budget, and environmental effectiveness, the biggest potential is for such Carbon Farming methods as capture by soils, biomethane, and perennial plants. As biomethane production is most directly related to biogas production, as well as zero tillage and minimal tillage to carbon capture by soils, it reaffirms that all these methods are interrelated and important for moving towards sustainable agriculture. Agroforestry in Latvian conditions got the lowest compliance in this rank, however, perennial plants received a relatively high ranking place.

Not only these carbon farming methods, but also calculations can be used in other countries with different levels of agricultural development. Since the calculations were made based on assumptions from scientific publications, it is recommended to reconstruct these estimates using accurate data if available.

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REFERENCES

[1] European Commission, Communication From The Commission To The European Parliament And The Council. Sustainable Carbon Cycles., Brussels, 2021.

[2] Dolge K., Blumberga D. Key Factors Influencing the Achievement of Climate Neutrality Targets in the Manufacturing Industry: LMDI Decomposition Analysis. *Energies* 2021:14(23):8006. https://doi.org/10.3390/EN14238006

[3] Kuramochi T., Ramírez A., Turkenburg W., Faaij A. Effect of CO_2 capture on the emissions of air pollutants from industrial processes. *Int. J. Greenh. Gas Control* 2012:10:310–328. https://doi.org/10.1016/j.ijggc.2012.05.022

[4] Gardarsdottir S. O., Normann F., Andersson K., Johnsson F. Process evaluation of CO_2 capture in three industrial case studies. *Energy Procedia* 2014:63:6565–6575. https://doi.org/10.1016/j.egypro.2014.11.693

[5] Kim J., Yu S., Yun S. T., Kim K. H., Shinn Y. J., Chae G. CO_2 leakage detection in the near-surface above natural CO_2-rich water aquifer using soil gas monitoring. *Int. J. Greenh. Gas Control* 2019:88:261–271. https://doi.org/10.1016/j.ijggc.2019.06.015

[6] Cheng J., Dong H., Zhang H., Yuan L., Li H., Yue L., Hua J., Zhou J. Improving CH_4 production and energy conversion from CO_2 and H_2 feedstock gases with mixed methanogenic community over Fe nanoparticles. *Bioresour. Technol.* 2020:314:123799. https://doi.org/10.1016/j.biortech.2020.123799

[7] Yang Z. Z., He L. N., Gao J., Liu A. H., Yu B. Carbon dioxide utilization with C-N bond formation: Carbon dioxide capture and subsequent conversion. *Energy Environ. Sci.* 2012:5:6602–6639. https://doi.org/10.1039/c2ee02774g

[8] Murcia Valderrama M. A., van Putten R. J., Gruter G. J. M. The potential of oxalic – and glycolic acid based polyesters (review). Towards CO_2 as a feedstock (Carbon Capture and Utilization – CCU). *Eur. Polym. J.* 2019: 119:445–468. https://doi.org/10.1016/j.eurpolymj.2019.07.036

[9] Muthuraj R., Mekonnen T. Recent progress in carbon dioxide (CO_2) as feedstock for sustainable materials development: Co-polymers and polymer blends. *Polymer* 2018:145:348–373. https://doi.org/10.1016/j.polymer.2018.04.078

[10] Bai H., Cheng T., Li S., Zhou Z., Yang H., Li J., Xie M., Ye J., Ji Y., Li Y., Zhou Z., Sun S., Zhang B., Peng H. Controllable CO adsorption determines ethylene and methane productions from CO_2 electroreduction. *Sci. Bull.* 2020:66(1):62–68. https://doi.org/10.1016/j.scib.2020.06.023

[11] Universities team up with plan to develop low-carbon aviation fuel from recycled CO_2 and bio-waste. *Renew. Energy Focus* 2016:17(2):50–55. https://doi.org/10.1016/j.ref.2016.02.008

[12] Adhikari B. M., Truong T., Prakash S., Bansal N., Bhandari B. Impact of incorporation of CO_2 on the melting, texture and sensory attributes of soft-serve ice cream. *Int. Dairy J.* 2020:109:104789. https://doi.org/10.1016/j.idairyj.2020.104789

[13] Di Caprio M. R., Brondi C., Di Maio E., Mosciatti T., Cavalca S., Parenti V., Iannace S., Mensitieri G., Musto P. Polyurethane synthesis under high-pressure CO_2, a FT-NIR study. *Eur. Polym. J.* 2019:115:364–374. https://doi.org/10.1016/j.eurpolymj.2019.03.047

[14] Shijian L., Dongya Z., Quanmin Z. CO_2 absorber coupled with double pump CO_2 capture technology for coal-fired flue gas. *Energy Procedia* 2018:154:163–170. https://doi.org/10.1016/j.egypro.2018.11.027

[15] European Comission, Technical Guidance Handbook: Setting up and implementing results-based carbon farming mechanisms in the EU (2021), Brussel, 2021.

[16] Gancone A., Pubule J., Blumberga D. Valorization methodology for agriculture sector climate change mitigation measures. *Environ. Clim. Technol.* 2021:25(1):944–954. https://doi.org/10.2478/rtuect-2021-0071

[17] European Comission. The European Green Deal.

[18] Sujatha M. P., Lathika C., Smitha J. K. Sustainable and efficient utilization of weed biomass for carbon farming and productivity enhancement: A simple, rapid and ecofriendly approach in the context of climate change scenario, *Environ. Challenges.* 2021:4:100150. https://doi.org/10.1016/J.ENVC.2021.100150

[19] Van Eck N. J., Waltman L. VOSviewer Manual version 1.6.10, CWTS Meaningful Metrics. 2019.

[20] LVĢMC. 2020. gadā iesniegtās siltumnīcefekta gāzu inventarizācijas kopsavilkums. (Summary of the greenhouse gas inventory submitted in 2020). ([Online]. [Accessed: 18 January 2021]. Available: https://www.meteo.lv/fs/CKFinderJava/userfiles/files/Vide/Klimats/Majas_lapai_LVGMC_2020_seginvkopsavilkums.pdf (In Latvian).

[21] IPCC, IPCC – Task Force on National Greenhouse Gas Inventories, 2. 2006. [Online]. [Accessed: 20 April 2020]. Available: https://www.ipcc-nggip.iges.or.jp/public/2006gl/

[22] CSP. Latvia's energy balance in 2017. (Latvijas energobilance 2017. gadā). 2018. [Online]. [Accessed: 20 April 2020]. Available: www.csb.gov.lv (In Latvian).

[23] Allen J. John Deere develops fully electric, autonomous tractor | Industrial Vehicle Technology International. [Online]. [Accessed: 20 April 2020]. Available: https://www.ivtinternational.com/news/agriculture/john-deere-develops-fully-electric-autonomous-tractor.html

[24] Blanco-Canqui H. Crop Residue Removal for Bioenergy Reduces Soil Carbon Pools: How Can We Offset Carbon Losses? *Bioenergy Res.* 2013:6:358–371. https://doi.org/10.1007/s12155-012-9221-3

[25] Šarauskis E., Buragiene S., Masilionyte L., Romaneckas K., Avižienyte D., Sakalauskas A. Energy balance, costs and CO_2 analysis of tillage technologies in maize cultivation. *Energy* 2014:69:227–235. https://doi.org/10.1016/j.energy.2014.02.090

[26] Hoffman E., Cavigelli M. A., Camargo G., Ryan M., Ackroyd V. J., Richard T. L., Mirsky S. Energy use and greenhouse gas emissions in organic and conventional grain crop production: Accounting for nutrient inflows. *Agric. Syst.* 2018:162:89–96. https://doi.org/10.1016/j.agsy.2018.01.021

[27] Augšņu degradācijas procesu, augsni saudzējošu lauksaimniecības paņēmienu un ar augsni saistītu politikas pasākumu sasaiste (Linking soil degradation processes, soil-conserving agricultural practices and soil-related policies). [Online]. [Accessed: May 1, 2020]. Available: https://esdac.jrc.ec.europa.eu/projects/SOCO/FactSheets/LV Fact Sheet.pdf

[28] Sørensen C. G., Nielsen V. Operational analyses and model comparison of machinery systems for reduced tillage, *Biosyst. Eng.* 2005:92(2):143–155. https://doi.org/10.1016/j.biosystemseng.2005.06.014

[29] Saldukaitė L., Šarauskis E., Lekavičienė K., Savickas D. Predicting energy efficiency and greenhouse gases reduction potential under different tillage management and farm size scenarios for winter wheat production. *Sustain. Energy Technol. Assessments* 2020:42:42100841. https://doi.org/10.1016/j.seta.2020.100841

[30] Tabatabaeefar A., Emamzadeh H., Varnamkhasti M. G., Rahimizadeh R., Karimi M. Comparison of energy of tillage systems in wheat production. *Energy* 2009:34(1):41–45. https://doi.org/10.1016/j.energy.2008.09.023

[31] Miltiņš R. Swedbank Business Network. Jaunās tehnoloģijas lauksaimniecībā = domāšanas maiņa. (New technologies in agriculture = change in thinking). [Online]. [Accessed January 18, 2021]. Available: https://businessnetwork.lv/ievads/izaugsme/raimonds-miltins-lauksaimniecibas-tehnologijas-53066 (In Latvian).

[32] Bumbiere K., Pubule J., Blumberga D. What Will Be the Future of Biogas Sector? *Environ. Clim. Technol.* 2021:25(1):295–305. https://doi.org/10.2478/RTUECT-2021-0021

[33] Latvijas Vides, Ģeoloģijas un Meteoroloģijas Centrs. 2022. gada siltumnīcefekta gāzu inventarizācijas kopsavilkums. Versija: Iesniegts ANO Vispārējai konvencijai par klimata pārmaiņām. (Center of Environment, Geology and Meteorology of Latvia. 2022 Greenhouse Gas Inventory Summary. Version: Submitted to the UN Framework Convention on Climate Change). [Online]. [Accessed: 15.04.2022}. Available: https://videscentrs.lvgmc.lv/files/Klimats/SEG_emisiju_un_ETS_monitorings/Zinojums_par_klimatu/Iesniegto_SEG_prognozu_kopsavilkumi/Majas_lapai_LVGMC_2021_segprognozes.pdf

[34] Indzere Z., Kubule A., Zihare L., Vamza I., Blumberga D. Analysis of Bioeconomy Affeting Factors - Climate Change and Production. *Env. Clim. Technol.* 2021:25(1):1293–1304. https://doi.org/10.2478/rtuect-2021-0098

[35] Yong Z. J., Bashir M. J. K., Hassan M. S. Biogas and biofertilizer production from organic fraction municipal solid waste for sustainable circular economy and environmental protection in Malaysia. *Sci. Total Environ.* 2021:776:145961. https://doi.org/10.1016/j.scitotenv.2021.145961

[36] Timonen K., Sinkko T., Luostarinen S., Tampio E., Joensuu K. LCA of anaerobic digestion: Emission allocation for energy and digestate. *J. Clean. Prod.* 2019:235:1567–1579. https://doi.org/10.1016/j.jclepro.2019.06.085
[37] Gancone A., Bumbiere K., Pubule J., Blumberga D. Sustainable biogas application in energy sector. *IEEE.* 2020. 10.1109/RTUCON51174.2020.9316593
[38] Wilken D., Strippel F., Hofmann F., Maciejczyk M., Klinkmüller L., Wagner L., Bontempo G., Münch J., Scheidl S., Conton M., Deremince B., Walter R., Zetsche N., Findeisen C. Biogas to Biomethane, Unido. 2017. [Online]. [Accessed February 23, 2021]. Available: https://issuu.com/fachverband.biogas/docs/btb
[39] Blumberga D., Dzene I., Al Sedi T., Rucs D., Prasls H., Ketners M. Finstervalders T., Folka S. Biogas: Handbook. 2009. https://ortus.rtu.lv/science/en/publications/5847
[40] Brémond U., Bertrandias A., Steyer J. P., Bernet N., Carrere H. A vision of European biogas sector development towards 2030: Trends and challenges. *J. Clean. Prod.* 2021:287. https://doi.org/10.1016/j.jclepro.2020.125065
[41] Latvijas Biogāzes asociācija. (Latvian association of biogas). [Online]. [Accessed February 23, 2021]. Available: http://www.latvijasbiogaze.lv/ (In Latvian).
[42] Meyer A. K. P., Ehimen E. A., Holm-Nielsen J. B. Future European biogas: Animal manure, straw and grass potentials for a sustainable European biogas production. *Biomass and Bioenergy* 2018:111:154–164. https://doi.org/10.1016/j.biombioe.2017.05.013
[43] Kaldis F., Cysneiros D., Day J., Karatzas KAG., Chatzifragkou A. Anaerobic Digestion of Steam-Exploded Wheat Straw and Co-Digestion Strategies for Enhanced Biogas Production. *App. Sc. Basel.* 2020:10:22.
[44] Muizniece I., Zihare L., Pubule J., Blumberga D. Circular Economy and Bioeconomy Interaction Development as Future for Rural Regions. Case Study of Aizkraukle Region in Latvia. *Environ. Clim. Technol.* 2019:23(3):129–146. https://doi.org/10.2478/rtuect-2019-0084
[45] Lauka D., Slisane D., Ievina L., Muizniece I., Blumberga D. When Bioeconomy Development Becomes a Biomass Energy Competitor. *Environ. Clim. Technol.* 2019:23(3):347–359. https://doi.org/10.2478/rtuect-2019-0100
[46] Zihare L., Spalvins K., Blumberga D. Multi criteria analysis for products derived from agro-industrial by-products. *Energy Procedia* 2018:147:452–457. https://doi.org/10.1016/j.egypro.2018.07.045
[47] Esteves E. M. M., Herrera A. M. N., Esteves V. P. P., Do R. V. Morgado C. Life cycle assessment of manure biogas production: A review. *Journal of Cleaner Production* 2019:219:411–423. https://doi.org/10.1016/j.jclepro.2019.02.091
[48] EMEP. EEA. Atskaites ziņojums un tehniski ekonomiskais pamatojums 'Biogāzes attīstības iespējas Madonas rajonā'. (Reference report and technical-economic justification 'Biogas development opportunities in Madona district') 2019. (In Latvian).
[49] Cavinato C., Fatone F., Bolzonella D., Pavan P. Thermophilic anaerobic co-digestion of cattle manure with agro-wastes and energy crops: Comparison of pilot and full scale experiences. *Bioresour. Technol* 2010:101(2):545–550. https://doi.org/10.1016/j.biortech.2009.08.043
[50] Shah F. A., Mahmood Q., Rashid N., Pervez A., Raja I. A., Shah M. M. Co-digestion, pretreatment and digester design for enhanced methanogenesis. *Renew. Sustain. Energy Rev.* 2015:42:627–642. https://doi.org/10.1016/j.rser.2014.10.053
[51] Bumbiere K., Gancone A., Pubule J., Kirsanovs V., Vasarevicius S., Blumberga D. Ranking of Bioresources for Biogas Production. *Environ. Clim. Technol.* 2020:24(1):368–377. https://doi.org/10.2478/RTUECT-2020-0021
[52] Biogāzes enerģija. LAEF. (Biogas energy). [Online]. [Accessed: January 3, 2020]. Available: https://www.laef.lv/lv/biogaze/
[53] Baumber A., Metternicht G., Cross R., Ruoso L. E., Cowie A. L., Waters C. Promoting co-benefits of carbon farming in Oceania: Applying and adapting approaches and metrics from existing market-based schemes. *Ecosyst. Serv.* 2019:39:100982. https://doi.org/10.1016/J.ECOSER.2019.100982
[54] EC courtesy translation LV NECP NATIONAL ENERGY AND CLIMATE PLAN OF LATVIA 2021–2030, n.d.
[55] Decarbonisation Pathways – Eurelectric – Powering People. [Online]. [Accessed: March 4, 2021]. Available: https://www.eurelectric.org/decarbonisation-pathways/
[56] Scarlat N., Dallemand J. F., Fahl F. Biogas: Developments and perspectives in Europe. *Renew. Energy* 2018:129:457–472. https://doi.org/10.1016/j.renene.2018.03.006
[57] Yu Q., Liu R., Li K., Ma R. A review of crop straw pretreatment methods for biogas production by anaerobic digestion in China. *Renewable and Sustainable Energy Reviews* 2019:107:51–58. https://doi.org/10.1016/j.rser.2019.02.020
[58] Fernández-González J. M., Martín-Pascual J., Zamorano M. Biomethane injection into natural gas network vs composting and biogas production for electricity in Spain: An analysis of key decision factors. *Sustain. Cities Soc.* 2020:60:102242. https://doi.org/10.1016/j.scs.2020.102242
[59] Hosseinipour S. A., Mehrpooya M. Comparison of the biogas upgrading methods as a transportation fuel. *Renew. Energy* 2019:130:641–655. https://doi.org/10.1016/j.renene.2018.06.089
[60] Li H., Mehmood D., Thorin E., Yu Z. Biomethane Production Via Anaerobic Digestion and Biomass Gasification. *Energy Procedia* 2017:105:1172–1177. https://doi.org/10.1016/j.egypro.2017.03.490

[61] Khan I. Waste to biogas through anaerobic digestion: Hydrogen production potential in the developing world - A case of Bangladesh. *Int. J. Hydrogen Energy* 2020:45(32):15951–15962. https://doi.org/10.1016/j.ijhydene.2020.04.038

[62] Kim C., Kim J., Joo S., Bu Y., Liu M., Cho J., Kim G. Efficient CO_2 Utilization via a Hybrid Na-CO_2 System Based on CO_2 Dissolution. *IScience* 2018:9:278–285. https://doi.org/10.1016/j.isci.2018.10.027

[63] Lecker B., Illi L., Lemmer A., Oechsner H. Biological hydrogen methanation – A review. *Bioresour. Technol.* 2017:245:1220–1228. https://doi.org/10.1016/j.biortech.2017.08.176

[64] Liquid Hydrogen Outline. [Online]. [Accessed: August 27, 2020]. Available: https://www.idealhy.eu/index.php?page=lh2_outline

[65] Encyclopedia of Soils in the Environment. ScienceDirect. [Online]. [Accessed: April 13, 2022]. Available: https://www-sciencedirect-com.resursi.rtu.lv/referencework/9780123485304/encyclopedia-of-soils-in-the-environment

[66] Buschmann A. H., Chopin T., Neori A., Halling C., Troell M., Hernández-González M. C., Aranda C. Ecological engineering in aquaculture: towards a better waste management in Western World mariculture. *Encycl. Ecol.* 2008:2463–2475. https://doi.org/10.1016/B978-008045405-4.00065-3

[67] Jamnadass R., Langford K., Anjarwalla P., Mithöfer D. Public–Private Partnerships in Agroforestry. *Encycl. Agric. Food Syst.* 2014:544–564. https://doi.org/10.1016/B978-0-444-52512-3.00026-7

[68] Eddy W. C., Yang W. H. Improvements in soil health and soil carbon sequestration by an agroforestry for food production system. *Agric. Ecosyst. Environ.* 2022:333:107945. https://doi.org/10.1016/J.AGEE.2022.107945

[69] Sivanpillai R., Shroder J. F. Biological and Environmental Hazards, Risks, and Disasters. *Biol. Environ. Hazards, Risks, Disasters.* Elsevier 2015:1–466. https://doi.org/10.1016/C2011-0-07027-8

[70] Agricology. Agroforestry for livestock systems. [Online]. [Accessed: April 13, 2022]. Available: https://www.agricology.co.uk/resources/agroforestry-livestock-systems

[71] Gupta J., Kumari M., Mishra A., Swati, M. Akram, I. S. Thakur. Agro-forestry waste management. A review. *Chemosphere* 2022:287:132321. https://doi.org/10.1016/J.CHEMOSPHERE.2021.132321

[72] TOPSIS method algorithm. Download Scientific Diagram. [Online]. [Accessed: February 29, 2020]. Available: https://www.researchgate.net/figure/TOPSIS-method-algorithm_fig4_253953426

[73] Roszkowska E. Multi-criteria decision making models by applying the topsis method to crisp and interval data. 2011. [Online]. [Accessed: July 20, 2022]. Available: https://mcdm.ue.katowice.pl/files/papers/mcdm11(6)_11.pdf

[74] Gancone A., Bumbiere K., Pubule J., Blumberga D. Sustainable biogas application in energy sector. 2020 IEEE 61st Annu. Int. Sci. Conf. Power Electr. Eng. Riga Tech. Univ. RTUCON 2020. https://doi.org/10.1109/RTUCON51174.2020.9316593

[75] Pielietotās augsnes apstrādes metodes dažāda ekonomiskā lieluma lauku saimniecībās. (Applied methods of soil treatment in farms of different economic sizes). [Online]. [accessed: July 20, 2022]. Available: https://data.stat.gov.lv/pxweb/lv/OSP_OD/OSP_OD__skait_apsek__metodes__laukstrukt_13/LSSA13_VI01.px/table/tableViewLayout1/ (In Latvian).

[76] KLPSP_projekts_20220118_SFC2021. (Project of Latvian KLPSP strategic plan for 2023–2027). In Latvian.

[77] Valsts zemes dienests. Zemes sadalījums zemes lietošanas veidos. (State Land Service. Distribution of land in land use types). [Online]. [Accessed: July 20, 2022]. Available: https://www.vzd.gov.lv/lv/zemes-sadalijums-zemes-lietosanas-veidos (In Latvian).

[78] Latvijā plāno atbalstīt vien no atkritumiem ražotu biogāzi, rosinot ražotājus kļūt par sanitāriem. (Latvia plans to support biogas produced only from waste, encouraging producers to become sanitary). [Online]. [Accessed: September 14, 2022]. https://www.la.lv/biogazes-razotajus-rosinas-klut-par-sanitariem (In Latvian).

[79] Zaļais izrāviens vai jauns OIK? Latvija gatavojas biometāna ražošanai. (Green breakthrough or new OIK? Latvia is preparing for biomethane production). [Online]. [Accessed: September 14, 2022]. Available: https://www.lsm.lv/raksts/zinas/zinu-analize/zalais-izraviens-vai-jauns-oik-latvija-gatavojas-biometana-razosanai.a394764/ (In Latvian).

[80] Elektriskā jauda un saražotā elektroenerģija no atjaunīgiem energoresursiem – Atjaunīgo energoresursu elektrostaciju veids un Laika periods. (Electric power and produced electricity from renewable energy resources – Type of renewable energy power plants and Time period). [Online]. [Accessed September 14, 2022]. Available: https://data.stat.gov.lv/pxweb/lv/OSP_PUB/START__NOZ__EN__ENA/ENA040/table/tableViewLayout1/ (In Latvian).

[81] Bumbiere K., Gancone A., Pubule J., Blumberga D. Carbon balance of biogas production from maize in latvian conditions. *Agron. Res.* 2021:19(1):687–697. https://doi.org/10.15159/AR.21.085

[82] Dabasgāzes imports un patēriņš (milj. m^3) – Rādītāji un Laika periods. (Natural gas import and consumption (million m^3) – Indicators and Time period). [Online]. [Accessed September 11, 2022]. Available: https://data.stat.gov.lv/pxweb/lv/OSP_PUB/START__NOZ__EN__ENB/ENB020m/table/tableViewLayout1/ (In Latvian).

[83] US EPA. Greenhouse Gas Equivalencies Calculator. [Online]. [Accessed September 11, 2022]. https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator#results

[84] European Biogas Association. Avoided emissions from biogas and biomethane can lead to a negative carbon footprint. [Online]. [Accessed September 9, 2022]. Available: https://www.europeanbiogas.eu/avoided-emissions-from-biogas-and-biomethane-can-lead-to-a-negative-carbon-footprint/ (In Latvian).

[85] O'Shea R., Lin R., Wall D. M., Browne J. D., Murphy J. D. Using biogas to reduce natural gas consumption and greenhouse gas emissions at a large distillery. *Appl. Energy.* 2020:279:115812. https://doi.org/10.1016/J.APENERGY.2020.115812

[86] Leppäkoski L., Marttila M. P., Uusitalo V., Levänen J., Halonen V., Mikkilä M. H. Assessing the carbon footprint of biochar from willow grown on marginal lands in Finland. *Sustain.* 2021:13(18):10097. https://doi.org/10.3390/su131810097

[87] 2020. gadā iesniegtās siltumnīcefekta gāzu inventarizācijas kopsavilkums. (Summary of the greenhouse gas inventory submitted in 2020). [Online]. [Accessed: September 13, 2022]. Available: https://www.meteo.lv/fs/CKFinderJava/userfiles/files/Vide/Klimats/Majas_lapai_LVGMC_2020_seginvkopsavilkums.pdf (In Latvian).

[88] Paustian K., Larson E., Kent J., Marx E., Swan A. Soil C Sequestration as a Biological Negative Emission Strategy. *Front. Clim.* 2019. https://doi.org/10.3389/fclim.2019.00008