Advanced biomethane production from intermediate and cover crops

ANALYTICAL NOTE No 1

Georgii Geletukha
Tetiana Zheliezna
Semen Drahniev
Petro Kucheruk
Volodymyr Kramar

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Abbreviations

AD
anaerobic digestion

AN
analytical note

CCP
catch crops and cover crops

DAM
day-ahead market

DOM
dry organic matter

EBA
European Biogas Association

GHG
greenhouse gases

JRC
Joint Research Centre

PAR
photosynthetically active radiation

PPPs
plant protection products

RED
Renewable Energy Directive

SAF
sustainable aviation fuel

SOC
soil organic carbon

UABIO
the Bioenergy Association of Ukraine

UAH
Ukrainian hryvna

USDA
U.S. Department of Agriculture

VAT
value-added tax

VS
volatile solids

BDR™
Biogasdoneright™

bcm
billion cubic metres

d.m., DM
dry matter

Mha
million hectares

s.u.
sowing unit

th. ha
thousand hectares

Introduction

The Analytical Note is prepared within the framework of the project "Ukrainian Biomethane Sector Development" financed by the Energy Community.

The Analytical Note **aims** to reveal the potential for intermediate/cover crops growing, harvesting, logistics and pre-treatment to obtain raw materials for the production of advanced biomethane in Ukraine.

Bioenergy plays a significant role in the global energy supply. Traditional biomass[1] makes up currently 54% of total biomass consumption for energy. Taking this into account, bioenergy now provides **2/3** of all renewable energy in the world, and its contribution to the global final energy consumption is about **12%**[2]**.** The widespread use of ***modern*** bioenergy technologies will be crucial for the global energy transition towards net-zero carbon emissions. Under the 1.5°C scenario of the International Renewable Energy Agency (IRENA), energy production from biomass is expected to almost **triple** by 2050, reaching 153 EJ/year[3].

The main challenge in this increase will be to ensure **sustainability.** Potential risks to the sustainability of the biomass energy supply chain are related to land use, competition with food supplies, air pollution, impacts on water and soil quality, impacts on biodiversity and some other factors. Therefore, ensuring the sustainability of biomass energy production along the entire supply chain, starting from the sustainable biomass feedstock, is an important element of bioenergy policy-making. Grown in the time intervals free from the cultivation of main crops in a crop rotation, **intermediate/cover crops** represent a valuable supplementary source of sustainable biomass.

The EU is currently experiencing a boom in the development of the **biomethane** sector. Biomethane is biogas upgraded to the quality of natural gas; it can be fed into gas pipelines, transported, stored and used on a par with natural gas. In particular, the EU is planning to increase biomethane production from 3.5 billion m^3/y in 2021 to 35 billion m^3/y in 2030[4]. Priority support is given to the production of biomethane from waste and residues that do not compete with food and feed.

According to Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (recast)[5] **(RED III)**, the share of biofuels and biogas produced from the feedstock listed in Annex IX shall be considered to be **twice its energy content** regarding their contribution to the EU's target on consuming renewable energy in transport (Article 27). At that, intermediate crops, such as catch crops and cover crops which are used for biogas/biomethane production are included in **Part B of Annex IX** of RED III.

In Ukraine, so far, intermediate and cover crops have been grown for further use as green manure or for feed production. Expansion of the area under these crops and their integration into biomethane

1 The inefficient use of solid biomass, such as firewood, charcoal, crop residues and animal dung for cooking and heating, mostly in developing countries.

2 IRENA, 2022. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Aug/IRENA_Bioenergy_for_the_transition_2022.pdf?rev=875a997481f04168b17499f1e5dc1473

3 EJ means 1018 Joules.

4 REPowerEU Plan, 2022. https://eur-lex.europa.eu/resource.html?uri=cellar:fc930f14-d7ae-11ec-a95f-01aa75ed71a1.0001.02/DOC_1&format=PDF

5 Directive (EU) 2018/2001. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02018L2001-20240716

supply chains, with nutrients returned to the soil with digestate, presents a new perspective for sustainable bioenergy and agriculture. The usage of intermediate and cover crops for biomethane production emphasizes an innovative approach, which requires a thorough analysis of feasible opportunities and prerequisites for successful implementation within Ukraine's context.
The obtained biomethane can be consumed domestically as replacement of natural gas and fossil motor fuels, as well as exported.

Ukraine can potentially capture up to 20% of the European biomethane market, produce over **20** bcm of biomethane a year and attract up to 40 billion EUR of investment in this sector[6]. Biomethane from intermediate and cover crops, which is the subject of the Analytical Note, may contribute by about **46%** (**9.2** bcm/y) to this total amount. For the development of domestic biomethane production, it is important to create prerequisites for the rational use of existing and prospective resources of **sustainable** biomass feedstock.

6 UABIO, 2024. https://www.epravda.com.ua/columns/2024/01/5/708445/

Definitions and terms

SECTION 1

Ukrainian literature

Crops that occupy the field for most time of the growing season are called **main crops.** After harvesting many of them, one can grow other crops to obtain additional products on condition that there is enough moisture in the soil[7].

Intermediate crops are those that are grown in the time interval free from the cultivation of main crops in crop rotations. Due to such crops, it is possible to obtain two harvests from the same area during a year, while irrigated lands may give even three harvests. This raises the solar radiation utilization rate, as a result of which the productivity of a hectare of arable land increases by one and a half to two times. At the same time, the soil is much longer under the cover of plants that synthesize organic matter. More than half of it remains in the soil in the form of post-harvest and root residues, which activate microflora, decompose into easily accessible nutrients, improve agrophysical properties, restore soil fertility and increase crop yields.

When growing two crops, the field is occupied by plants from early spring to late autumn; when growing winter intermediate crops, the field is occupied by plants also in winter. The constant presence of the plant cover has a positive effect on the physical properties of the soil, the migration of salts in it and the microclimate of the surface layer.

According to the State Standard of Ukraine DSTU 4691:2006 "Agriculture. Terms and definitions of concepts", "an **intermediate crop** is an agricultural crop that is grown when the field is free from the main crop". Various agricultural crops can be grown as intermediate crops to obtain an additional harvest of grain, green mass, hay, and haylage. Also, their vegetative mass can be used as organic fertilizer[8].

Depending on the biological characteristics and cultivation technology, intermediate crops are divided into **post-hay harvest, post-harvest, winter, and under-sown** crops[7].

7 V.P. Gudz, I.D. Prymak, Y.V. Budionnyi, S.P. Tanchyk «Farming», 2010. https://textbook.com.ua/geografiya/1473445276 (chapter 3.2.13. Intermediate crops in crop rotations)

8 M.P. Kosolap, O.P. Krotinov. Farming system No-Till: tutorial. – K.: «Logos», 2011. – 352 p.

Post-hay harvest crops are those that are grown after crops are harvested for green fodder, silage or hay in the current year and use a smaller part of the possible vegetation period. **Post-harvest** crops are grown after the main crops are harvested in the current year. While the vegetation period of post-hay harvest crops is up to 140-150 days, it is much shorter for after-harvest crops (70-100 days), and conditions for providing moisture and heat are worse. In this regard, after-harvest crops must grow quickly, be undemanding to heat, light, and moisture, have a short vegetation period, be resistant to autumn frosts, and be suitable for use in different phases of growth.

Fig. 1.1. Growing a mix of post-harvest crops after maize in the USA (Photo by the authors of the AN).

Winter intermediate crops are sown in the year of harvesting the main crop, and harvested in the spring of the following year. Such winter crops are intermediate because they grow and develop in the intermediate summer-autumn and early spring periods and occupy an intermediate place between the two main crops of the crop rotation. The main green mass of intermediate crops is formed due to the moisture and warmth of the early spring period; in addition, many of the intermediate crops quickly increase their vegetative mass also in autumn.

Under-sown crops are those that are sown in the spring under the cover of grain and other crops and harvested in autumn of the same year (after harvesting main crops) or in the following spring. Under-sowing can be carried out under the shoots of spring and winter crops. Under-sown crops are valuable because, unlike other intermediate crops, they do not require separate tillage, since they are sown under the main winter or spring crops. The biological requirements of under-sown crops are best met by main crops that vacate the field early. These include fodder crops, which are grown to obtain early green fodder, as well as early winter and spring grain crops. At the same time, an under-sown crop at the beginning of its vegetation, that is during the period of growth under cover, should be shade-tolerant, grow slowly, and use little moisture and nutrients from the soil so as not to suppress the main crop.

The term **"intermediate crop"** is used in the agronomic literature of Ukraine, while the term **"cover crop"** is more common in the English-language literature[8]. The term "cover crop" is used in relation to crops that are grown primarily to create plant cover, regardless of whether the plant mass will be incorporated into the soil in the future as green manure or will remain on the soil surface in the form of plant residues. The practicability of using cover crops depends on a correctly defined main task that needs to be solved by growing cover crops, and on their selection justified for this purpose. Intermediate crops that are grown specifically for incorporation into the soil as fertilizer are called **green manure.**

RED III and other European legislation

EU legislation[9] states that if several crops are grown in succession on the same area during the same crop year, the **main crop** is the crop with **the highest** production value. If the production value does not determine this, the main crop is the crop that occupies the land **the longest.**

Commission Regulation (EU) 2021/2286 of 16 December 2021[10] defines the use of **cover crops or intermediate crops** as a soil conservation method. These crops are sown specifically to reduce the loss of soil, nutrients and plant protection products during the winter or other periods when the land would otherwise be bare and susceptible to losses. The economic interest of these crops is low, and the main goal is soil and nutrient protection. Normally they are ploughed in during spring before sowing another crop and are not harvested or used for grazing.

9 https://knowledge4policy.ec.europa.eu/glossary-item/main-crop_en#:~:text=Where%20during%20one%20harvest%20year,ground%20for%20the%20longest%20time.

10 COMMISSION REGULATION (EU) 2021/2286 of 16 December 2021 https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX-%3A32021R2286

In RED III[5], intermediate crops are in fact **excluded** from the food/feed ones (Article 2 "Definitions", point 40):

> *"food and feed crops" mean starch-rich crops, sugar crops or oil crops produced on agricultural land as the main crop **excluding** residues, waste or lignocellulosic material and **intermediate crops**, such as **catch crops and cover crops**, provided that the use of such intermediate crops does not trigger demand for additional land".*

Intermediate crops as biomass feedstock are included in Part A and Part B of Annex IX of RED III. The difference lies in the purpose of their use – for the production of biofuel for the ***aviation sector*** (Part A) or ***not*** for the aviation sector (Part B).

Part A of Annex IX contains feedstocks for the production of biogas for transport and **advanced** biofuels, in particular:

> *"(t) **intermediate crops**, such as catch crops and cover crops that are grown in areas where due to a short vegetation period the production of food and feed crops is limited to one harvest and provided their use does not trigger demand for additional land, and provided the soil organic matter content is maintained, where **used** for the production of **biofuel for the aviation sector**".*

Part B of Annex IX includes feedstocks for the production of biofuels and biogas for transport[11]:

> *(f) **Intermediate crops**, such as catch crops and cover crops, and excluding feedstocks listed in Part A of this Annex, that are grown in areas where due to a short vegetation period the production of food and feed crops is limited to one harvest and provided their use does not trigger demand for additional land and provided the soil organic matter content is maintained, where **not used** for the production of **biofuel for the aviation sector**.*

According to the International Sustainability and Carbon Certification system ISCC EU [12], which includes the requirements of the RED III, **intermediate crops** can be covered by ISCC certification if their cultivation meets the sustainability requirements:

> ***Principle 1:*** *Protection of land with high biodiversity value or high carbon stock.*
>
> ***Principle 2:*** *Environmentally responsible production to protect soil, water and air.*
>
> ***Principle 3:*** *Safe working conditions.*
>
> ***Principle 4:*** *Compliance with human and labour rights and responsible community relations.*
>
> ***Principle 5:*** *Compliance with land rights, laws and international treaties.*
>
> ***Principle 6:*** *Good management practices and continuous improvement.*

Intermediate crops can include **catch crops, cover crops or ley crops**. They are fast-growing and are planted outside the period in which the main crops are cultivated. Intermediate crops are planted either to be marketed (e.g., as fodder for livestock) or to improve the soil fertility of the arable land for main crops. Besides compliance with the sustainability requirements, it also has to be verified that the crops are cultivated outside the cultivation period for main crops and that the cultivation is part of a crop rotation scheme (i.e., no permanent/perennial cultivation).

Under certain conditions, intermediate crops may be certified analogous to agricultural residues (i.e., no calculation of GHG emissions for the cultivation of raw materials is required but compliance with the requirement on soil quality and carbon protection). This approach may be applied if the cultivation of the intermediate crop aims at ***improving soil quality and not biomass production*** and if no nitrogen fertilization is applied to increase biomass yields. In the case of biomass production, in particular for biogas, the assessment of GHG emissions during cultivating cover crops will be required for the certification.

In this Analytical Note, the terms **"intermediate crops"** and **"cover crops"** will be used as **close concepts** regarding agricultural crops that are grown in the time interval free from the cultivation of main crops of the crop rotation, for **various** purposes, including protecting the soil surface from erosion and absorbing excess mineral fertilizers, and biomass of these crops can be harvested for further use as feedstock for **biogas** and **biomethane** production.

11 The share of biofuels and biogas produced from the feedstock listed in Part B of Annex IX in the energy content of fuels and electricity supplied to the transport sector shall, except in Cyprus and Malta, be limited to 1.7% (Article 27 of RED III).

12 https://www.iscc-system.org/wp-content/uploads/2024/01/ISCC_EU_201_System_Basics_4.1_January2024.pdf

General approach to growing intermediate and cover crops for biomethane production

SECTION 2

Factors for crop growth

The efficiency of crop yield formation is determined by the interaction of growth factors necessary for plant metabolic processes. These include solar radiation, temperature (progression), soil characteristics and the availability of water, as well as the controlled supply of macro- and microelements. Knowledge of these interactions is important for the selection of appropriate crops and the design of growing systems[13].

Green plants in the process of photosynthesis form organic substances from inorganic substances (carbon dioxide and water), and the organic substances accumulate in biomass. A schematic process of energy conversion in the system "photosynthesis – anaerobic fermentation – oxidation" using the example of glucose without taking into account losses during the conversion is shown in **Fig. 2.1**. As a result of anaerobic fermentation, this biomass decomposes and turns into biogas, the basis of which is methane (55-75%), carbon dioxide (25-45%) and digestate (the fermented mass). During the oxidation of the obtained methane, thermal energy is released. Biogas, therefore, is a renewable energy source containing solar energy stored in biomass.

Biomethane is a gaseous fuel obtained from biogas after carbon-dioxide is separated; the concentration of methane in it is 95-98%. Biomethane is a close analogue of natural gas, and therefore can be transported via existing gas networks and used in the same appliances and industrial processes without modification. **In Ukrainian legislation, biomethane means biogas, which according to its physical and chemical characteristics meets the requirements of legal acts on natural gas for input to the gas transmission or gas**

13 Energy from Organic Materials (Biomass). A Volume in the Encyclopaedia of Sustainability Science and Technology, Second Edition. Martin Kaltschmitt (Editor) https://doi.org/10.1007/978-1-4939-7813-7

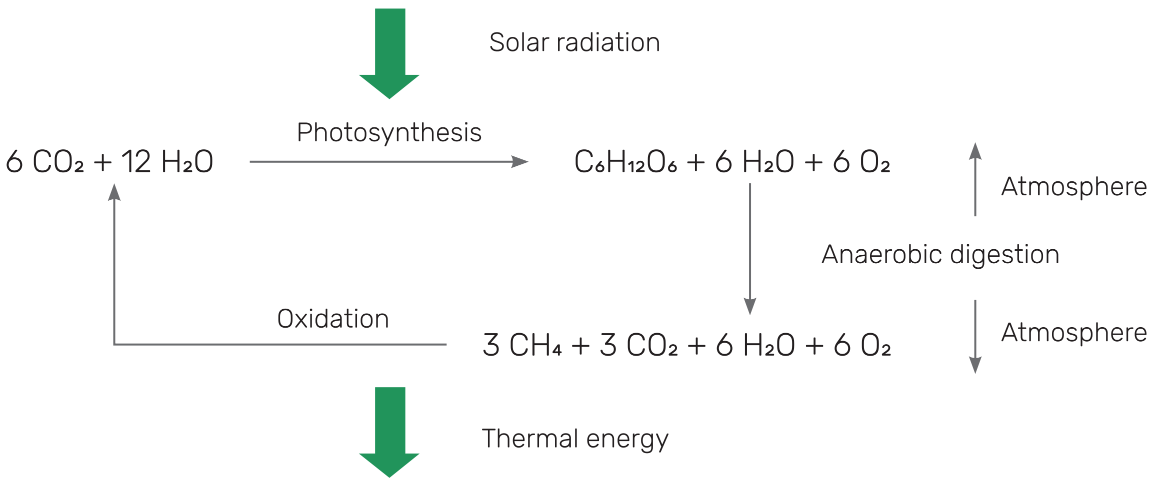

Fig. 2.1. Scheme of the energy conversion process in the system "photosynthesis – anaerobic fermentation – oxidation"[13].

distribution system[14]. Thanks to this compatibility and renewable origin, **biomethane holds significant potential for reducing greenhouse gas (GHG) emissions across its entire life cycle, making it a key component in decarbonizing energy systems, particularly in hard-to-abate sectors** such as transport, heating, and dispatchable power. It is important to emphasize that, like natural gas, biomethane produces CO_2 when burned. However, unlike fossil fuels, this CO_2 is part of a short biological cycle, having recently been captured from the atmosphere by plants. Thus, the true climate benefit of biomethane lies in its complete value chain, from feedstock sourcing and production to end use.

Photosynthesis is the main physiological process that results in 90–95% of the dry matter of plants, and therefore the harvest and its quality. The potential yield of agricultural crops is determined by **photosynthetically active radiation (PAR),** under the influence of which photosynthesis occurs. The green surface of leaves and the entire plant do not absorb radiant energy completely. Theoretically, it is possible to increase the efficiency of PAR to 5-6%, but in field conditions, the efficiency of PAR does not even reach 2%. In particular, the coefficient of utilization of PAR by plants is 0.74-1.12 for winter wheat, 0.69-1.63 for grain maize, and 1.34-1.84% for sugar beet in production conditions[15].

The potentially active energy of solar radiation is lost particularly unproductively because the actual vegetation period of plants is shorter than potentially possible, considering, for example, the length of the period with average daily temperatures above 5°C. Especially insufficient use of solar radiation energy occurs in the spring months (March, April and, partly, May), when the illumination is good for active photosynthetic activity, but the temperatures are still low; solar energy is also used unproductively in late summer and in autumn, especially after harvesting grain spiked crops (winter wheat, barley, winter rye and others)[16].

Therefore, from an agronomic point of view, it is important that during the vegetation period the conditions of growing crop approach the photosynthetically established growth limits **(Fig. 2.2).** In moderate climate, harvesting and reproducing a sufficient leaf area index during successive crop cultivation limit the period for optimized use of solar radiation. Ecological groups of plants are well adapted to the light regime of their habitats. Growing intermediate crops can be considered one of the methods for improving the use of PAR.

The process of photosynthesis is also affected by **temperature**. The **minimum** is characterized by the temperature at which photosynthesis begins. In the moderate zone, photosynthesis of most plants stops at approximately 0°C. The **optimum** is the temperature at which photosynthesis is most stable and has the highest rate. For agricultural C3 plants[17], the optimal temperatures are in the range of 20-30°C, and for C4 plants[18] of hot regions the range is 30-45°C. The temperature optimum for photosynthesis is not strictly fixed and depends on the stage of plant development and the complex of external factors. The **maximum** is the temperature after which photosynthesis stops. The maxima are in a wide temperature range between 35°C and 50°C. For most C3 plants, photosynthesis is inhibited at 35°C. In field conditions, the productivity of photosynthesis almost does not change in the temperature range 16 to 29°C. At high temperatures, the total intensity of photosynthesis of C4 plants is higher than that of C3 plants[19].

The influence of the **water regime** on photosynthesis is determined by its influence on the entire complex of a plant life. Plants of C3 and C4 groups differ in the efficiency of using

14 Code of the Gas Transmission System of Ukraine https://zakon.rada.gov.ua/laws/show/z1378-15#Text

15 Fertilizers and their use: Reference book. – K. : Aristei, 2010. – 254 p.

16 Kirilesko O.L. Photosynthetic activity and productivity of forage crops in intermediate sowing (2015) https://fri-journal.com/index.php/journal/article/download/381/301/

17 C3 plants use C3 through photosynthesis with CO2 fixation in the Calvin cycle, the first product of which is a three-carbon molecule. These plants are common in geographical areas with moderate climate. C3 plants include wheat, rye, oats, barley, rice, sugar beet, tobacco, potatoes, and legumes.

18 C4 plants carry out C4 photosynthesis with the formation of the first product with a four-carbon molecule. They are common in the arid tropical climate zone, but can also grow in moderate climate zones. C4 plants include maize, sugarcane, various types of millet. C4 plants are characterised by high intensity of photosynthesis and higher yield in the arid tropical zone. They use high temperature and high light intensity more efficiently, and tolerate drought better than C3 plants.

19 Makrushin M.M., Makrushina Ye.M., Peterson N.V., Melnykov M.M. Plant physiology. / Edited by professor M.M. Makrushin. Textbook. – Vinnytsia: Nova Knyga, 2006. – 416 p. https://snvlk.at.ua/_ld/0/2_Fisiologi_m.pdf

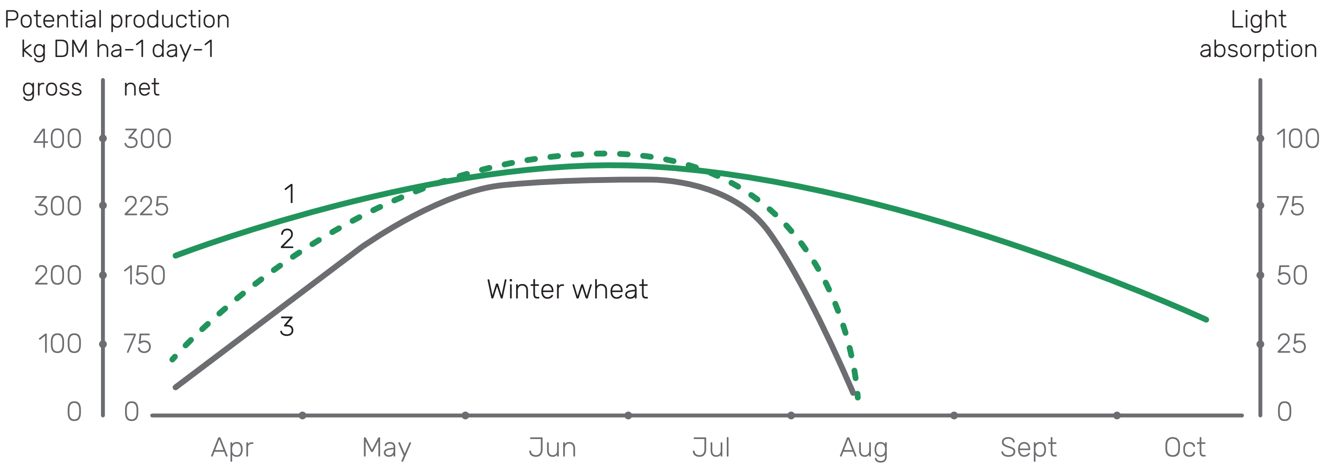

Fig. 2.2. Potential production of winter wheat determined by available radiation levels (1); percentage of available radiation utilized by the plant (2); calculation of daily growth rate (3)[13].

transpired[20] water for the formation of dry matter. C4 plants spend water more economically: to form 1 kg of dry matter they spend 250-350 l of water, while C3 plants spend 600-800 l[19]. If lack of water leads to wilting of leaves, and then the plant receives water again, then normal photosynthesis is restored no earlier than after 2-7 days[19].

To ensure effective photosynthesis and high yields, it is necessary to provide **balanced nutrition** for agricultural crops. Carbon is absorbed by plants mainly from the atmosphere, hydrogen and oxygen are obtained from water, while nitrogen and nutrients, which are part of ash residue, enter the plant from the soil[15]. The chemical composition of different plant species is different and depends on the amount, forms and methods of applying mineral and organic fertilizers, as well as the availability of soil nutrients. There is more nitrogen in grain than in straw, and there is less nitrogen in root crops than in leaves. Each crop absorbs nutrients differently, but in the first period of growth, when the leaf apparatus develops, it first uses more nitrogen, and then more phosphorus and potassium. By applying fertilizers, one can control the processes of plant nutrition, change the quality of the harvest and influence the fertility as well as the physical, chemical and biological properties of the soil. From a crop production perspective, planning the return of crop residues to the field is part of a plant nutrition strategy[13]. The main objectives of this planning are to optimize plant nutrition and to maintain and improve soil functions. The basic principle is that nutrients removed from the soil must be returned.

20 Transpiration is a physiological process of evaporation of water by a plant. https://dovidka.biz.ua/transpiratsiya-roslin

Sequential cropping is practised with certain characteristics in different countries around the world. For example, in South America, sequential cropping systems are capable of producing ***two main crops***. In Europe, climatic conditions usually ***do not allow*** the cultivation of two main crops[21]. However, it is possible to grow a ***second crop for silage*** as an intermediate crop to use it as a feedstock for biomethane production. Such a crop (for example, maize or triticale) is harvested early, before reaching full maturity, and therefore has a relatively short growing period.

Features of growing intermediate crops and cover crops

Intermediate crops and intermediate crop mixtures can complement existing crop rotations and make them more flexible as well as contribute to improving the cropping system in many ways. Intermediate crops are grown between main crops, usually after the previous harvest of grain crops. The main crops are maize, sugar beet, wheat, rye, barley, rapeseed, oats and legumes. In turn, intermediate crops such as oilseed radish, mustard or field grasses are mainly used as green manure[22]

21 Sequential silage crops as advanced feedstock under the EU RED II. A Gas for Climate Paper, October 2021. https://gasforclimate2050.eu/news-item/gas-for-climate-study-recommends-sequental-crops-be-included-in-redii-annex-ix/

22 Green manure is special crops that are planted to restore the soil or give it specific properties. They play their role in two acts. First, green manure protects the soil from weeds and winds by the plant mass as well as saturates the soil with trace elements during the vegetation process. Then these plants are cut, and their stalks saturated with minerals are used as fertilizer. They are ploughed in the ground or left on the surface as mulch. https://alfagro.com.ua/uk/siderati-vidi-koli-siyati/

(nutrients are accumulated and then released) or as livestock feed[23].

The positive effect of intercropping is that with optimal soil nutrition and moisture conditions, they provide high crop yields. It is also important that when fertilizers are applied based on the removal of nutrients by two or three harvests, the yield of subsequent crops does not decrease, but, on the contrary, significantly increases[24].

A **post-hay harvest** intermediate crop is grown in the current year after the main crop is harvested for ***green mass***. Peas, rapeseed, fodder cabbage, annual cereal-legume mixtures and many other crops that are able to vegetate and intensively produce organic matter in a relatively cool autumn period can be post-hay harvest crops. In the southern regions, post-hay crops can also be grown for the purpose of obtaining the ***main product***. These crops are millet, buckwheat and early-ripening potato varieties. The most common forecrops for post-hay harvest intermediate crops are maize for green mass and cereal-legume mixtures harvested in early or mid-summer.

A **post-harvest** intermediate crop is grown in the current year after harvesting the forecrop for the ***main product*** in the form of grain, seeds, root crops or tubers. Post-harvest intermediate crops are planted mainly after winter and spring spiked crops, less often after leguminous crops, early potatoes and other crops, the harvest time of which falls approximately in mid-summer. To obtain ***green mass*** from post-harvest intermediate crops, oats and lupine are grown in Polissia; peas, oats, and rapeseed in the Forest-Steppe; maize, sunflower, Sudan grass, and sorghum in the Steppe. However, post-harvest crops can be successfully grown in the Forest-Steppe and Steppe zones only in years with sufficient precipitation in the summer-autumn period and on irrigated lands.

A **winter** intermediate crop is sown in early autumn after the main crop and harvested ***green*** in the spring of the following year before sowing late spring crops. Such intermediate crops are mostly rye and wheat or their mixtures with woolly vetch, rapeseed and perco[25]. Winter intermediate crops are planted after the same forecrops as for main winter crops; spring crops of late sowing date are mainly grown after the winter intermediate crops.

Under-sown intermediate crops grow under the cover of main crops for half or more of the vegetation period, after which they grow intensively and form harvest in the same year. An example of an under-sown intermediate crop can be rapeseed or mustard, sown under barley. After the latter is harvested, the under-sown plants begin to grow intensively and manage to form a good harvest of green mass before the onset of cold weather. Cultivation of such intermediate crops is successful in areas with sufficient moisture and on irrigated lands of other natural zones. On poor lands of Polissia, they practice growing under-sown serradella or lupine for green manure, which is sown in the spring, mostly under the grass of winter rye, sometimes under spring piked crops[26].

Main ***requirements*** for intensive technologies for growing ***intermediate*** crops are as follows[24]:

> *- timely harvesting of the forecrop, and the minimum interval between harvesting the main crop and sowing of an intermediate crop;*
>
> *- selection of the most productive varieties and hybrids and their placement in specialized crop rotations taking into account the biological characteristics of the crops;*
>
> *- ensuring optimal thickness of sowing;*
>
> *- providing an optimal level of mineral nutrition for plants, which should not limit their real productivity;*
>
> *- optimal moisture supply for crops, which makes it possible to most fully realize the positive effect of all other factors of plant life on the yield;*
>
> *- timely and high-quality harvesting of an intermediate crop.*

A **cover crop** is any plant that is sown and protects the soil from erosion by covering it with its biomass. Cover crops can be sown together with the main crop in the field or after it; then they can be treated with herbicide before sowing the next crop or ploughed into the soil **(Fig. 2.3)**[27]. Cover

23 https://www.kws.com/ua/uk/agroservis/sivozmina/promizhni-kultury/

24 Technology for growing two-three harvests a year. https://buklib.net/books/34388/

25 Perco is a hybrid of colza and Chinese cabbage.

26 http://www.tsatu.edu.ua/rosl/wp-content/uploads/sites/20/lekcija-8.klasyfikacija-i-orhanizacija-sivozmin.pdf

27 https://propozitsiya.com/ua/pokryvni-kultury-perevagy-ta-osoblyvosti-efektyvnogo-vykorystannya

crops are sown at different times (spring, late summer or autumn), over the entire field or in the rows. Some cover crops die in winter and do not require their residues to be ploughed in soil, while in other cases the plant residues must be removed. Typical ground cover crops are annual grasses (sorghum, Sudan grass), vegetables (turnips, radishes) and small grains (legumes, rye)[28].

Fig. 2.3. Suppression of cover crop vegetation by mechanized rollers in autumn (Photo by the authors of the AN).

There can be plants of one or more species on one field. As practice shows, the results of the second option are more fruitful[29]. To make the most of each crop in the mix, you should combine different types of root systems and root lengths (e.g., phacelia + horse beans + Chinese radish). This way, there will be no competition between the plants for the same nutrients. It is also worth mixing crops of different heights: tall plants can be a support for creeping and low plants[30].

Winter cover crops are sown in late summer or autumn to provide soil cover in the autumn and winter periods. The crop for sowing should be selected in accordance with the climatic conditions of the zone. Legumes are often used to fix atmospheric nitrogen and enrich the soil with it. The most suitable legume is vetch, and among cereals it is rye; they can be sown both separately and in mixtures. Changes in climatic conditions in Ukraine, which occur due to global warming, are favourable for winter crops: the growing season is lengthened; winters are softened, and the intensity of temperature increases in the spring period decreases. Under these conditions, to reduce production costs, it would be advisable to use the sowing of small-seeded winter crops by the broadcast method.

Spring cover crops are grown during a certain part of one vegetation season. This group equally includes both heat-loving and cold-resistant crops that can be sown after various grain-spiked crops. These include peas, soybeans, cowpeas from the legume group, and Sudan grass, sorghum, and buckwheat from non-legumes.

The choice of cover crop type depends on the purpose of their use and the specifics of a particular field. Most often, such plant cover performs several functions simultaneously[29]. If the use of cover crops involves providing subsequent crops in the crop rotation with ready-made biologically bound nitrogen, then it is worth choosing a species from the legume family, for example, cowpea (it binds nitrogen and has a narrow C:N ratio in plant residues). If cover crops are to act as a mulch layer and serve as a means of suppressing weeds, then it is worth choosing a species with a wide C:N ratio, i.e., cover crops should grow a lot of biomass and meet the characteristics that ensure the suppression of weed growth (Sudan grass or sorghum). Typical intermediate crops and cover crops that are grown in different parts of the world are listed in **Appendix 1.**

Intermediate and cover crops as feedstock for the production of biogas/biomethane

Intermediate and cover crops as feedstock have considerable potential for energy production[31]. Fast growth, generally low soil requirements, absence of competition with main crops which are used for food production, and high susceptibility to ensiling, which makes their long-term storage possible, are features that favour the use of this biomass in the energy sector. In addition, the possible reduction of the carbon footprint of the energy industry as a result of the use of renewable sources is a significant advantage of using intermediate and cover crops for biogas production. This effect is noticeably manifested when the fermentation

28 https://superagronom.com/slovnik-agronoma/pokrivni-kulturi-id20111

29 Cover crops: value for agriculture. bit.ly/44PBuWU

30 Cover crops. Reference book (Soufflet Agro Ukraine). https://www.soufflet-agro.com.ua/media/filer_public/30/ad/30ad6456-a305-4547-83e2-572c68a68a90/sa_cover_crop_guide_ua_web.pdf

31 Słomka, A.; Pawłowska, M. Catch and Cover Crops' Use in the Energy Sector via Conversion into Biogas – Potential Benefits and Disadvantages. Energies 2024, 17, 600. https://doi.org/10.3390/en17030600

residues, rich in organic matter and more stable than untreated aboveground biomass, are returned to the soil as a source of nutrients and starting components for the formation of humus.

The vegetation season of crops lasts from seed germination and the emergence of shoots to harvest ripening, and at the same time, plants go through different stages of development, which determine both the volume and chemical composition of biomass. Main substances formed during photosynthesis and high-molecular carbohydrates, lipids and proteins formed in subsequent metabolic processes, serve to form the substance of plant cells, which mainly consists of macromolecules[13]. When growing plants for energy, it is important to obtain biomass with a high content of target substances, which will be further processed into biofuels and biogas. The change in the composition of different groups of substances during the generative phase using the example of corn (maize[32]) is shown in **Fig. 2.4.** Due to the increase in starch reserves, the mass of the cob changes significantly in relation to the mass of the rest of the plant. Due to the transportation and transformation of sugars, as well as lignification of the cell wall (characterized as crude fibre), the digestibility of maize production residues (corn stover) simultaneously decreases.

The rate and completeness of the decomposition of various components of organic matter in the process of methane fermentation differs significantly. Biomass with a high content of sugar or starch is fermented faster than feedstock containing more cellulose and hemicellulose **(Fig. 2.5).** For biogas, the grain maturity factor is not decisive, except that the specific biogas yield will be slightly higher or lower, unlike the case of biodiesel and bioethanol. For biodiesel production, the seeds must have a high oil content; for bioethanol production, the grain must have a high starch content, which occurs at full ripeness. Therefore, growing intermediate crops and cover crops for biogas/biomethane production allows for more flexible adaptation to the limited vegetation period between main crops.

32 Terms "maize" and "corn" are used as synonyms in the Analytical Note.

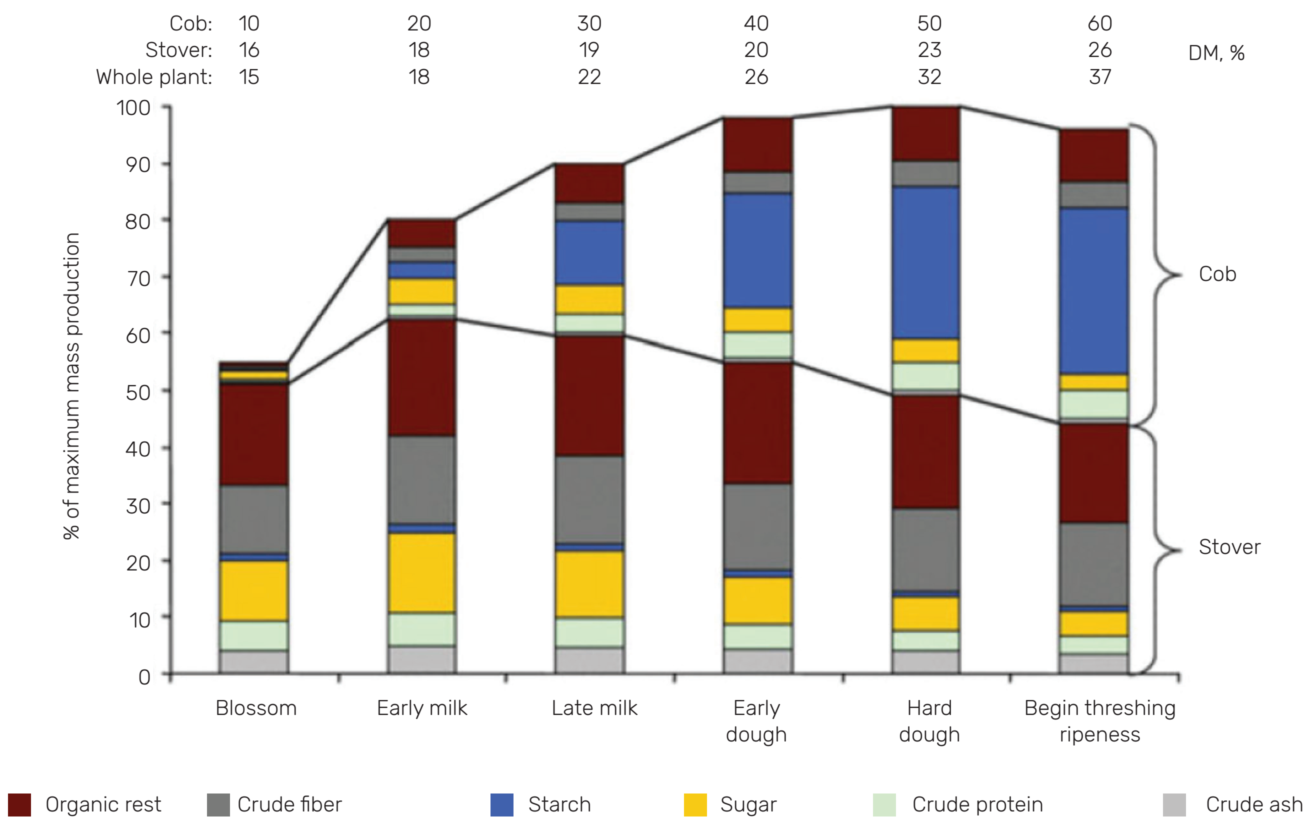

Fig. 2.4. Change in dry matter content (%) and its composition in corn from flowering to threshing maturity (divided into cobs and corn stover)[13]

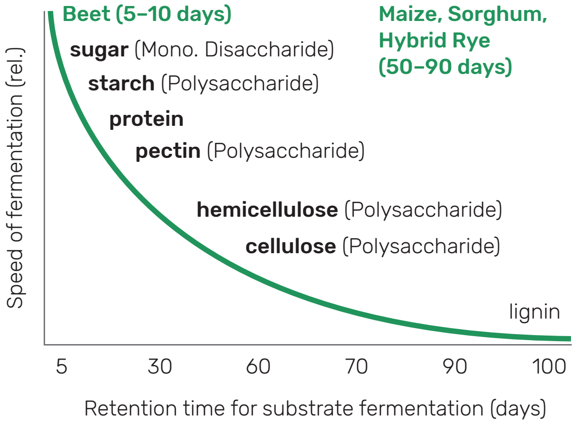

Fig. 2.5. Relative characteristics of methane fermentation for different crops[33]

Results of anaerobic digestion studies of biomass of selected cover crops are presented in **Table 2.1.** The yield of CH_4 from cover crops is comparable to the yield of CH_4 from corn stover, which is typically in the range of 250-350 l CH_4/kg volatile solids, depending on pre-treatment and operating conditions. Pre-treatment and constant mixing can increase methane yield. The complexity of anaerobic digestion of cover crops is associated with lignin stability, biomass flocculation, variation in C/N ratio, harvesting and storage characteristics, and relatively low methane yield. Three methods used to increase biogas yield and digester stability are co-digestion, pre-treatment, and ensiling.

33 Biogas in practice. KWS http://www.aylshamgrowersrenewables.co.uk/media/SlideShow/Biogas%20in%20Practice_Guide.pdf

Table 2.1. Specific methane yield from biomass of selected catch crops and cover crops[34]

Crop	Part of crop	Methane yield (m^3/t VS)
White mustard (Sinapis alba)	Tops	352
Oil seed rape (Brassica napus spp. oleifera)	Straw	420
Radish (Raphanus sativus)	Shoots	293–304
Rape (Brassica napus arvensis)	Tops	334
Rape (Brassica napus)	Not reported	340
Winter rye (Secale cereale montanum)	Straw	360
Rye (Secale cereale)	Whole plants	140–275
Triticale (Triticale)	Whole plants	212–286
Triticale (Triticale)	Whole plants	396
Faba bean (Vicia faba)	Straw	440
Faba bean (Vicia faba)	Whole plants	387
Ryegrass (Lolium sp.)	-	410
Ryegrass (Lolium sp.)	-	490
Clover (Trifolium sp.)	Vegetative stage	210
Clover (Trifolium sp.)	Flowering stage	140
Grass hay	-	350
Oat	-	260
Lupine (Lupinus polyphyllus)	Whole plants	310–360
Vetch oat (50% Vicia sativa)	Whole plants	400–410
Red clover (Trifolium pratense)	Whole plants	310–320
Red clover (Trifolium pratense)	Whole plants	238–293
Red/white clover – ryegrass (Trifolium pratense, Trifolium repens L, Lolium perenne L.)	Whole plants	281–315
Maize (corn)	Corn stover	256 ± 15

34 https://encyclopedia.pub/entry/54759

In addition, cover crops like other lignocellulosic biomass can be used as for the production of biodiesel, bioethanol, and sustainable aviation fuels. In the reviewed studies, the yield of liquid biofuels and biogas from cover crops varies significantly due to the diversity of species/varieties, climatic conditions/regions, soil conditions, agricultural practices, and processing methods. The following methods have been tested to increase the yields of crops and biofuels/biogas: (1) breeding or genetic modification of cover crops to increase oil content, reduce lignin content, and improve biomass digestibility; (2) soil and moisture management practices and agronomic practices to increase grain/seed and biomass yields; (3) improving conversion technologies to produce more energy from cover crops; (4) optimizing the supply chain (i.e., harvesting, drying, storage, transportation, and pre-treatment) to preserve biomass nutrients and reduce costs[35].

Further research is needed to exploit the potential of cover crops for bioenergy more effectively. Genetic engineering tools can be revolutionary for the industry, especially their application to improve the digestibility of cover crop biomass and increase its starch content. Optimizing the biomass supply chain is critical for scaling up the production system. Improving the efficiency of biomass conversion into biogas and biofuels requires improvements and the creation of new technologies.

35 Yang, L.; Lamont, L.D.; Liu, S.; Guo, C.; Stoner, S. A Review on Potential Biofuel Yields from Cover Crops. Fermentation 2023, 9, 912. https://doi.org/10.3390/fermentation9100912

The impact on soil and sustainability issues related to the use of intermediate and cover crops for biomethane production

SECTION 3

One of the most important aspects of the sustainability of biomass as a feedstock for biofuels is the absence of competition with food and feed production. In the case of the use of intermediate and cover crops for energy, an important question is also to what extent these crops change their traditional agronomic functions such as soil protection from erosion, improvement of soil quality etc.

Results of theoretical studies by European experts[36] (2022) indicate that the use of cover crops for biogas production with subsequent application of digestate to the field has a **positive effect** on carbon accumulation in the soil and reduction of CO_2 emissions from the soil. If we assume the organic carbon content (C_{org}) in the aboveground part of a cover crop at 100 units, then its balance when incorporating biomass into the soil is -4 to 28. In the case of anaerobic fermentation of the aboveground biomass of a cover crop with the return of digestate to the field, the organic carbon balance is **positive** at the level of **9-29 (Fig. 3.1).** At that, the cover crop continues performing its traditional ecological functions (protection of soil from erosion, etc.), and the risk of negative impacts is low.

36 Launay C., Houot S., Frédéric, S. et al. Incorporating energy cover crops for biogas production into agricultural systems: benefits and environmental impacts. A review. Agron. Sustain. Dev. 42, 57 (2022). https://doi.org/10.1007/s13593-022-00790-8

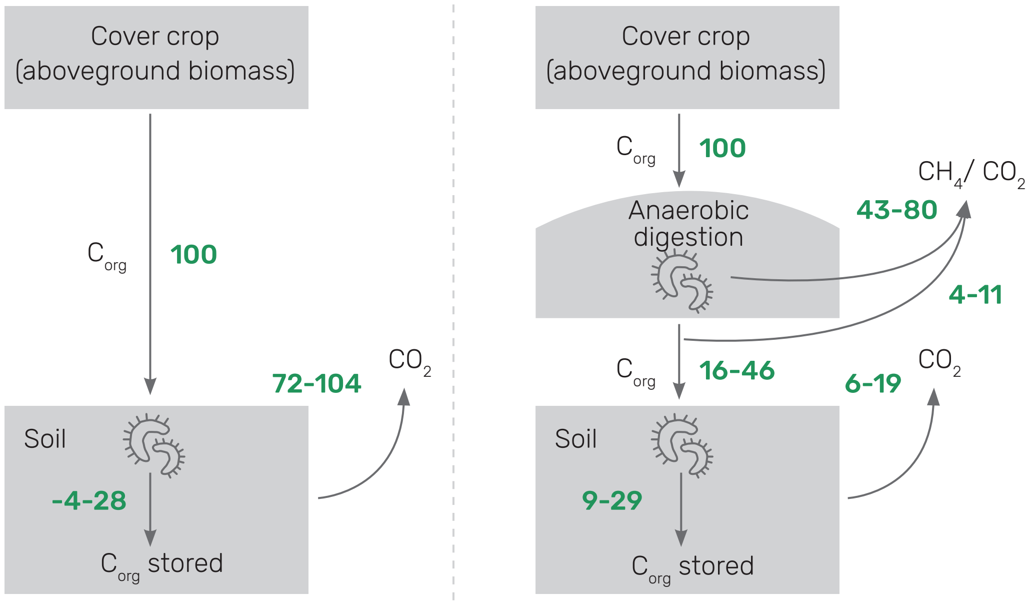

Fig. 3.1. Carbon balance in case of incorporating the aboveground biomass of a cover crop into the soil and in case of returning the cover crop digestate to the field[36]

Austrian experts conducted more than 5-year field research of the impact of growing and using cover crops for biogas production on soil and groundwater[37] (Syn-Energy project 2010-2015). Five cover crop options were investigated, most of which were mixtures of at least 3 plant species with 50% legumes.

Results of the study showed that when harvesting biomass of cover crops with a yield of 2.5 t d.m./ha with the return of an equivalent volume of digestate to the field, the **humus carbon input** to the soil is **112** kg/ha. If the same cover crops are applied to the soil as green manure, the humus carbon input is only **80** kg/ha. The higher the biomass yield per hectare is, the higher the positive effect on humus content is. When growing cover crops for biogas, the volume of biomass is bigger due to early sowing and late harvesting. Compared to fallow, **the risk of erosion is reduced** by 50% by growing cover crops for biogas production. For cover crops used as green manure, this effect is lower.

Positive results regarding the preservation of soil **carbon stocks** were also obtained when modelling examples of growing cover crops as feedstock for a biogas plant with the return of digestate to the field in France[38]. Four examples were studied in different regions of the country:

> *I – Ile-de-France (Paris area, Oceanic climate, Luvisol soil type[39]);*
>
> *II – Southwest region (Oceanic to Mediterranean climate, Luvisol and Calcisol soil types);*
>
> *III – Rhône-Alpes (central to South-eastern France, Semi-continental climate, Luvisol soil type);*
>
> *IV – Western France (Oceanic climate, Cambisol soil type).*

Presented in literature research results are given mainly for the Ile-de-France region (1st crop rotation option), so these data are presented below. In total, three crop rotation options with different cover crops were considered for Ile-de-France **(Table 3.1).** In France, the most common cover crop that remains in the field is mustard (Sinapis alba). It is usually sown from mid-August

37 Biogas from Cover Crops and Field Residues: Effects on Soil, Water, Climate and Ecological Footprint. https://publications.waset.org/10005395/biogas-from-cover-crops-and-field-residues-effects-on-soil-water-climate-and-ecological-footprint

38 Energy cover crops for biogas production increase soil organic carbon stocks: A modeling approach (2022). https://www.researchgate.net/publication/365637796_Energy_cover_crops_for_biogas_production_increase_soil_organic_carbon_stocks_a_modeling_approach

39 Luvisol, Calcisol, Cambisol are soil types according to the World Reference Base for Soil Resources (https://en.wikipedia.org/wiki/World_Reference_Base_for_Soil_Resources). Luvisol is a typical fertile soil for France. It has clay-enriched subsoil (high-activity clays). Calcisol is characterised by the accumulation of secondary carbonates. Cambisol is a soil with little or no profile differentiation (moderately developed).

Table 3.1. Crop rotation options with cover crops investigated for Ile-de-France region[38].

Crop rotation 1:
Rapeseed – winter wheat – **cover crop*** – maize for grain – winter wheat
* ***Winter barley*** *(10 t d.m./ha) in case of further anaerobic digestion.* ***Mustard*** *(2 t d.m./ha) in case of leaving the cover crop in the field.*
Crop rotation 2:
Rapeseed – winter wheat – winter barley – **cover crop**** – winter wheat
** ***Maize for silage*** *(6 t d.m./ha) in case of further anaerobic digestion.* ***No cover crop*** *in case of no further anaerobic digestion.*
Crop rotation 3:
Rapeseed – winter wheat – winter barley – **cover crop***** – sugar beet – winter wheat
*** ***Maize for silage*** *(6 t d.m./ha) in case of further anaerobic digestion.* ***Mustard*** *(2 t d.m./ha) in case of leaving the cover crop in the field.*

to mid-September, and incorporated into the soil from November to January. Winter barley (sowing in autumn, harvesting in spring) was the cover crop for obtaining feedstock for a biogas plant in crop rotation option 1.

It is assumed that in all the crop rotation options, the entire volume of crop residues of the main crops is returned to the soil. It is determined that the main annual amount of humified carbon enters the soil with the above-ground part of the plant residues, and in the case of leaving the cover crop in the field, this volume is larger **(Fig. 3.2).** However, the total annual amount of carbon input into the soil (main crop residues, cover crop residues, digestate) is higher in the case of growing the cover crop as a feedstock for a biogas plant with the digestate returned to the field: **1.37 t** of humified carbon/ha/y versus **1.27 t** of humified carbon/ha/year when incorporating the cover crop biomass into the soil.

Simulation of the soil condition over 30 years shows that organic carbon content could increase from 50 t C/ha (baseline) to 50.5 t C/ha under cover cropping with digestate return. In the alternative scenario (remaining biomass in the field), organic carbon content could decrease to 49.4 t C/ha **(Fig. 3.3).**

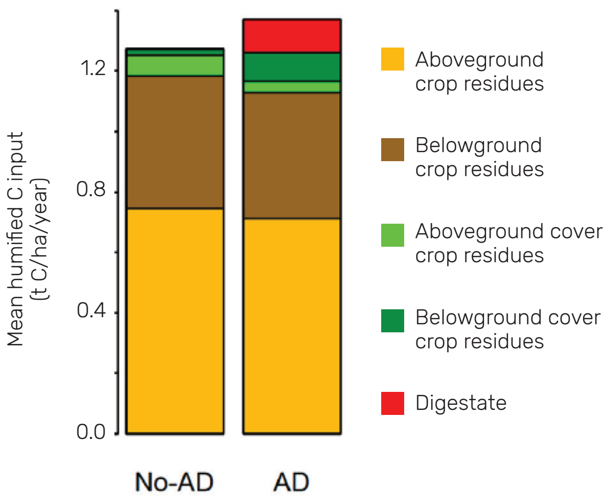

Fig. 3.2. Mean yearly humified C input for no-AD and AD scenarios for the Ile-de-France region[38].

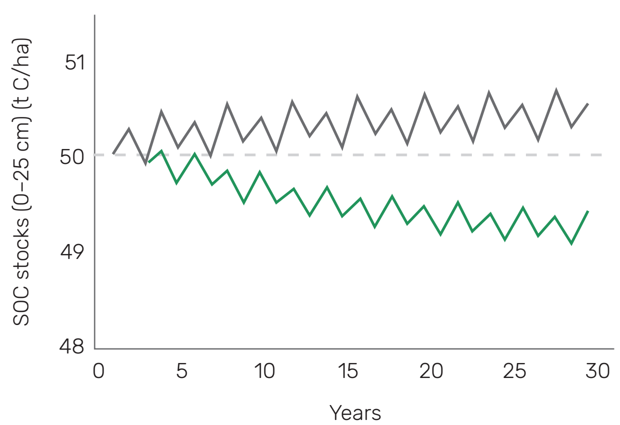

Fig. 3.3. Simulated SOC stock (0-25 cm) evolution for no-AD and AD scenarios for the Ile-de-France region[38].

International experience of growing intermediate/cover crops for bioenergy

SECTION 4

Study by JRC of Spain, France, the Netherlands, and Romania experience

The European Commission's Joint Research Centre (JRC) studied the experience of growing catch crops and cover crops (CCP) in selected regions of Spain, France, the Netherlands and Romania[40]. The main results of the study, which was carried out by surveying farmers, are presented in **Table 4.1.** It was determined that the most commonly grown catch and cover crops are common vetch (Spain), white mustard (France, Romania) and Italian/Annual ryegrass (the Netherlands). The main forecrops of these crops are wheat (Spain, France, Romania), barley (France) and grain/silage maize (the Netherlands). Most often, the additional crop is sown after the main crop is harvested, and under-sowing to the main crop is rarely used.

In the studied regions of the Netherlands, Italian/Annual ryegrass is widely grown as a *winter cover crop* after silage maize on sandy soils. The soil is ploughed in March/April, shortly before sowing maize. The cover crop is sown in the period from late October to early November and harvested the following year in March/April. In other countries (Spain, France, Romania) the main crop is most often a winter crop. *A spring cover crop* (e.g., white mustard) is sown in July/August and harvested in October/November before the main crop is sown.

In the majority of the studied cases (about 80% of the surveyed farmers, who could choose several answers), the biomass of the catch crops and cover crops is incorporated into the soil. Of all the surveyed farmers, 10% harvest catch and cover crops for livestock feed, 7% for sale, 6% for their own use, 1% for bioenergy (in particular, 2% of the surveyed farmers in France and 1% in Romania), and 2% for other needs.

40 Adoption of cover crops for climate change mitigation in the EU. JRC, 2019.
https://publications.jrc.ec.europa.eu/repository/handle/JRC116730
https://op.europa.eu/en/publication-detail/-/publication/0638ab96-f939-11e9-8c1f-01aa75ed71a1/language-en

Biogasdoneright™ conception by the example of an Italian farm

In Italy, sequential cultivation (i.e., harvesting two crops per year) is widespread thanks to the introduction of a new model for sustainable food, feed and biogas production – **Biogasdoneright™** (BDR™). This model is gradually gaining the status of a globally recognized system for sustainable agricultural development with biogas production. In the BDR™ model, the **main** crop is grown for food or feed, while the **intermediate** crop can be used for **biogas/biomethane** production. Accordingly, a farm operating under this system can use the digestate from the biogas plant as organic fertilizer instead of purchasing additional mineral fertilizers. Currently, the Biogasdoneright™ model is used on more than 600 farms in Italy, as well as in France; $10 million has been invested in pilot studies in the USA[41].

Let us consider an actual example of BDR™ implementation on an Italian farm. This farm, with 320 hectares of land and 150-milk cow livestock, is located in the Po valley near Ferrara (northern Italy). In 2012, a 1 MWh biogas plant was built on this dairy farm. Manure, dairy slurry from the stable and maize silage were used as feedstock for the biogas production. After the biogas plant had been built, maize was grown as a single-crop: silage was harvested as feedstock for the biogas plant on 270 ha and as livestock feed on 30 ha. On the remaining 20 ha, alfalfa was grown also for livestock feed. Due to the lack of feedstock, the farm additionally purchased maize silage for the biogas plant in an amount equivalent to its cultivation on 71 ha.

To fully provide the biogas plant with its own feedstock and optimize land use, the farm

41 The Role of Sequential Cropping and Biogasdoneright™ in Enhancing the Sustainability of Agricultural Systems in Europe (2021). https://www.mdpi.com/2073-4395/11/11/2102

Table 4.1. Results of JRC's study on growing catch and cover crops in selected EU countries[40].

Indexes	Country (region)			
	Spain (northwest, Castilla y León)	France (Central region)	The Netherlands (Overijssel in the east and Flevoland in the centre)	Romania (Muntenia in the south)
Number of questioned farmers	155	162	151	155
Number of farmers that grow CCP	26	120	149	78
Average farm size, ha	136	182	72	773
Average acreage of CCP, ha	17.0	31.4	12.5	101.3
Main types of catch and cover crops	Common vetch (Vicia sativa)	White mustard (Sinapis alba) Black oat (Avena strigosa) Phacelia (Phacelia tanacetifolia) Common vetch (Vicia sativa) Egyptian/Berseem clover (Trifolium Alexandrinum) Oil radish (Raphunus sativus)	Italian/Annual ryegrass (Lolium multiflorum) English ryegrass (Lolium perenne) Black oat (Avena strigosa) White mustard (Sinapis alba)	White mustard (Sinapis alba) Black oat (Avena strigosa) Common vetch (Vicia sativa) Brown mustard (Brassica juncea)
Main forecrops for CCP	Wheat Barley	Wheat Barley Rapeseed	Maize for grain/ silage Rye Wheat	Wheat Maize for grain Sunflower Rapeseed Barley
Growing period of CCP before termination or harvest, weeks	14.9	13.0	21.5	13.0

introduced new crop rotations with the inclusion of ***intermediate/cover crops***. The land area was divided into several plots (30 ha, 110 ha, 60 ha, 100 ha, 20 ha – a total of 320 ha) with two crops grown per year on each, except for one (20 ha with alfalfa) **(Table 4.2).** Intermediate/cover crops are used only as **feedstock** for the biogas plant. Maize for silage is the intermediate crop on the 110-ha plot (feedstock for the biogas plant) and the main crop on the 30-ha plot (livestock feed). The main crops are used for livestock feed or sale. They **are not used** as feedstock for the biogas plant, except sorghum for silage (10 ha).

Thus, after the introduction of new crop rotations, the structure of the farm's own feedstock, which fully meets the needs of the biogas plant (in tons of fresh matter), became the following: wheat silage (1,350 t/y), maize silage (6,600 t/y), triticale silage (4,500 t/y), sorghum silage (360 t/y), a mixture of triticale/nitrogen-fixing crop biomass (2,100 t/y) plus chicken manure (3,650 t/y), cow manure (3,504 t/y), and cow slurry (5,256 t/y).

Table 4.2. New crop rotations with intermediate/cover crops on the farm near Ferrara (Italy)[42].

Crops on different land plots	Area under crops, ha			Final use		
	Winter crops	Mono-crops	Summer crops	Dairy stable	Market	Feedstock for biogas plant
The plot of 30 ha:						
Silage wheat*	30					30
Maize for silage**			30	30		
The plot of 110 ha:						
Wheat for grain**	110				110	
Maize for silage*			110			110
The plot of 60 ha:						
Mix: winter cereal/nitrogen-fixing crops*	60					60
Maize for grain**			60		60	
The plot of 100 ha:						
Triticale for silage*	100					100
Sorghum for silage**			10			10***
Soybean**			90		90	
The plot of 20 ha:						
Alfalfa		20		20		
Total area, ha	300	20	300	50	260	310

** Intermediate/cover crops.*
*** Main crops. **
*** The only exception is the use of sorghum for silage (the main crop on 10 hectares) as feedstock for the biogas plant.*

42 BIOGASDONERIGHT®. ANAEROBIC DIGESTION AND SOIL CARBON SEQUESTRATION A SUSTAINABLE, LOW COST, RELIABLE AND WIN WIN BECCS SOLUTION. https://www.consorziobiogas.it/wp-content/uploads/2017/05/Biogasdoneright-No-VEC-Web.pdf

Growing cover crops in the USA

Cover crop cultivation is booming in the United States. Cover crop acreage increased by 50% to 6.2 Mha between 2012 and 2017. According to USDA, this area reached 8.1 Mha in 2020, with the potential to grow to 40.5 Mha by 2025[43].

Farmers use a variety of cover crops and different strategies to grow them. Cover crops are included in crop rotations with cotton and silage corn much more often than with grain corn and soybeans. The most common cover crops are rye (cereal rye or annual ryegrass) and winter wheat. To prepare the field for planting the main crop, cover crops are usually destroyed with herbicide or tillage. There are also practices when cover crops are grazed by livestock or harvested According to the rules of USDA's support programs, such harvesting is allowed only for hay or silage, and harvesting for grain/seed (i.e., for sale) is ***prohibited***. At the same time, support programs in some states allow harvesting cover crops for sale, but the amount of support is reduced. For example, in Maryland cover crops from 20-40% of the area could be harvested for sale during 2007-2017[44].

USDA assesses progress in growing cover crops not so much by the growth of the actual area of their cultivation, but by the increase in the *share* of this area in the total harvested area of agricultural crops (except alfalfa). During 2012-2017, this share increased on average from 3.4% to 5.1% in the USA. According to this indicator, the cultivation of cover crops is most developed in the eastern states of the country **(Fig. 4.1),** where the share in question comes to **15%** or even more. For example, in Maryland (an eastern state with access to the Atlantic Ocean) this share was **33%** in 2017.

In 2023, USDA's Agricultural Research Service issued the Cover Crop Chart (v. 4.0), which is a decision aid to help select and manage cover crops **(Fig. 4.2).** The chart, patterned after the periodic table of elements, includes information for 70 crop species that may be planted individually or in mixtures. Information on the growth cycle, relative water use, plant architecture, seeding depth, forage quality, pollination characteristics, and nutrient cycling are included for most crops.

Today, active research is being conducted in the United States on the possibilities of using cover crops for biofuel production. For example, implementing the "Italian" Biogasdoneright™ concept for **biogas** production is being studied[41]. In addition, the possibility of introducing Camelina as a 3rd crop in standard corn-soybean crop rotations in the Midwestern United States is being investigated. The projected use of Camelina is the production of **renewable diesel**[45].

43 Anaerobic Digestion of Cereal Rye Cover Crop (2022). https://www.mdpi.com/2311-5637/8/11/617

44 Cover Crop Trends, Programs, and Practices in the United States (USDA, 2021).
https://ageconsearch.umn.edu/record/309562/

45 Biofuel Producer Bets on Camelina as Low-Carbon Feedstock.
https://advancedbiofuelsusa.info/biofuel-producer-bets-on-camelina-as-low-carbon-feedstock

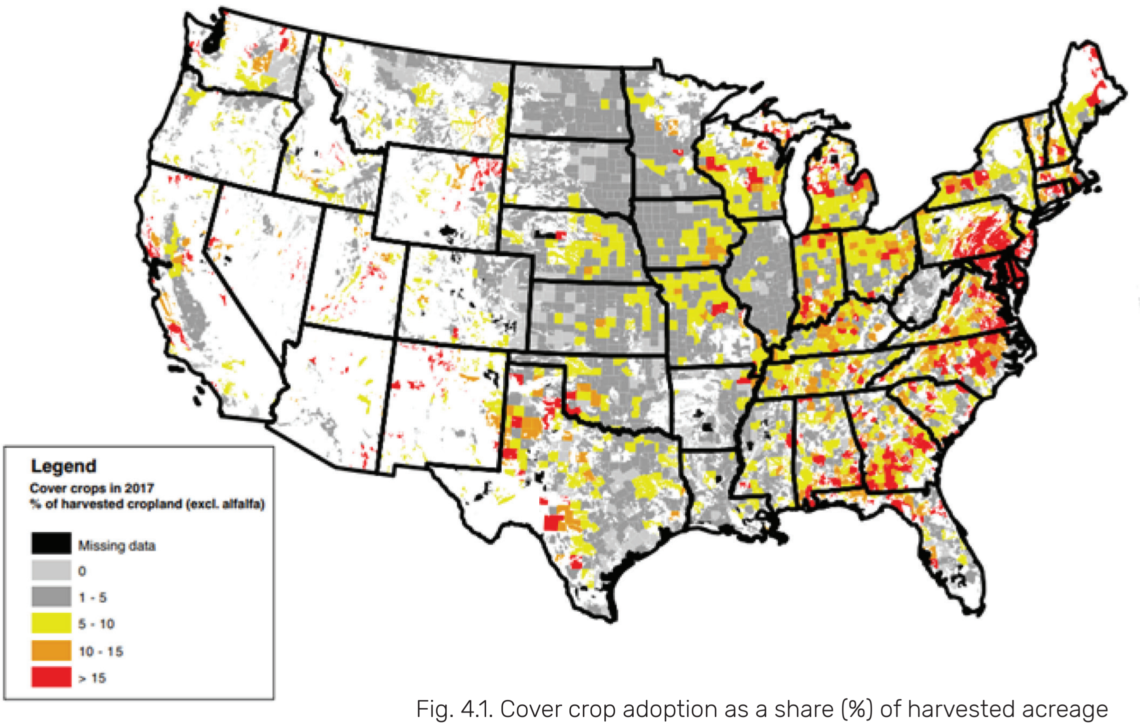

Fig. 4.1. Cover crop adoption as a share (%) of harvested acreage by county (excluding alfalfa), 201744

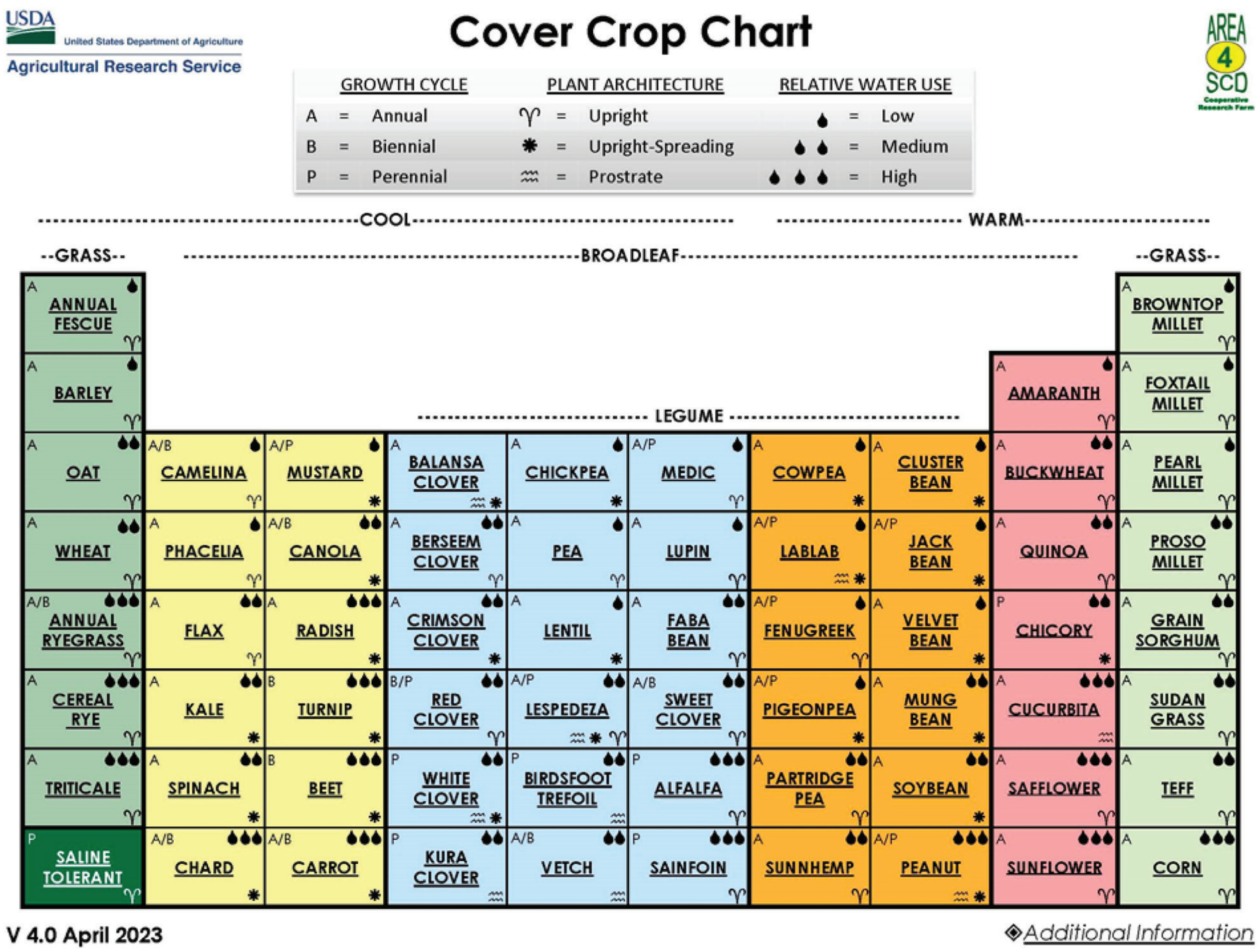

Fig. 4.2. USDA-ARS Cover Crop Chart (v 4.0, April 2023)[46]

46 https://www.ars.usda.gov/plains-area/mandan-nd/ngprl/docs/cover-crop-chart/

Potential of intermediate and cover crops for energy in Europe and the USA

SECTION 5

Europe

Today, the main feedstock for biogas production in European countries is agricultural residues (Bulgaria, Cyprus, Germany), manure (Denmark, Italy, Hungary), energy crops (Slovakia, Serbia, Germany, Croatia), sewage sludge (Switzerland, Norway, Sweden), industrial solid waste (Ukraine, Belgium) **(Fig. 5.1)**. Biogas from sequential crops (that is intermediate/cover crops) is produced in noticeable volumes in Serbia (> 20% in the total feedstock structure), Italy and Bulgaria, and in small volumes in Greece, Slovenia, Cyprus. On the whole, the share of this type of feedstock in the total volume of biogas production in Europe remains insignificant.

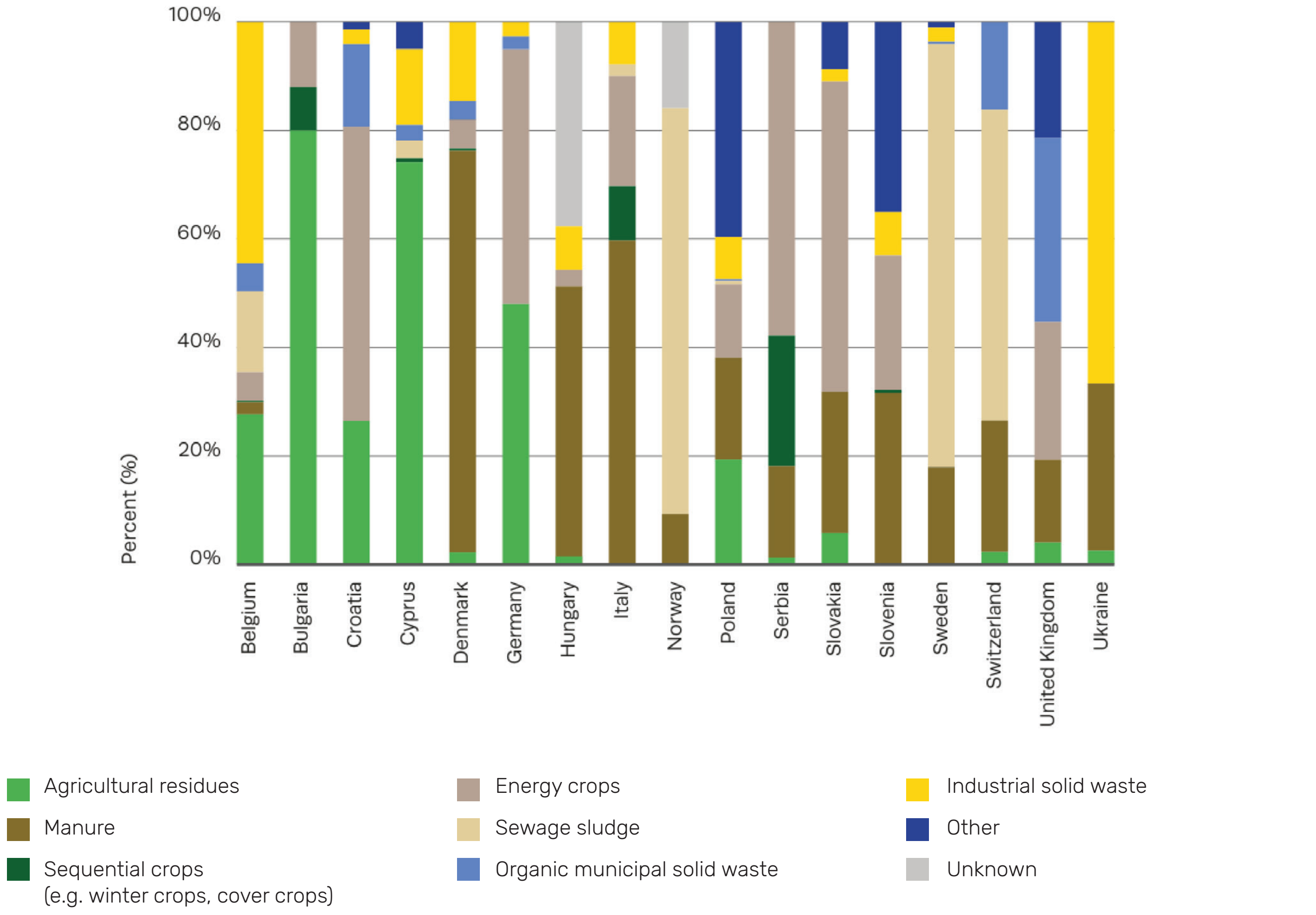

Fig. 5.1. Structure of feedstocks used for biogas production in selected European countries, 2023[47] [48]

47 Excluding landfill and industrial wastewater.

48 EBA Statistical Report 2024. https://www.europeanbiogas.eu/eba-statistical-report-2024/

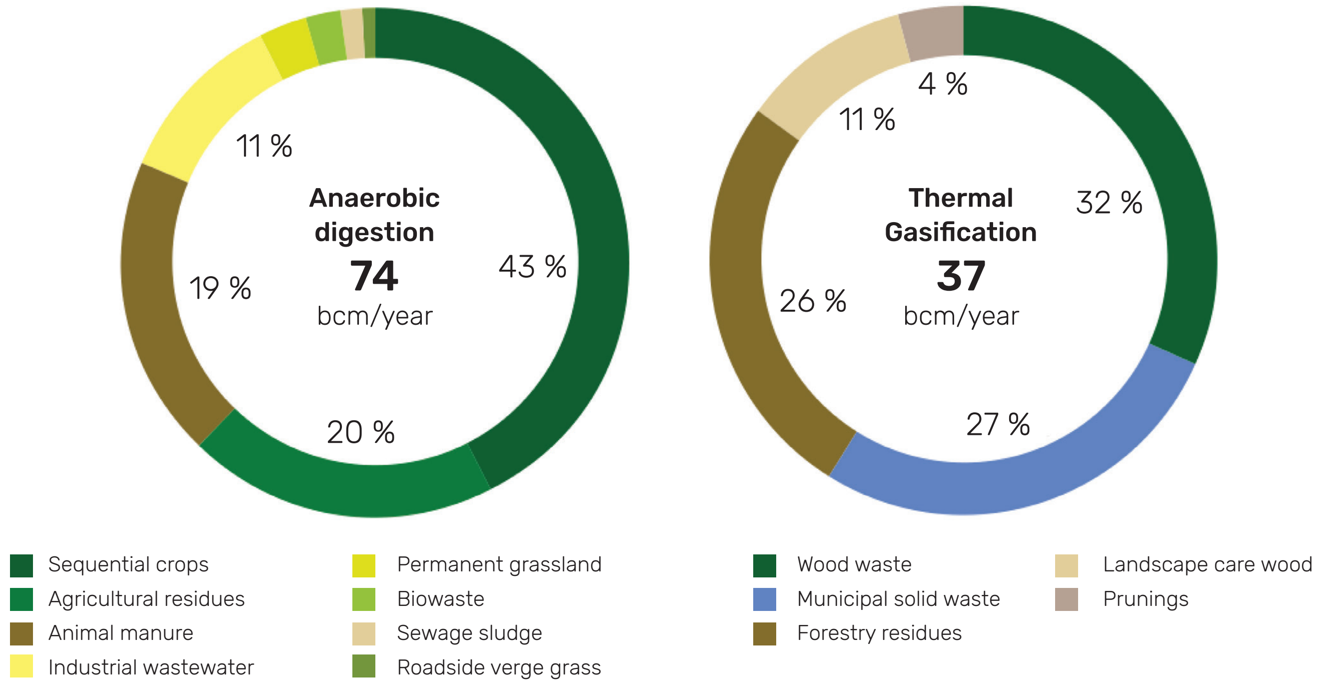

Fig. 5.2. The potential and feedstock structure for biomethane production by anaerobic digestion and thermal gasification in Europe in 2040[48 49]

The updated estimate[49] (2024) by **Guidehouse**[50] shows that up to 44 bcm of biomethane could be produced in 2030 and 165 bcm in 2050 in Europe, of which 40 bcm in 2030 and 150 bcm are for the EU-27. In 2040, Europe could produce 111 bcm of biomethane, of which 101 bcm relates to the EU-27. This potential is made up of 74 bcm from anaerobic digestion (67% of the total) and 37 bcm from thermal gasification (33% of the total) **(Fig. 5.2).** This corresponds to an increase of five to seven times compared with current levels. The Guidehouse report expects biogas production to continue to be dominated by anaerobic digestion. The increase in anaerobic digestion is largely driven by greater deployment of sequential crops, and increased mobilisation of waste and residues. The key forecast feedstocks in 2040 are **sequential crops (43%, *which provides* 32 bcm/y)**, agricultural residues (20%) and animal manure (19%) (see **Fig. 5.2**).

49 Biogases towards 2040 and beyond. Guidehouse, EBA, 2024. https://guidehouse.com/-/media/new-library/services/sustainability/documents/2024/biogases-towards-2040-and-beyond.ashx

50 London office of the international consultancy company https://guidehouse.com/

It is expected that in 2040, leaders in biomethane production from intermediate/cover crops will be Spain (~5.7 bcm/y), France (5.5 bcm/y), Italy (4.4 bcm/y), and Germany (3.5 bcm/y) **(Fig. 5.3)**.

Results of estimations carried out by **ENGIE**[51 52] are close to Guidehouse's forecast. According to ENGIE, the potential of biomethane production from intermediate crops in the EU-27 plus 10 countries outside the EU may come to **44** bcm/y (462 TWh/y) in 2050. This is **26%** of the total potential of biomethane production (167 bcm/y or 1767 TWh/y)[53]. At that, some countries may have a share of intermediate crops in the feedstock mix for biomethane production that is much more than the average. For example, in Turkey, Poland, Hungary, Bulgaria, and Serbia, the share could reach 50% and more **(Fig. 5.4)**.

51 ENGIE (France) is a company that operates in the field of renewable energy (https://www.engie.com/en)

52 Geographical analysis of biomethane potential and costs in Europe in 2050 (ENGIE, 2021). https://www.engie.com/sites/default/files/assets/documents/2021-07/ENGIE_20210618_Biogas_potential_and_costs_in_2050_report_1.pdf

53 In ENGIE's study, results are presented in TWh. Translation into bcm is done in EBA Statistical Report 2022. https://www.europeanbiogas.eu/__trashed-3/

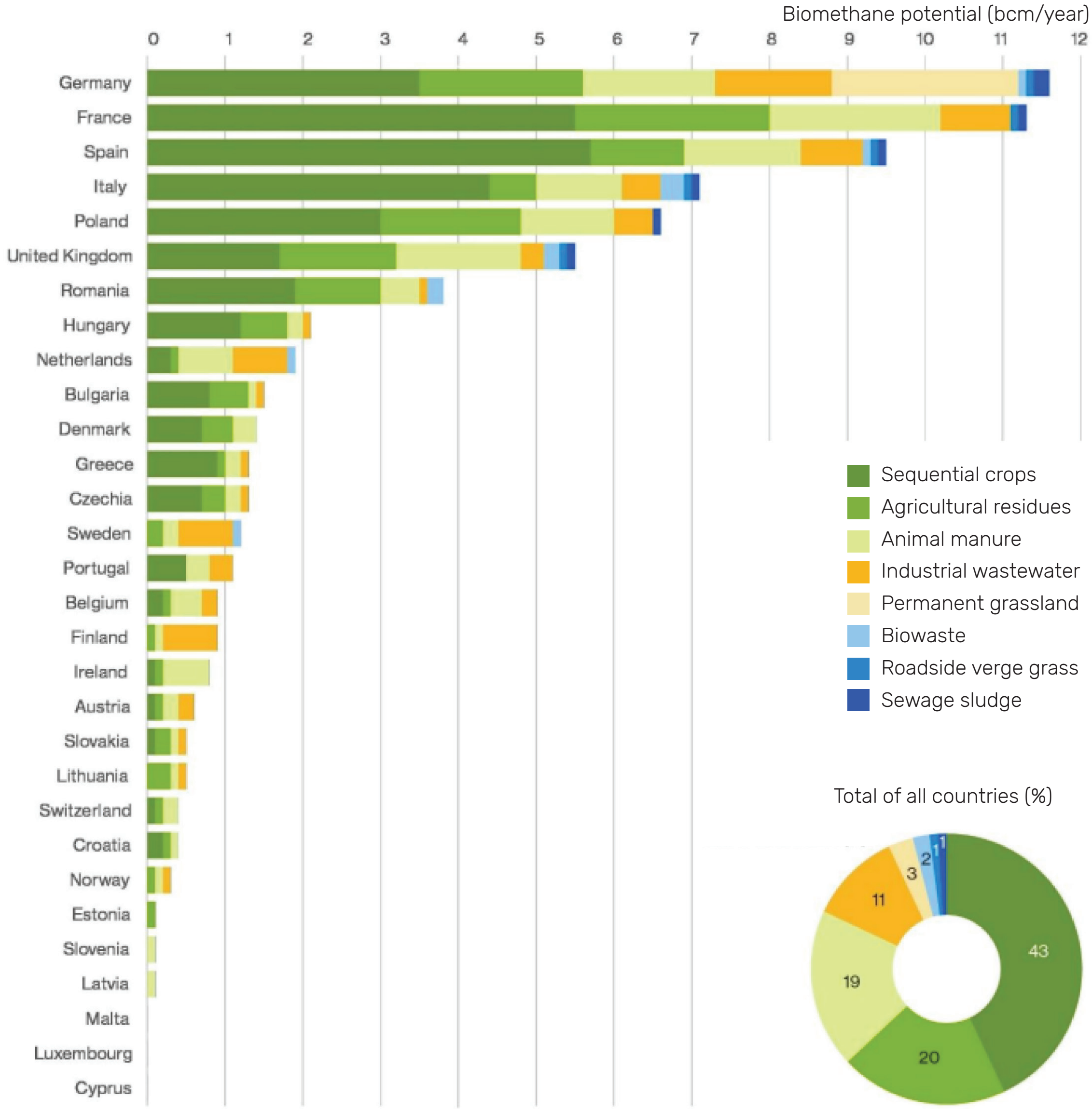

Fig. 5.3. Biomethane potential (bcm/y) per feedstock type in Europe in 2040 for anaerobic digestion[49]

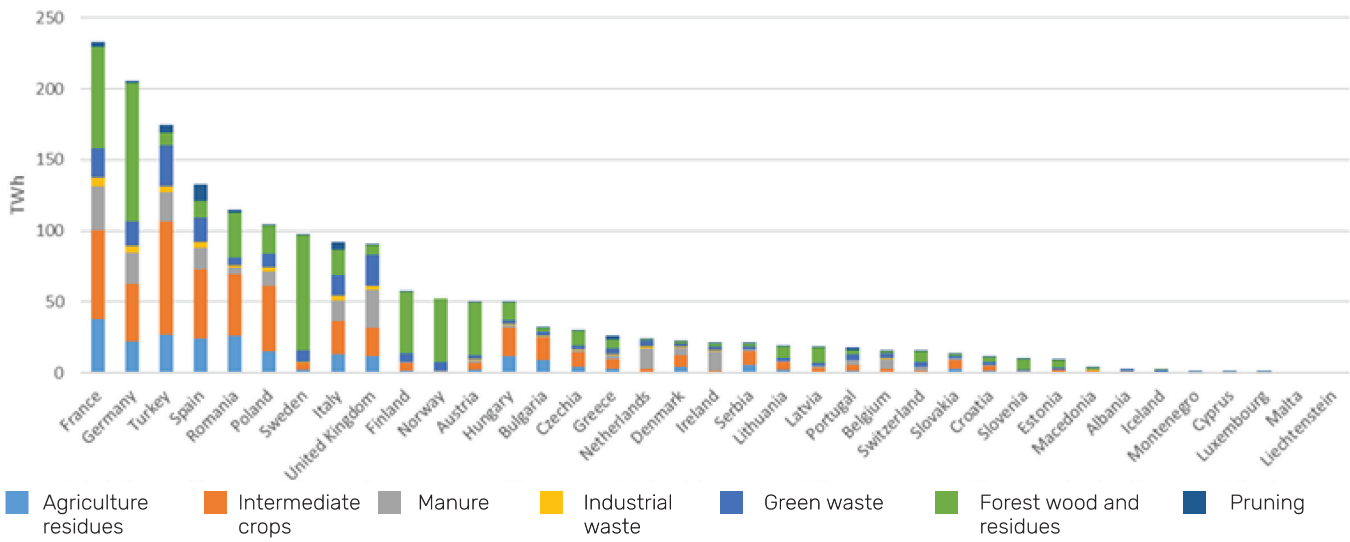

Fig. 5.4. Projected potential (TWh) and structure of biomethane production by feedstock type in the EU-27 and other European countries, 2050[52]

Table 5.1. Percentages of land dedicated to sequential cropping in Europe in the conservative scenario and maximum scenario, and corresponding hectares[54].

Climate (countries)[1]	Conservative scenario: share of land under summer crops[2] intended for sequential cropping[4]	Land area intended for sequential cropping, 1000 ha	
		Conservative scenario: 20%[3]	Maximal scenario: 80%[3]
Mediterranean (Central and Southern Spain, Portugal, Southern France, Italy, Greece, Albania)	23%	2651	10604
Atlantic (Central and Northern France, Ireland, United Kingdom, Belgium, the Netherlands)	22%	3943	15773
Continental (Germany, Luxemburg, Denmark, Poland, Austria, Switzerland, the Czech Republic, Slovakia, Hungary, Romania, Bulgaria, the Balkan area)	31%	8945	35781

1. Countries of the Boreal region (Norway, Sweden, Finland, Estonia, Latvia, and Lithuania) were not included in the study as their climate conditions are not suitable for sequential cropping.
2. Maize, sorghum, soybean, sunflower, and maize for silage.
3. Assumed share of the total area under main crops.
4. Expert estimation. A single conservative value 20% was adopted for all the climate types.

A group of Belgian experts from Ghent University assessed the potential for biomethane production from intermediate/cover, or **sequential**, crops in Europe, taking into account the type of climate zones of different regions[54]. The study covered the EU-28 (excluding several countries in the Boreal region[55]), as well as Switzerland, Albania and the Balkan countries outside the EU. According to the results, the potential for biomethane production from intermediate/cover crops in Europe ranges from **46** bcm/y (*the conservative scenario*) to **185** bcm/y (*the maximum scenario*). The conservative scenario estimate is almost identical to the ENGIE results presented above.

In the conservative scenario, the area of land suitable for the implementation of a sequential cropping system in different climatic zones of Europe is estimated as a percentage of the area under certain spring crops **(Table 5.1)**. For the calculation, a single conservative value of **20%** of *the total area* under main crops was adopted for all the climatic zones. In the maximum scenario, which is considered an estimate of *the theoretical* potential, this value is **80%**.

There were developed 2 crop rotation options with intermediate/cover crops for each climate type, which is 6 in total **(Fig. 5.5)**. Maize, triticale, barley, sorghum, legume cover crops, oat, green rye, ryegrass were considered as intermediate/cover crops **(Table 5.2)**.

54 Magnolo, F., Dekker, H., Decorte, M. et al. The Role of Sequential Cropping and Biogasdoneright™ in Enhancing the Sustainability of Agricultural Systems in Europe. Agronomy 2021, 11. https://doi.org/10.3390/Agronomy11112102

55 The Boreal region includes Norway, Sweden, Finland, Estonia, Latvia, and Lithuania.

Table 5.2. Intermediate/cover crops considered in the assessment of biomethane production potential in Europe[54].

Sequential crop	Average biomass yield, t d.m./ha	Biogas yield, m³/t d.m.
Mediterranean (North and South):		
Maize	16.5	620
Triticale	13.5	570
Barley	11	570
Sorghum	13.5	570
Legume cover crops	8.5	510
Atlantic:		
Sorghum	7	570
Maize	14	620
Oat	7.6	570
Triticale	9.3	570
Barley	4.5	570
Continental:		
Maize	14	620
Green rye (early harvest)	6.5	570
Sorghum	10	570
Ryegrass	9	570

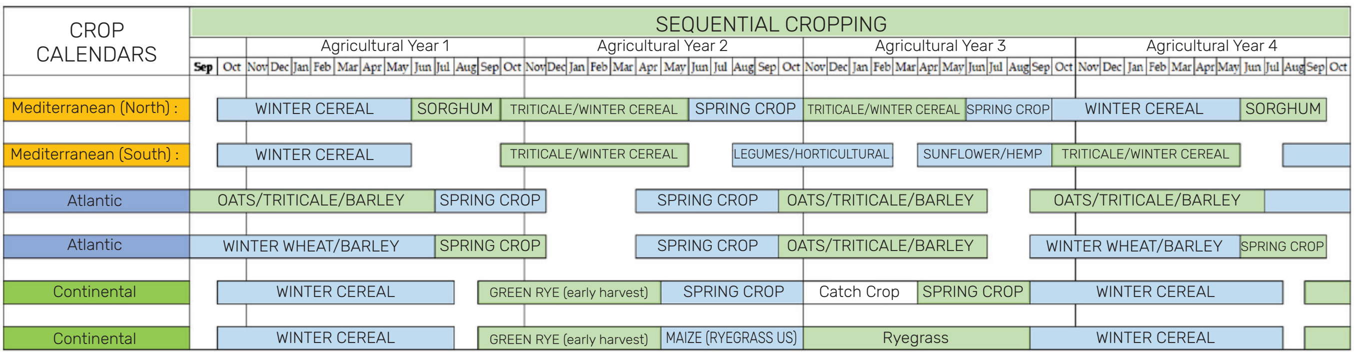

Fig. 5.5. Sequential cropping calendars for different climate types[54]

Results of the estimate showed that the biggest potential of biomethane production from sequential crops is for the European region with continental climate: 26 bcm/y (the conservative scenario) to 105 bcm/y (the maximum scenario) **(Table 5.3).** This region includes Germany, Luxemburg, Denmark, Poland, Austria, Switzerland, the Czech Republic, Slovakia, Hungary, Romania, Bulgaria, and the Balkan area.

Table 5.3. Potential of biomethane production from sequential crops in Europe[54].

Indexes	Regions of Europe by climate type		
	Mediterranean	Atlantic	Continental
Area under summer sequential crops, 1000 ha:			
- conservative scenario	1326	1972	4473
- maximum scenario	6513	9612	19026
Area under winter sequential crops, 1000 ha:			
- conservative scenario	1326	1972	4473
- maximum scenario	4092	6161	16754
Biogas yield, m^3/ha:			
summer sequential crops	8925	6248	7140
winter sequential crops	6050	4066	4418
Potential of biomethane production, bcm/y:			
- conservative scenario*	**9.9**	**10.2**	**25.8**
- maximum scenario**	37.9	42.5	104.9

** **45.9** bcm/y in total.*

*** **185.4** bcm/y in total.*

In April 2025, Task Force 3.1 of the Biomethane Industrial Partnership (BIP) published the report "The potential for sequential & rotational cropping for sustainable biomethane production across Europe"[56]. This report builds on the described above work of Magnolo et al.[54] and uses a novel approach to modelling biomethane potential from novel crop rotations. Sequential (intermediate) crops are introduced as an additional crop into an existing crop rotation, during periods where the land is usually bare (not productive) between two main crops. Within this report, rotational crops are defined as those grown within a long (5+ year) crop rotation, which aligns with the sustainable growth principles. The methodology for assessing the deliverable biomethane potential took into account the uncertainty factor (80%) and five key correction factors which would impact the deliverability of sequential/rotational cropping across Europe:

> *Food and fuel.*
>
> *Competition for biomass from other renewable technologies.*
>
> *Compatibility with different types of arable farming.*
>
> *Arable land readiness.*
>
> *Climate risk.*

It is estimated that the EU-27 has the potential to produce 44.0 bcm of biomethane per year from sequential/rotational crops **(Table 5.4)**.

56 https://bip-europe.eu/wp-content/uploads/2025/04/BIP-Task-Force-3.1_Biomethane-Potential-Novel-Cropping-Systems_April2025.pdf

Table 5.4. Deliverable biomethane potentials from sequential/rotational crops for EU-27[56].

EU countries	Maximum biomethane potential from novel crop rotations (bcm)	Correction Factors						Deliverable biomethane potentials from novel crop rotations (bcm)
		Food vs fuel	Biomass competition	Arable Compatibility	Arable land readiness*	Climate impact	Uncertainty	
Austria	0.2	100%	98%	89%	78%	Unknown	80%	0.1
Belgium	0.9	95%	98%	71%	78%		80%	0.4
Bulgaria	2.8	100%	98%	94%	78%		80%	1.6
Croatia	1.1	95%	98%	92%	78%		80%	0.6
Cyprus	0.2	100%	98%	78%	78%		80%	0.1
Czechia	2.2	100%	98%	92%	78%		80%	1.2
Denmark	1.9	95%	98%	86%	78%		80%	0.9
Estonia	0.1	90%	98%	90%	78%		80%	0.0
Finland	0.7	90%	98%	84%	78%		80%	0.3
France	18.4	95%	98%	89%	78%		80%	9.5
Germany	9.5	100%	98%	88%	78%		80%	5.1
Greece	2.8	100%	98%	84%	78%		80%	1.4
Hungary	3.7	100%	98%	91%	78%		80%	2.1
Ireland	0.2	90%	98%	95%	78%		80%	0.1
Italy	12.7	100%	98%	83%	78%		80%	6.4
Latvia	0.2	90%	98%	90%	78%		80%	0.1
Lithuania	0.3	90%	98%	89%	78%		80%	0.1
Luxembourg	0.1	100%	98%	96%	78%		80%	0.1
Malta	0.0	100%	98%	68%	78%		80%	0.0
The Netherlands	0.8	90%	98%	59%	78%		80%	0.3
Poland	10.0	100%	98%	88%	78%		80%	5.4
Portugal	0.6	95%	98%	70%	78%		80%	0.2
Romania	6.2	100%	98%	95%	78%		80%	3.6
Slovakia	0.1	100%	98%	92%	78%		80%	0.1
Slovenia	0.1	100%	98%	94%	78%		80%	0.1
Spain	10.4	95%	98%	61%	78%		80%	3.7
Sweden	0.8	90%	98%	89%	78%		80%	0.4
TOTAL EU27	**87.0**							**44.0**

**It should be notes that as soil health improves across Europe, the deliverable biomethane potential will also increase.*

The USA

In the United States, the potential area for growing **oilseed cover crops** for *sustainable aviation fuel (SAF)* [57] production is estimated at **28.7** Mha as of 2021, growing to **29.3** Mha by 2035[58]. The oilseed crops considered are Carinata, Camelina, and Pennycress. According to another estimate[59], the potential area for growing rye as a cover crop in the United States is 40 Mha in a rotation with corn or corn-soybean. The use of this potential would allow the production of about 150 Mt (dry basis) of rye biomass per year.

57 According to the International Air Transport Association (IATA), SAF has three key characteristics: its production is sustainable, i.e., it does not disrupt the ecological balance and does not deplete natural resources; it is produced from feedstock that is an alternative to crude oil; it has jet fuel properties that meet the technical and certification requirements for use in commercial aircrafts https://www.iata.org/contentassets/d13875e9ed784f-75bac90f000760e998/saf-what-is-saf.pdf

58 Oilseed Cover Crops for Sustainable Aviation Fuels Production and Reduction in Greenhouse Gas Emissions Through Land Use Savings, 2022. https://www.frontiersin.org/articles/10.3389/fenrg.2021.790421/full

59 Rye as an Energy Cover Crop: Management, Forage Quality, and Revenue Opportunities for Feed and Bioenergy (2022). https://www.mdpi.com/2077-0472/12/10/1691

Opportunities for growing intermediate and cover crops for advanced biomethane production in Ukraine including the regional aspects

SECTION 6

Agroclimatic conditions of Ukraine for growing intermediate and cover crops

Most of Ukraine has a temperate continental climate, which is favorable for growing a variety of agricultural crops, particularly cereals and oilseeds, similar to the climate of parts of Central and Eastern Europe, as well as regions of the Midwestern USA. At the same time, significant areas of Ukraine's cropland are located in the risky farming zone (areas with a natural deficit of precipitation), where there is a constant risk of loss of crop volume in an excessively dry year or loss of crop quality in an excessively rainy year[60]. Temperature conditions, both seasonal and year-round, have a major impact on agricultural production. To determine the feasibility of growing intermediate crops and cover crops, it is necessary to consider **temperature trends** and **precipitation characteristics** in detail, which is the subject of this section.

The steady **increase of air temperature over 10°C** in spring determines the beginning of active

60 Adamenko T. Climate change and agriculture in Ukraine: what should farmers know? German-Ukrainian agro-political dialogue, 2019. https://drive.google.com/file/d/1Xw5LrJAFoZvg5RmbcF0PwDrQAQ87Ncyx/view?pli=1

Fig. 6.1. Dates of increasing air temperature over 10°C in spring[61]

vegetation of most plants[61]. The occurrence of air temperature 10°C most often begins from the south and southwest and very rarely from the east **(Fig. 6.1)**. The intensity of synoptic processes affects the degree of spatial distribution: simultaneous coverage of the entire territory or only the southern part. Increasing air temperature over 10 °C begins in mid-April in the Crimea, southern regions and the Transcarpathian lowland at the earliest.

In the west and extreme northeast, this transition occurs on April 25-27, and in the rest of the territory, moving from south to north – from April 15 to 25. From south to north, the increase of temperature over 10°C in spring takes place within 10 days, and from east to west within 8-10 days. The transition of temperature is characterized, as a rule, by significant deviations in dates. The period of establishing such a temperature can last a month, or maybe several days. The amplitude of the extreme dates of a stable transition over 10°C in spring varies from 38-42 days (in most of the country) to 46-57 days in the western regions. The duration of the period with an air temperature equal to or above 10 °C increases from 155 days in the Zhytomyr region and in the northeast to 184-196 days in Zakarpattia (or *Transcarpathia*), in the southern regions and the steppe Crimea.

The decrease in the average daily temperature in autumn occurs somewhat faster than the increase in spring. The period with an air temperature of 15 to 10°C is considered a continuation of summer when the active vegetation of agricultural crops is still ongoing. In the western regions, this period lasts 30-34 days, gradually decreasing to 18-20 days in the east of the country. With the decrease of temperature below 10°C, the vegetation of the main heat-loving crops ceases. However, this period of cessation of active vegetation is quite long due to the influence of the soil warmed up during the summer.

The earliest transition below 10°C is observed in the extreme northeast: September 28-30 **(Fig. 6.2).** In most of the country, the transition of

61 Atlas on «Agroclimatic resources of Ukraine» / edited by T.I. Adamenko, M.I. Kulbida, A.L. Prokopenko. – Kyiv, 2016.– 113 p.

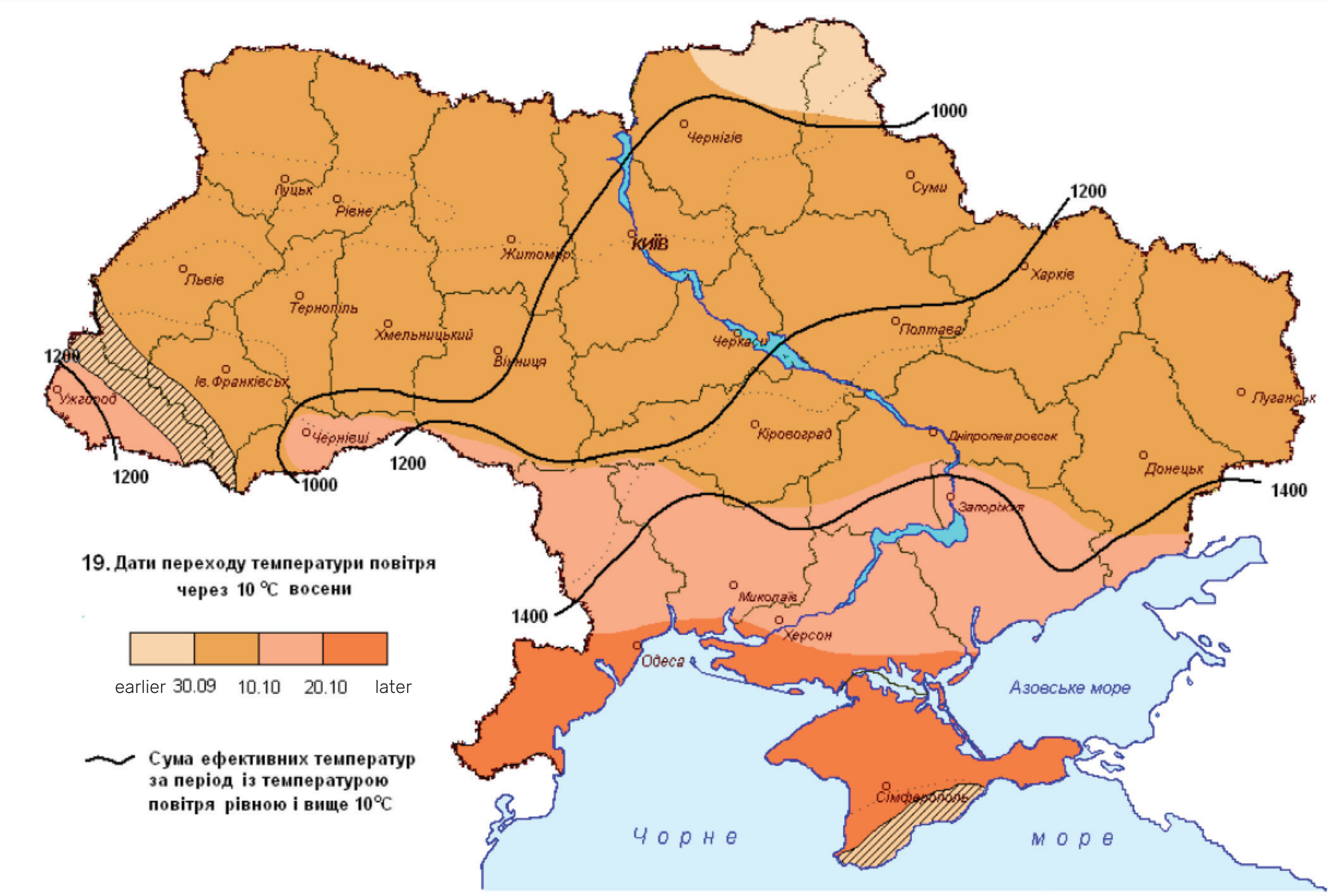

Fig. 6.2. Dates of decreasing air temperature below 10⁰C in autumn[61]

temperature occurs in the first decade of October; in the southern and Zakarpattia regions – in the second decade of October; in Crimea, in the south of Odesa, Mykolaiv and Kherson regions – at the beginning of the third decade of October. On the sea coasts, the transition is somewhat later than in the adjacent territories. In the east and west of the country, the transition occurs almost simultaneously. The amplitude of the dates of the stable transition below 10°C in autumn almost throughout the territory ranges from 38-40 in the east to 45-58 days in the west and south.

Precipitation is the main source of replenishment of water reserves and moisture reserves in the soil. Precipitation is distributed unevenly across the territory of Ukraine; its annual amount decreases from the west and northwest to the south and southeast. In the north-western part of the country, the amount of precipitation is 600-700 mm per year; in the Carpathian region (*other names are Ciscarpathia and Prykarpattia*) and on the plains of Transcarpathia the amount is > 700 mm in some places. In the southern regions, 400-500 mm of precipitation falls per year, and in some areas of the Kherson region and the steppe Crimea, the amount is < 400 mm. In the rest of the country, the annual amount of precipitation ranges from 500 to 600 mm. In the central part of the Carpathians, the annual amount of precipitation exceeds 1000 mm, and in the highlands even 1500 mm.

The map with the amount of precipitation for the warm period (April-October) is shown in **Fig. 6.3.** Rain precipitation prevails in the warm period of the year, its amount being 75-80% of the annual amount. The largest amount of precipitation falls on June-July. September and October are the driest months of the warm period. The largest daily maximums of precipitation are observed in the summer months (mainly in July). The amount of precipitation in the warm period is distributed similarly to the annual amount, namely decreasing from the west and northwest to the east and southeast (from 400-550 mm to 320-380 mm, respectively). According to this characteristic, the amount of precipitation is 500 to 300 mm in most territory of the country.

Fig. 6.3. Amount of precipitation (mm) in warm period (April-October)[61]

On the Transcarpathian plain, the amount of precipitation is 445-635 mm, and in the extreme southern regions and the steppe Crimea, it is < 300 mm. On the sea coast, the amount of precipitation decreases to 230-260 mm during the warm period. On the plain territory during summer showers, daily maximums can reach 150-170 mm, even up to 200 mm. This period is also characterized by the highest intensity of precipitation. During the warm period, a significant amount of precipitation can occur, which sometimes even exceeds the average annual values. Maximum values (excluding mountainous areas) range from 600-700 mm in most of the territory to 800-1000 mm in the west of the country. In dry years, the minimum amount of precipitation in the warm period is from 85-100 mm in the southern regions to 140-240 mm in the rest of the territory.

The average annual air temperature is the main parameter for assessing **climate change**[60]. In Ukraine, this temperature has increased by 1.2°C over the last thirty years; if we calculate it over the last 10 years, then by 1.7 °C. However, for effective agricultural management, it is very important to know not only how the average annual air temperature is changing, but also what the trends in average monthly and seasonal temperatures are. The planning of fieldwork largely depends on these changes.

The number of days with very high temperatures (above +30-35°C), or the number of days with heat stress, has increased throughout the country. In the southern regions, there were an average of 30-40 such days during the growing season, but now there are 50-65; in the northern and western regions, there were less than 10 such days, but now there are more than 15-30.

The change in temperature regime in the warm period of the year has affected the thermal resources of Ukraine. The indicator of the sum of active (positive) air temperatures above +10°C, accumulated during the warm period, is used for the assessment of the thermal resources. A comparison of these sums for different periods shows their increase on average by 200-400°C **(Table 6.1).**

Table 6.1. Sums of active air temperatures above + 10°C in the agroclimatic zones of Ukraine in different time periods[60].

Agroclimatic zone	Time periods		
	1961-1990	1991-2009	2010-2019
Steppe	3145	3400	3550
Forest-Steppe	2705	2950	3150
Polissia	2500	2770	2950

As a result of climate change, the period of active vegetation of agricultural crops has already been extended by 10 days or more. This provides additional opportunities for growing all types of heat-loving agricultural crops. The effectiveness of precipitation is reduced due to an increase in air temperature. An increase in temperature by 1°C threatens Ukraine with the disappearance of the sufficient moisture zone (Polissia and the western Forest-Steppe), which is rather small right now, and the transition of this zone to unstable and insufficient moistening[62].

In Ukraine, PAR is calculated based on measurements and transition coefficients from integrated solar radiation obtained from spectral experimental studies[63]. Seed producers indicate the amount of PAR required to obtain an optimal yield[64]. Due to the cultivation of two crops, the use of solar energy for photosynthesis and the formation of organic matter increases significantly. While spring-sown maize during the growing season used only 0.73% of PAR energy that falls on crops during the maximum growing season, vetch + oats 0.52%, and spring barley 1.32%, then for two crops of different sowing dates this indicator increased significantly: up to 1.47-1.68% for spring barley + post-harvest crops, and up to 1.48-1.65% for vetch-oats + winter crops + maize[16].

Heat resources: The total sum of active temperatures (when passing through +10 °C) in Ukraine varies from north to south from 2000 to 3600 °C. The sum of temperatures for obtaining a harvest of green mass of early spring mixtures is 700-800°C[65]. Thus, throughout the territory of Ukraine, there is enough heat for growing post-hay harvest and post-harvest crops for green fodder, and in the southern regions for grain. The period of possible vegetation of intermediate crops (sown after various forecrops) until the stable fall of temperature ranges from 60-70 to 120-140 days.

Depending on the crop, the harvest can be obtained after 55-70 to 100 days, including the harvest of grain after 70-90 days. It is important to take into account that when growing field crops as summer intermediate crops, their vegetation period is significantly reduced. Truth to tell, the period of development phases of post-harvest crops, the vegetation of which falls on August-October, on the contrary, is prolonged due to a decrease in temperatures. However, the accumulation of vegetative mass when selecting cold-resistant crops occurs satisfactorily and well.

In most territories of Ukraine, **moisture** is the main limiting factor for the yield of intermediate crops, especially for summer post-hay harvest crops (for example, after maize for green fodder), post-harvest crops and under-sown crops. At that, moisture reserves available before sowing do not have a significant impact on yield in the conditions of the Forest-Steppe. In summer, this moisture can at best only provide the emergence of sprouts and the initial growth of plants.

Domestic experience of growing intermediate crops for feed production

Ukraine has gained considerable experience in cultivating intermediate crops for feed production, which can also be used to grow feedstock for bioenergy, in particular, for the production of biogas and biomethane.

In spring and autumn, biomass of intermediate crops is used for green fodder, for the production of silage, hay, and grass powder[66]. In addition, these crops increase the product yield per unit

62 https://www.donausoja.org/wp-content/uploads/2023/02/Atlas-Climate-change-in-Ukraine.pdf

63 https://uhmj.org.ua/index.php/journal/article/view/196/190

64 https://agrotimes.ua/article/rujnuemo-pogodni-mifi/

65 Zinchenko O. I. Feed production: Educational publication. – 2nd issues, supplemented and improved. – K.: Higher Education (Vyshcha Osvita), 2005. – 448 p. (in Ukrainian). https://www.isgkr.com.ua/images/sampledata/doc/literatura/kormovirobnictvo_zinchenko_o_i.pdf

66 Handbook on feed production for performing practical tasks by students of the Faculty of Agronomy, Junior Bachelor qualification, specialty 201 Agronomy. – Uman: Editor-publication division, 2021. – 63 p. (in Ukrainian).

area, leave up to 45-60 centner/ha of roots and stubble residues in the soil, reduce weed infestation and improve soil structure.

Winter intermediate crops for green fodder are sown at the same time as for grain. In Polissia, rapeseed, perco and mustard are sown in the first half of August, in the Forest-Steppe they are sown in the second half of August (until August 25). The optimal time for sowing rye of fodder varieties is September 5 to 10 in Polissia and the Forest-Steppe, and this time for grain varieties of rye and wheat is September 20 to 25. In the Steppe, intermediate crops are grown only on irrigated lands; they are sown after harvesting main crops in spring, summer, and early autumn.

Post-harvest and post-hay harvest crops are selected depending on soil and climatic conditions. They should have a short growing period, be undemanding to heat, light, and moisture, and be resistant to early frosts. Preference is given to those that have a lower seeding rate and low seed cost. Agrarians mainly grow maize and its mixtures with peas, lupine, fodder beans and soybeans, as well as turnips, and sunflower with pea as early post-hay harvest and post-harvest crops; in Polissia and the Carpathian region, lupine is also grown. For sowing in late July - early August, it is recommended to use white mustard in a mixture with peas and turnip-stubble (six-week turnips); in the Steppe, also pea and vetch-oat mixtures are recommended. In the second decade of August, it is better to sow white mustard and oilseed radish, and in the Steppe, also pea or vetch-oat mixtures.

Under-sown crops are placed in forage, field and special crop rotations before spring crops. Winter cover crops are sown after crops of occupied fallow[67], perennial grasses and early leguminous crops. When growing under-sown crops under the cover of spring crops, the latter are placed after hoed crops, late leguminous and industrial crops.

In the developed field, fodder and special crop rotations, intermediate crops can occupy up to 20-50% of the crop rotation area. Of the individual types of intermediate crops, preference should be given to winter and under-sown intermediate crops in the Carpathians, to winter, under-sown and post-hay harvest intermediate crops in the Ciscarpathia (Prykarpattia) and Polissia, to winter and post-harvest intermediate crops in the Forest-Steppe, and to post-harvest crops in the Steppe.

The structure of the sown areas of Polissia and Ciscarpathia makes it possible to place intermediate crops after cereals and annual grasses before spring crops in field crop rotations. For example, 1 – clover, 2 – winter wheat + post-harvest crops, 3 – flax + post-hay harvest crops, 4 – potatoes, root crops, 5 – barley + winter intermediate crops, 6 – maize for silage, 7 – winter rye + post-harvest crops, 8 – lupine, annual grasses + post-hay harvest crops, 9 – oats with under-sown clover.

On sandy and clay-sandy soils, a crop rotation rich in intermediate crops is recommended: 1 – lupine for green mass, 2 – rye + post-harvest crops, 3 – potatoes, 4 – rye + winter intermediate crops.

In 10-field crop rotations of the Forest-Steppe farms with a grain-beet-livestock direction of pork and poultry meat, milk and beef production, post-harvest crops are placed after winter wheat before spring grain or hoed crops, and in the Steppe after winter wheat before root crops and maize for grain; winter intermediate crops are placed after winter barley before maize for green fodder.

As plants grow and develop, the dry matter content in the green mass of forage plants during the growing season increases from 8-12% in the initial phases to 18-22% in the earing (budding) – flowering period. Then this content increases in the milky-wax and waxy ripeness phases to 27-30% and more (forage grasses, maize, winter rye and winter wheat for feed, early spring legume-cereal mixtures)[65]. The content of crude protein (or the total nitrogen) in the dry matter of plants after earing and budding, that is, after the onset of the generative period, on the contrary, decreases sharply. This is explained by the fact that at the beginning of the growing season, plants are very watered and intensively absorb nitrogen: they need 2-3 times more nitrogen per unit of dry matter than in the generative phases. Further, in the process of growth and accumulation of dry matter, they undergo the so-called "growth dilution" of nitrogenous nutrients. During a short growing season (40-55 days), winter and early spring crops as well as maize can accumulate 55-85% of the gross amount of protein and 24-48% of dry matter is **(Table 6.2)**.

67 Occupied fallow is fallow occupied by cultivated plants that are removed early to get the field ready for tillage; these crops create favorable conditions for subsequent crops.

Table 6.2. Yield of dry matter and protein in different phases of crop development[65].

Crop	Vegetation phase	Dry matter		Protein	
		centner/ha	%	kg/ha	%
Winter rye	Booting1 Start of earing Flowering	20.5 42.6 52.2	38.4 81.6 100	330 532 506	65.4 100.5 100
Winte wheat	Booting Start of earing Full earing	29.9 49.3 62.0	48.2 69.5 100	429 540 524	81.7 103 100
Maize of spring period	10 leaves Formation of cobs Milky-wax ripeness	18.0 59.0 76.2	23.6 77.3 100	258 442 426	54 103.8 100
Maize as a post-hay harvest crop; 45 cm row-spacing	8-9 leaves 10-11 leaves Formation of cobs	9.3 19.3 46.7	19.8 41.3 100	149 265 480	31 55.2 100
Maize as a post-hay harvest crop; 70 cm row-spacing	8-9 leaves 10-11 leaves Formation of cobs Milky-wax ripeness	5.7 11.2 34.6 49.8	11.5 23.5 69.5 100.0	89.5 144 388 338	26.5 41.3 114.8 100
Oat	Start of booting Full booting Emergence of panicle Full phase of panicle Milk ripeness Milky-wax and wax ripeness	12.3 26.4 43 54 57 68	18.1 38.8 64.7 79.2 83.8 100	230 378 58.8 620 690 690	33.4 54.4 85.4 89.7 100 100

Since plants accumulate dry matter more slowly, the total amount of it in 2-3 harvests or in 5-6 grazing cycles may slightly exceed or be approximately the same as when growing one, but highly productive crop during the growing season. The main gain is a 1.5-2-fold increase in protein yield.

Correct alternation of a scientifically substantiated set of crops in combination with progressive methods of soil treatment, fertilization, and maximum inclusion of intermediate crops in crop rotations make it possible to intensively use the land, increase its fertility, and improve the physical properties of the soil. Different fodder crops are used as post-hay harvest, post-harvest, under-sown, and winter intermediate crops in different zones of Ukraine **(Table 6.3).**

Intensive breeding and optimized production systems have contributed to significant increases in crop yields over the past decades. Many crops that are harvested at peak biomass yield for silage and used for biogas production are therefore known as feedstocks for food or feed production[13].

In addition to crops from the Poaceae family (true grasses such as maize, sorghum and other cereals), leaves of sugar beet and other similar crops can also be used for biogas production. The use of perennial species from the Asteraceae (aster family), Malvaceae (mallow family) and Polygonaceae (knot-grass family) for biogas production is also being discussed. Brassica (mustard family) types are not suitable due to the high sulphur content of the biomass.

Table 6.3. Ecologically sound zoning of fodder crops for use as intermediate crops in different soil and climatic zones of Ukraine[65].

Crop	For-est-Steppe	Steppe	Polissia and western regions of Ukraine	Non-chernozem (non-black earth) zone
Feed rye	4	4	4	4
Feed wheat	4	4	4	4
Maize	1; 2	1; 2	1; 2	1
Sudan grass	1; 3	1; 2; 3	1; 0	1; 0
Rapeseed				
winter rapeseed, winter cress	2; 4	4	1; 2; 4	1; 2; 4
spring rapeseed	1; 0; 2	2; 0	1; 2	1; 2
Sorghum	1; 0	1	1; 2	1; 2
Soybean	1	1	1	–
Vetch				
spring vetch	1	–	1; 2; 0	1; 0
winter vetch – Vicia pannonica	4	4	4	4
Pea	2	2	1; 2	1; 2
Lupine	–	–	1; 2	1
Sunflower	1; 2	1; 2	1; 2	1
Oat	2	2	1; 2	1; 2
Oil radish	1; 2	1; 2	1; 2	1; 2
Spring barley	2; 0	2; 0	2; 0	2; 0
Annual clover	3	3	3	–

Note: 1 – post-hay harvest crops; 2 – post-harvest crops; 3 – under-sown crops; 4 – winter intermediate crops; 0 – in some regions.

ntroduction of intermediate and cover crops in crop rotation for biogas production

In Ukraine, from 1990 to 2022, the share of areas under fodder crops in the structure of agricultural crops decreased considerably, from 37% to 6% **(Fig. 6.4).** At the same time, there was a rapid increase in the share of areas under industrial crops, from 12% to 35%. The share of areas under grain and leguminous crops also increased, from 45% to 52%, as well as the share of areas under root crops, tubers, vegetables, food melons and gourds, from 6% to 7%. It should be noted that the largest share of areas under cereals and leguminous crops was 57% in 2011 and 2013, but then they began to be replaced by industrial crops.

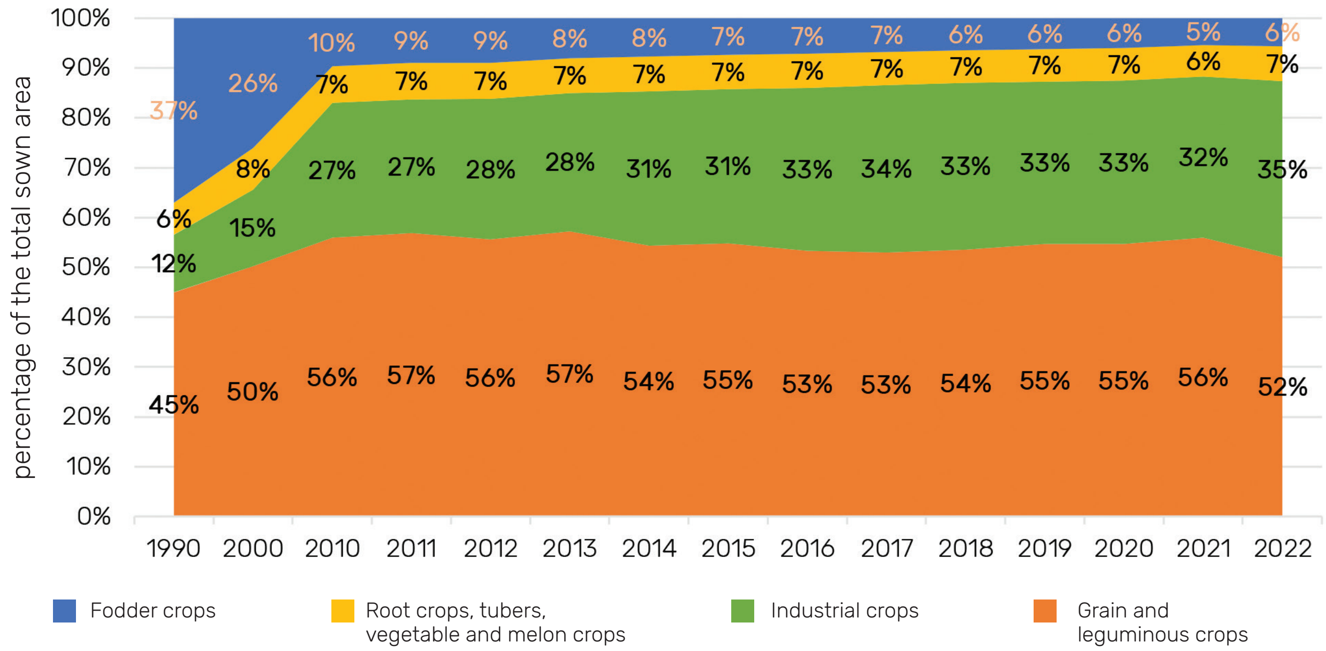

Fig. 6.4. Evolution of the structure of sown area by crops in Ukraine during 1990-2022[68]

68 https://www.ukrstat.gov.ua/

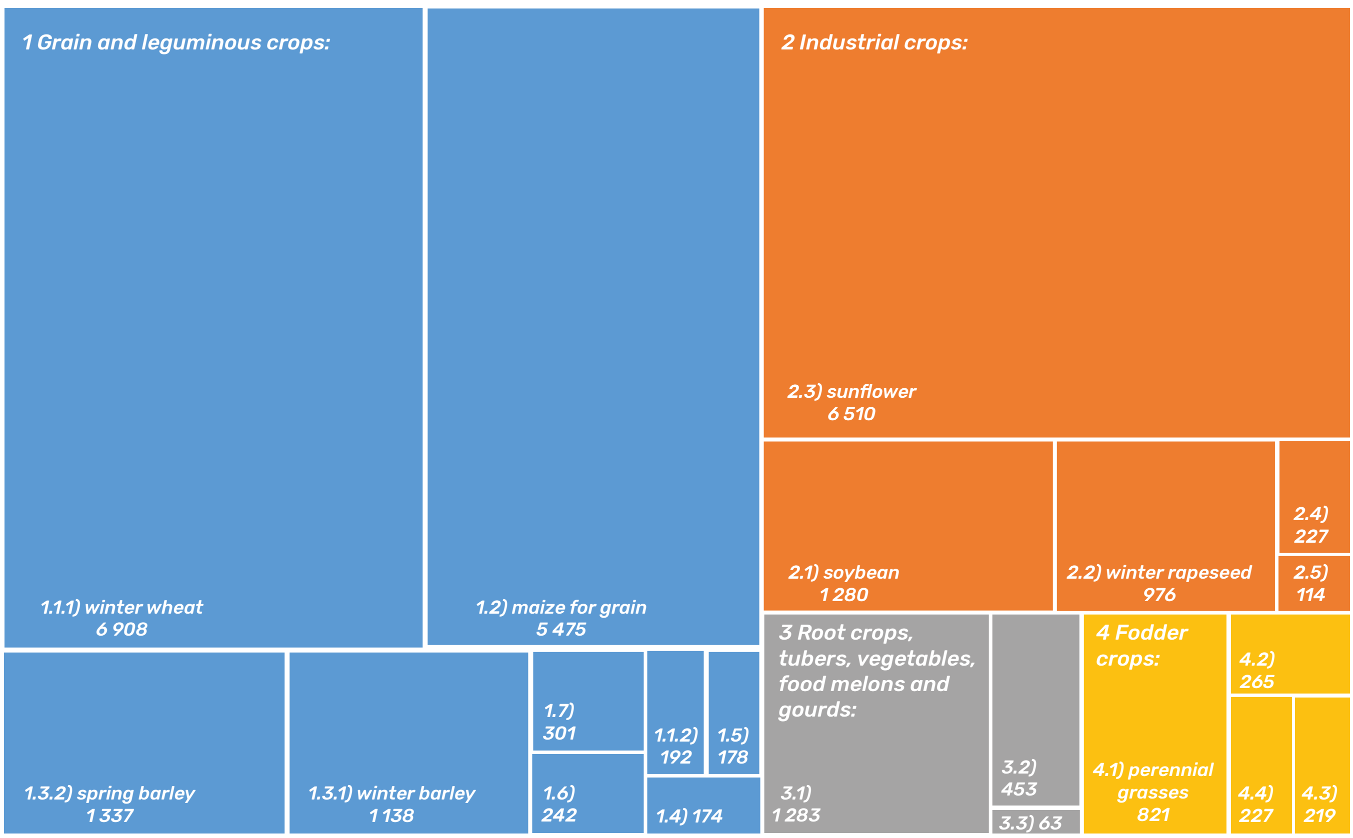

Fig. 6.5. Stricture of the sown area under agricultural crops in 2021, 1000 ha.
1 Grain and leguminous crops: 1.1.1) winter wheat; 1.1.2) spring wheat; 1.2) maize for grain; 1.3.1) winter barley; 1.3.2) spring barley; 1.4) winter rye; 1.5) oat; 1.6) pea; 1.7) other crops.
2 Industrial crops: 2.1) soybean; 2.2) winter rapeseed; 2.3) sunflower; 2.4) sugar beet; 2.5) other crops.
3 Root crops, tubers, vegetables, food melons and gourds: 3.1) potato; 3.2) open ground vegetables; 3.3) food melons and gourds. ***4 Fodder crops:*** 4.1) perennial grasses; 4.2) annual grasses; 4.3) fodder maize; 4.4) other crops.

Fig. 6.5 presents a diagram with data from the State Statistics Service of Ukraine on the areas of individual agricultural crops by crop groups: (1) grain and leguminous crops, (2) technical crops, (3) fodder crops, and (4) root crops, tubers, vegetables, food melons and gourds. In total, agricultural crops occupied 28387.5 th. ha in 2021. The largest areas were occupied by winter wheat (about 6.9 Mha), sunflower (6.5 Mha), maize for grain (5.5 Mha), soybeans (1.3 Mha), spring barley (1.3 Mha), winter barley (1.1 Mha), rapeseed (1 Mha) and potatoes (1.3 Mha, of which 98.5% is located at households). Thus, the following **main agricultural crops** can be distinguished: winter wheat, winter and spring barley, maize for grain, sunflower, soybean and rapeseed. These crops occupy more than 4/5 of the sown area in Ukraine, and the **cultivation of intermediate and cover crops for bioenergy can potentially be introduced in the rotation of these crops.**

Approaches to determining the **optimal ratio of agricultural crops** in different soil and climatic zones of Ukraine are described in the Order of the Ministry of Agrarian Policy of Ukraine and the Ukrainian Academy of Agrarian Sciences No. 440/71 of 18.07.2008[69]. The scientific principles of creating crop rotations envisage the correct selection of forecrops and the optimal combination of single-species crops with observance of the permissible periodicity of their return to the same field. At the same time, it is necessary to adapt production to the natural and climatic conditions of the regions. The productivity of crops largely depends on their placement in the crop rotation. The possibility of obtaining the maximum yield depends on the placement of crops after the best forecrops. It is necessary to avoid excessive inclusion of crops that are biologically close to each other (spiked grains, legumes) in the crop rotation. It is not recommended to place spiked grains after spiked crops for more than two years, as well as legumes after legumes.

In present conditions, with growing demand for grain and oilseed products, an example of the optimal short crop rotation can be, in particular, a ***four-field*** crop rotation with the following crops[70]:

> *1) perennial leguminous grasses, leguminous or fodder crops;*
>
> *2) winter wheat;*
>
> *3) sunflower, leguminous crops, maize and others, except for grain stubble crops;*
>
> *4) spring barley, spring wheat, annual grasses, and annual grasses with the under-sowing of perennial grasses.*

To plan the cultivation of intermediate and cover crops, in addition to their biological interaction with forecrops and aftercrops in crop rotation and their impact on soil fertility, it is important to determine the periods when the fields are free from main crops, but at the same time, there are favourable agroclimatic conditions for plant vegetation. The generalized typical periods for cultivating main agricultural crops in Ukraine are shown in **Fig. 6.6.** Thus, winter wheat is mainly sown in September-October and harvested in July-August, while maize is sown in April-May and harvested in September-November. Therefore, if maize is grown in crop rotation after winter wheat, there is an opportunity to introduce **post-harvest intermediate crops,** the biomass of which can be used for bioenergy.

69 https://zakon.rada.gov.ua/rada/show/v0440555-08#Text

70 https://agro-business.com.ua/agro/ahronomiia-sohodni/item/10145-systema-dynamichnoi-sivozminy.html

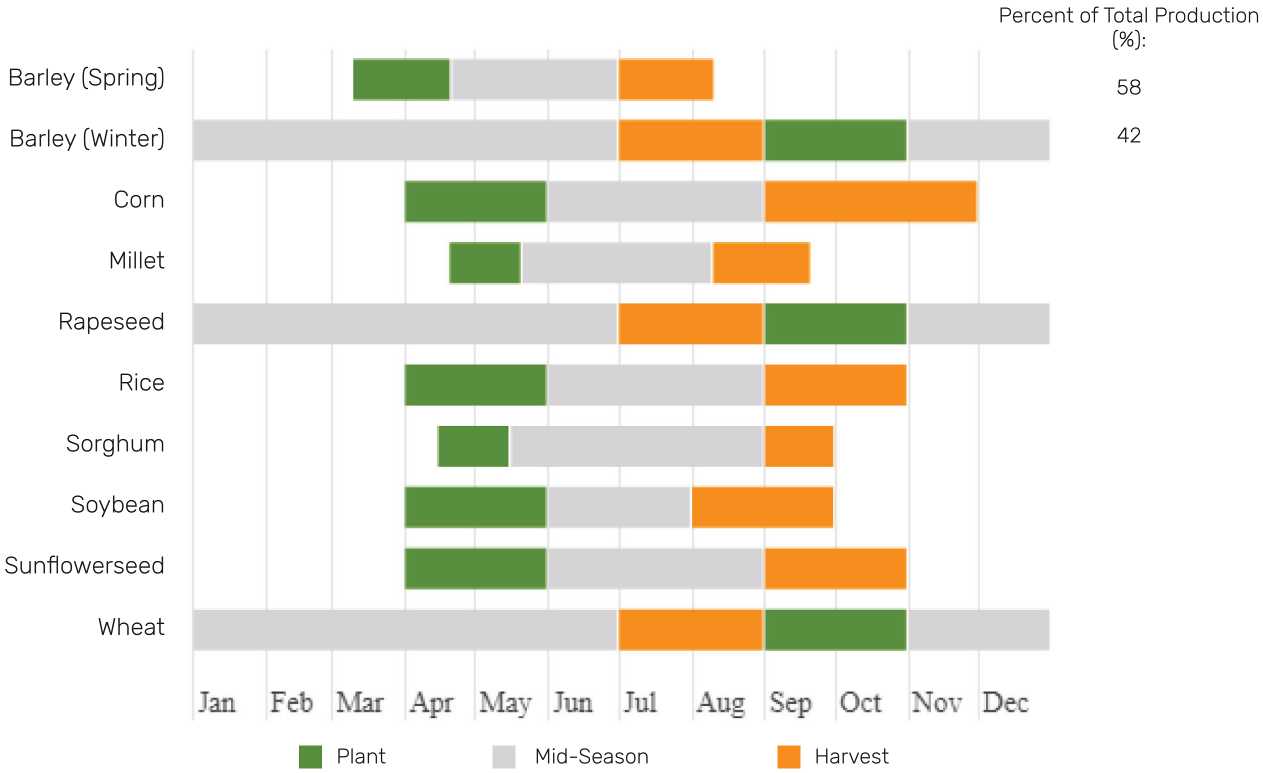

Fig. 6.6. Crop calendar for Ukraine[71]

71 https://ipad.fas.usda.gov/countrysummary/Default.aspx?id=UP

A similar approach can be used to introduce **intermediate crop** cultivation after winter rapeseed before grain maize.

In Ukraine, the following crops can be used as intermediate crops for biomass production in the current year and subsequent biogas/biomethane production: spring cereals (after early preceding crops), corn (early-maturing hybrids under favourable conditions), sorghum, and vetch. For early biomass harvesting in the following year for similar bioenergy use, winter intermediate crops such as green rye (KWS Propower[72], KWS Magnifico[73]), triticale (Veleten[74]), winter wheat, and winter barley (at early stages of development) can be considered. Furthermore, other types of intermediate and cover crops are also being explored. Among these, amaranth is promising due to its drought resistance, resilience, and ability to quickly build up significant biomass for obtaining green mass intended for further biogas and biomethane production[75]. The green mass yield of amaranth ranges within 50-90 t/ha and can reach 100-150 t/ha[76]. Soufflet Agro Ukraine has published a reference book on cover crops[77], which contains characteristics of 21 plants from the Asteraceae, Watercress, Brassica, Legume, Flax and Buckwheat families. This reference book can be used when planning the introduction of cover crop cultivation in Ukraine.

KWS offers special winter rye hybrids for biogas production. The green mass of hybrid rye yields 4,320 m^3 of biomethane/ha **(Table 6.5)**, which is 31% less than per hectare of maize for silage (maize as an energy crop).

72 https://www.kws.com/ua/uk/produkty/zernovi/zhyto/oglyad-gibry-div-ozymogo-zhyta/kws-propauer/

73 https://www.kws.com/ua/uk/produkty/zernovi/zhyto/kws-mag-nifiko/

74 https://agroflyer.com/ru/tritikale-ozime-veleten-rrnns-9171.html

75 https://uabio.org/wp-content/uploads/2025/02/Vykorystannya_amarantu_v_bioenergetytsi.pdf#page=4.00

76 https://agrarii-razom.com.ua/culture/amarant-na-zeleniy-korm

77 https://www.soufflet-agro.com.ua/media/filer_public/30/ad/30ad6456-a305-4547-83e2-572c68a68a90/sa_cover_crop_guide_ua_web.pdf

In 2021, KWS gave SEC "Biomass" three silage samples: rye silage RS 39 (harvested before spike emergence), RS 65 (harvested after flowering), and RS 73 (harvested in the milky-wax ripeness phase). All the samples were tested for dry matter content, organic matter content, and biogas yield. Results of the studies showed that as the growing period increased, the amount of dry matter also increased, while the ash content of the silage decreased **(Fig. 6.7)**.

With the extension of the harvesting period, the methane yield per kilogram of biomass also increases. As for the methane yield per kilogram of organic matter, the value is up to 350 l/kg DOM when harvesting before the pike emerges. When harvesting after flowering, the yield decreases a bit (to 300 l/kg DOM). The highest methane yield (350 l/kg DOM and more) can be achieved in the case of harvesting in the milky-wax ripeness phase. These figures are close to those obtained for maize silage.

Thus, the potential of methane yield is the highest for rye silage harvested in the milky-wax ripeness phase. Silage harvested in the flag leaf phase (late April - early May) also shows high results. Harvesting during this period is advisable for farms with normal moisture supply because another crop can be sown after rye.

Table 6.5. Comparison of the yield of biogas and biomethane[78].

Indexes	Maize as energy crop	Hybrid rye
Yield of green mass (t/ha)	60	35-40
Content of dry matter, %	27-31	33-36
Yield of biogas, m^3/t (green mass)	200	200
Methane conversion, %	53	54
Yield of methane, m^3/t (green mass)	105	108
Yield of methane from area, m^3/ha	6300	4320

Sample code	Dry matter	Dry orgaic matter (DOM)
	%	% d.m.
RS-39	26.78	89.05
RS-65	32.99	91.41
RS-73	36.13	94.97

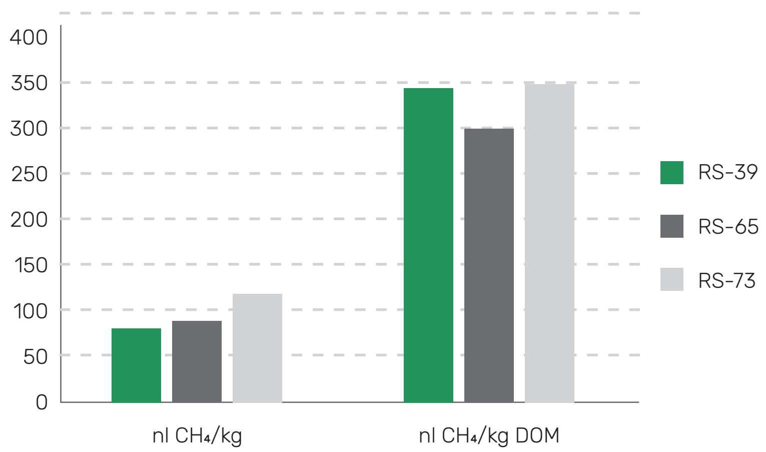

Fig. 6.7. Results of experimental study by SEC "Biomass" of biogas yield from rye silage[79]

78 https://www.kws.com/ua/media/cereals_ua/katalog-gibrydiv-ta-sortiv-zernovyh-kultur-ta-ozymogo-ripaku-2023.pdf

79 https://propozitsiya.com/ua/zlakovi-sylosy-perspektyva-dlya-vyrobnyctva-biogazu

Feasibility of growing and harvesting intermediate and cover crops in Ukraine

SECTION 7

Initial data

Let us consider an example of growing intermediate (cover) crops for biogas production in the existing crop rotation between winter rapeseed and grain corn (maize) on 2000 ha in the Forest-Steppe zone **(Table 7.1)**. It is proposed to sow post-harvest crops in July on 1000 ha after winter rapeseed which will be harvested in June-July, and then to sow winter intermediate crops in August on the remaining 1000 ha area after winter rapeseed. Post-harvest crops will be harvested in October-November. Winter intermediate crops will be harvested in May before the start of sowing maize. The choice of intermediate crops is determined by their ability to quickly form green mass from July to November for post-harvest crops and from August to May for winter intermediate crops.

In Ukraine, there is a practice of sowing a vetch-oat mixture as a post-hay harvest crop and a post-harvest crop to provide livestock with green fodder, harvest hay and obtain green manure. It is preliminarily proposed to grow a vetch-oat mixture as a post-harvest crop, and hybrid rye as a winter intermediate crop. The yield of green mass of a vetch-oat mixture will be conservatively assumed as 4 t d.m./ha, or 13.3 t/ha of biomass with 70% moisture content. The same for the green mass of winter rye is 8 t d.m./ha and 26.7 t/ha (70% biomass moisture content). It should be noted that the yield of green mass of intermediate crops can be significantly higher, in particular, 27.8 t/ha[80] for a vetch-oat mixture and 42 t/ha[81] for winter rye hybrids. Therefore, to obtain a high yield of biomass per unit of area, it is advisable to conduct trial sowing different types of cover crops and select varieties that are optimal for the local conditions.

The duration of green mass harvesting is up to 2 weeks. The approximate distance of biomass transportation is 20 km. The harvested green mass should be ensiled. Let us determine the costs of growing and harvesting a green mass of winter rye and vetch-oat mixture.

80 https://propozitsiya.com/ua/rol-pokrivnih-kultur-pid-chas-virosh-chuvannya-bagatorichnih-trav

81 https://superagronom.com/news/269-viroschuvannya-ozimogo-ji-ta-na-korm-vigidnishe-vid-posivu-bagatorichnih-trav

Table 7.1. An example of introducing intermediate crop cultivation into an existing crop rotation.

<table>
<tr><th colspan="12">1st year (months)</th><th colspan="12">2nd year (months)</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th></tr>
<tr><td colspan="24">Existing crop rotation</td></tr>
<tr><td colspan="6">Winter rapeseed</td><td></td><td colspan="9">Fallow</td><td colspan="7">Grain maize</td><td></td></tr>
<tr><td colspan="24">New crop rotation (post-harvest crop)</td></tr>
<tr><td colspan="6">Winter rapeseed</td><td colspan="5">Post-harvest crop</td><td colspan="5">Fallow</td><td colspan="7">Grain maize</td><td></td></tr>
<tr><td colspan="24">New crop rotation (winter intermediate crop)</td></tr>
<tr><td colspan="7">Winter rapeseed</td><td colspan="9">Winter intermediate crop</td><td></td><td colspan="6">Grain maize</td><td></td></tr>
</table>

Cost estimation for growing and harvesting rye as a winter intermediate crop

Winter rye stalk is a straw of 70 to 200 cm high[82]. It blooms in 2 weeks after earing. 1000 seeds weigh 13-55 g. Winter rye grows well on podzolic, sandy, peat bog, heavy clay and other soils. It gives higher yields on chernozems and dark grey forest soils. It is not very demanding on heat. The seeds begin to germinate at a soil temperature of 1-2°C at a depth of sowing. At 12-14°C, shoots appear in 6-8 days after sowing. The tillering phase occurs in 10-15 days after the emergence of shoots. Cold resistance is high. The increment of green mass increases until the flowering phase. When harvested in the tube phase and with moisture in the soil, the plant grows well and gives a high yield of after-grass. The duration of the growing season is 270-360 days. Winter rye is grown for fodder in the Forest-Steppe, Polissia, and the Steppe. It occupies the leading place in the "green conveyor" system. In the spring, the green mass is used for animal feeding.

Hybrid rye from KWS company is a high-tech crop that combines all the advantages of rye as a species – plasticity, adaptability, resistance to diseases, pests and soil and soil-climatic factors. At the same time, it has the advantages of the heterosis effect, high yield and stability. The technology for growing KWS hybrid rye for silage is shown in **Fig. 7.1.**

The increment of green mass of rye increases before the beginning of earing. After the exit into the tube, the fibre content increases, the specific weight of the leaves decreases, the quality of green fodder deteriorates, and animals consume the fodder less readily[83]. The optimal phase for harvesting rye for silage is the full exit of BBCH 39 flag leaf[84] before the spike exit[85].

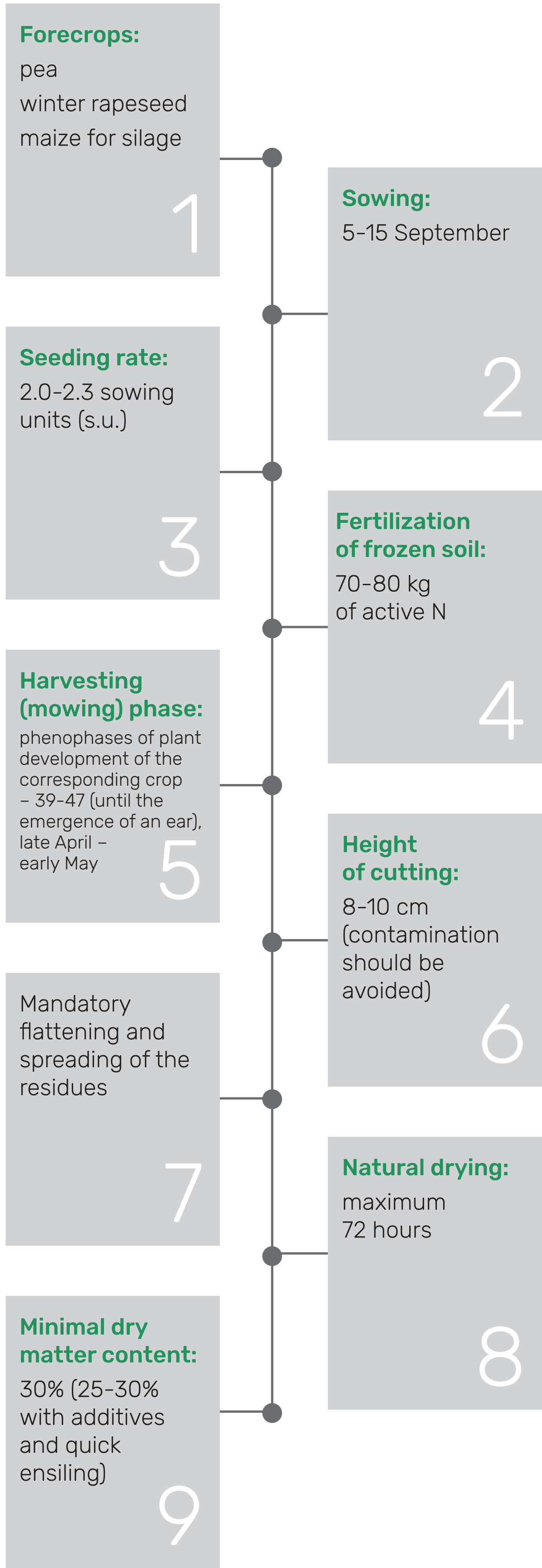

Fig. 7.1. Technology for growing KWS hybrid rye for silage[79]

82 https://crops.udau.edu.ua/assets/files/kormi/korm.dovid-nik.2018.pdf

83 https://dspace.mnau.edu.ua/jspui/bitstream/123456789/3174/1/Antipova_L.Kormovirob_KL_2014.pdf

84 BBCH is an international system for describing plant development stages, used in agronomy to standardize the definition of plant development at all stages. https://agroexp.com.ua/uk/chto-takoe-vvsn

85 https://superagronom.com/articles/378-jito-ozime-teh-nologiya-viroschuvannya-obrobitok-gruntu-dobriva-nasinnya-za-hist-ta-zbirannya

To reduce the moisture content of the green mass, rye is mowed and left in the field for wilting before being laid for ensiling. The dry matter content of 30-35% in the biomass reduces the risks of deterioration of ensiling due to excess moisture and improves the nutritional value of the final product. The general scheme of harvesting a green mass of rye with preliminary drying looks like this:

> *1. Mowing with flattening (wide spreading or moderate mowing).*
>
> *2. Turning over (1-2 times) for faster and more uniform moisture loss.*
>
> *3. Windrowing (with a windrow former) when the moisture content drops to 65-70%.*
>
> *4. Picking up the windrows with a forage harvester, chopping and transporting biomass to the laying site.*

Based on the data in **Fig. 7.1,** a list of technological operations for growing and harvesting hybrid rye for silage was determined to estimate the costs of cultivation **(Table 7.2).** The technology under consideration assumes fertilizing frozen soil at a rate of 70-80 kg of active nitrogen. Given that the digestate after fermentation of rye silage mass in a biogas plant is applied to the fields as fertilizer, nutrients will be returned for the next crop of the crop rotation. Therefore, the cost of mineral fertilizers will not be taken into account.

At a seed sowing rate of 2 s.u./ha and a cost of 45 EUR/s.u. excluding VAT, the cost of seeds will be 90 EUR/ha. Plant protection products (PPPs) will be used if necessary[86], so let us take into account the cost of one treatment by herbicides and fungicides as 10 EUR/ha excluding VAT. Thus, the cost of seeds, growth regulators and PPPs will be 100 EUR/ha.

For 1000 hectares, labour cost is 6993 EUR, and fuel consumption is 74863 litres. The cost of diesel fuel is 1 EUR/l excluding VAT. Lubricant cost is 15% of the diesel fuel cost. We assume that expenditures on maintenance and repair of machinery are 5% of the machinery cost. The depreciation period of machinery is 8 years. The total production costs for growing and harvesting green mass of winter rye are given in **Table 7.3.**

Thus, the **specific cost** of growing and harvesting a green mass of winter rye from 1000 ha with delivery to the silo is **13.4 EUR/t** or 44.7 EUR/t d.m. at the biomass moisture content of 70%. If we exclude the technological operations of applying mineral fertilizers (see No. 3-5 in **Table 7.2**) and flattening, turning over and windrowing (see No. 7-9 in **Table 7.2**), the specific costs of growing and harvesting rye will be 12.2 EUR/t or 40.7 EUR/t d.m.

Cost estimation for growing and harvesting a vetch-oat mixture as a post-harvest crop

Spring vetch (pea) occupies a leading place in terms of fodder value among annual leguminous grasses. It is used for fodder in the form of green mass, hay, silage, grass and grain flour. Spring vetch is sown mainly in mixtures with oats or barley, cabbage and other crops. The yield of spring vetch in a mixture with oats is 200-350 centner/ha of green mass, 50-75 centner/ha of hay, and 15-25 centner/ha of seeds[87].

Vetch is a moisture-loving crop; in arid conditions, its yield decreases sharply. It absorbs the most water during the intensive growth of vegetative mass and the phases of flowering and fruit formation. The vegetation period lasts 75-90 days, and when grown for green mass, the duration of the growing season is 50-70 days.

The vetch-oat mixture is also grown as a post-hay harvest crop and post-harvest crop. For the formation of 1 ton of hay, spring vetch removes 6 kg of P_2O_5, 15-17 kg of K_2O, a lot of calcium and magnesium, as well as molybdenum from the soil. It responds positively to the direct application of fertilizers and also uses their aftereffect when the forecrop is fertilized. If mineral fertilizers were not applied during the main or pre-sowing tillage, it is advisable to apply granulated superphosphate (50 kg/ha) during sowing.

The sowing method is an ordinary row and narrow-row one, which ensures uniform placement of seeds in the area. At the same time, weeds are well suppressed by vetch plants.

86 https://www.kws.com/ua/uk/produkty/zernovi/zhyto/tehlogiya-vy-roshchuvannya-gibrydnogo-zhyta/

87 Progressive technologies for growing fodder crops / Editors: D.I. Mazorenko and G.Ye. Maznev. – Kharkiv: «Maidan». – 2008. – 333 p.

Table 7.2. List of technological operations for growing and harvesting winter rye for silage, and fuel consumption data.

Name of technological operations	Unit	Area/ mass	Set of machinery		Production rate, ha/h (t/h)	Specific fuel consump-tion, l/ha (l/t)	Fuel consump-tion, l
			Motor machinery	Agricultural machinery			
1. Disking	ha	1000	NH 7.315HD	BDVP-7,2	6	10.0	10000
2. Winter rye sowing	ha	1000	NH 7.315HD	Lemken Solitair 9/600	5	7.0	7000
3. Fertilizer loading	t	(235)	Manitou 733		(3.5)	(0.6)	141
4. Fertilizer transportation	t	(235)	Вантажівка		(3.5)	(0.8)	188
5. Fertilization of frozen soil	ha	1000	NH td 5.140	Amazone ZA-M 1501	15	1.0	1000
6. Spraying PPPs	ha	1000	John Deer M4040		35	0.6	600
7. Mowing with flattening	ha	1000	NH td 6.180	Krone EasyCut B1000 CR	10	2.2	2200
8. Turning over	ha	1000	NH td 5.140	Krone KWT 2000	15	1.0	1000
9. Windrowing	ha	1000	NH td 5.110	Krone TC 1370	10	1.4	1400
10. Collection by self-propelled forage harvester	ha	1000	Krone BigX630		3	30.0	30000
11. Transportation	t	(26667)	Lorries (trucks)		(80)	(0.8)	21333
Total							**74863**

Table 7.3. Specific expenditure for growing and harvesting winter rye for silage on 1000 ha.

N	Articles of expenditure	Cost, EUR/t	Share, %	Notes
1	Labour	0.26	2.0%	4 EUR/h or 32 EUR/shift of 8 hours; 0.22 norm*shift/ha
2	Fuel and lubricants	3.26	24.3%	Diesel: 74.9 l/ha. Lubricants: 15% of the diesel cost
3	Maintenance and repair	1.75	13.0%	5% of the machinery cost
4	Depreciation of equipment	4.36	32.6%	8 years
5	Seeds and PPPs	3.75	28.0%	Seeds (2 s.u./ha), PPPs
	Total	**13.38**		

For green fodder and hay, vetch is sown at a rate of 2.2-2.4 million/ha and oats at a rate of 1.4-2 million/ha of similar seeds. In the Steppe, the seeding rate is reduced by 15-20%. For germination, vetch seeds require sufficient moisture, so they are inserted to a depth of at least 4-5 cm. In the case of light soils and dry weather, the depth is increased to 5-6 (7) cm.

Vetch crops and their mixtures for fodder purposes are usually little affected by pests and diseases. Therefore, pesticides are not used for these crops.

For green mass and grass flour, the vetch-cereal mixture is harvested at the beginning of vetch flowering, for hay and haylage – in the full flowering phase, and for silage – in the phase of blue-grey beans.

The list of technological operations for growing and harvesting spring vetch with oats on 1000 ha is presented in **Table 7.4.** When sowing, it is recommended to apply 50 kg/ha of granulated superphosphate, the cost of which is not taken into account due to returning nutrients with the digestate from a biogas plant to the field. The cost of seeds of a vetch-oat mixture at the sowing rate of 2.2 million/ha of vetch seeds and 1.5 million/ha of oat seeds is 80 EUR/ha excluding VAT.

For 1000 hectares, labour cost is 4682 EUR, and fuel consumption is 51967 litters. The cost of diesel fuel is 1 EUR/l excluding VAT. Lubricants cost is 15% of the diesel cost. We assume that expenditure on maintenance and repair of machinery is 5% of the machinery cost. The depreciation period of the machinery is 8 years. The total production costs for growing and harvesting green mass of winter rye are given in **Table 7.5.**

Thus, **the specific cost** of growing and harvesting a green mass of vetch and oats from 1000 ha at the yield of **13.3 t/ha** with delivery to the silo is **18 EUR/t** or 60 EUR/t d.m. at 70% biomass moisture content.

Table 7.4. Technological operations for growing and harvesting spring vetch with oats for silage.

Name of technological operations	Unit	Area/ mass	Set of machinery		Production rate, ha/h (t/h)	Specific fuel consump-tion, l/ha (l/t)	Fuel consump-tion, l
			Motor machinery	Agricultural machinery			
1. Disking	ha	1000	NH 7.315HD	BDVP-7,2	6	10.0	10000
2. Sowing with applying mineral fertilizers	ha	1000	NH 7.315HD	Lemken Soli-tair 9/600	5	7.0	7000
3. Mowing with flattening	ha	1000	NH td 6.180	Krone Easy-Cut B1000 CR	11	2.0	2000
4. Turning over	ha	1000	NH td 5.140	Krone KWT 2000	15	1	1000
5. Windrowing	ha	1000	NH td 5.110	Krone TC 1370	10	1.3	1300
6. Collection by self-propelled forage harvester	ha	1000	Krone BigX630		5	20.0	20000
7. Transportation	t	(13333)	Lorries (trucks)		(67)	0.8	10667
Total							**51967**

Table 7.5. Specific expenditure for growing and harvesting vetch and oats for silage on 1000 ha.

N	Articles of expenditure	Cost, EUR/t	Share, %	Notes
1	Labour	0.35	2.0%	4 EUR/h or 32 EUR/shift of 8 hours, 0.15 norm*shift /ha.
2	Fuel and lubricants	4.52	25.2%	Diesel: 52 l/ha. Lubricants: 15% of the diesel cost.
3	Maintenance and repair	2.02	11.3%	5% of the machinery cost.
4	Depreciation of equipment	5.05	28.2%	8 years
5	Seeds	6.00	33.4%	Seeds: 2 million/ha for vetch and 1.5 million/ha for oats.
	Total	**17.95**		

Feasibility study of biomethane production from intermediate and cover crops in Ukraine

SECTION 8

To assess the technical and economic parameters of a project on biomethane production from intermediate and cover crops, the following project concept is considered. The feedstock is supplied by an agricultural enterprise that owns **10 thousand hectares** of land in a compact location within one management district, as well as a **pig farm** with an average livestock of **18 thousand heads**. It is assumed that 20% of the land is allocated for growing cover/intermediate crops, of which 1000 ha are allocated for the post-harvest green mass of vetch-oat mixture, and another 1000 ha for winter rye as an intermediate crop. The choice of this model is due to the fact that the use of manure in advanced biomethane production projects allows for additional reductions in greenhouse gas emissions and, consequently, its carbon footprint. This, in turn, may increase the demand for such biomethane and its possible selling price when exported to the European renewable biofuels market.

Given the assumed yield of these crops, their yield will total 40 kt/y, including 26,667 t of winter rye and 13,333 t of vetch-oat mixture (*see* ***section 7 for more details***). For the storage and use of such feedstock during the year, it is planned to build concrete silos of about 60 thousand m^3 total volume. With 6% of the silage mass storage losses, the actual supply of the feedstock to a biomethane plant will be 25,067 t/y of winter rye silage of 30% DM content and 12,533 t/y of vetch-oat mixture silage of 30% DM content. The estimated manure yield from the pig farm is 90 kt/y. The assumed manure moisture is 96%.

To meet the needs of the entire biomethane complex in electricity and heat, it is planned to partly produce biogas from maize silage with subsequent combustion of the biogas in a cogeneration plant. The assessed need for maize silage is 14,014 t/y, which requires the supply of 14,909 t/y of green maize mass of 35% DM content to the silo. With the yield of the maize green mass of 50 t/ha, it will be necessary to allocate about 300 ha, or 3% of the land of the enterprise under consideration. Using part of the produced biogas to meet the complex's own energy needs is considered a way to reduce the carbon footprint of the produced biomethane, and therefore to increase the possible price of its guarantees of origin.

The concept of the biomethane production project assumes that rye silage, vetch-oat mixture silage and maize silage will be supplied by a separate division of the agricultural company at a price that takes into account profitability at the level of 25%. At the same time, the costs of ensiling and supplying silage from the silo to the biogas plant will be included in the biomethane project costs. The digestate formed during the feedstock processing into biogas is expected to be applied to the company's fields for the main crops. The costs of transporting and applying digestate are not included in the biomethane project costs.

The technological concept of the project involves the production of biogas in an agricultural-type biogas plant with horizontal cylindrical reactors. The biogas plant will include main fermenters and a fermenter for post-digestion. Part of the produced biogas, after preliminary drying and removal of hydrogen sulphide, will be fed into a cogeneration plant for electricity and heat production. The main part of biogas will be fed into an installation for biogas purification and enrichment (upgrading) to biomethane. The project considers the option for carbon dioxide purification to food quality and liquefaction of CO_2 released during the biogas enrichment process. A boiler plant on pellets from agricultural biomass is envisaged, which will provide the heating of the bioreactors during biological start-up, as well as backup in case of downtime of the biogas cogeneration plant.

The concept for the final product use assumes that the produced biomethane will be supplied into Ukraine's gas-transport system with the sale of guarantees of origin on the European market of renewable biofuels. The food carbonic acid will be sold on the domestic market, and the digestate will be applied to the company's fields. The estimated equivalent cost of digestate may be 2.95 EUR/t.

The financial model takes into account the price of digestate for the agricultural company at 1.8 EUR/t including VAT.

The assessed yield of biogas from the input mass of the silage mixture is 10.46 million nm^3/y with 57% CH_4 concentration **(Table 8.1)**.

Biogas originating from rye silage, vetch-oat mixture silage and manure in the volume of 7.7 million nm^3/y, or about 880 nm^3/h, will be sent for enrichment. The enrichment is planned using membrane technology. The volume of produced biomethane that will be injected into the gas transmission network is 4.46 million nm^3/y, the content of CH_4 being 98%. The mass of produced commercial liquefied carbon dioxide of 99.99% purity will be 5620 t/y.

The digestate output will be approximately 128,249 t/y. After the separation in a screw separator, 106,153 t/y of the liquid fraction will be sent into a lagoon for storage until applied to the fields twice a year. The lagoon volume will be 58,400 m^3. The output of the solid fraction of the digestate will be 22,096 t/y.

The total electricity needs of the entire biomethane complex will be 6,386 MWh/y, which includes the biogas production complex, digestate separation, biogas enrichment to biomethane, CO_2 liquefaction, and biomethane compression for supplying into the gas transmission network. The total connected electrical load is 729 kW_e.

To maintain the required temperature in the bioreactors, it will be necessary to supply 7485 MWh/year. The heat produced in the cogeneration plant, taking into account the waste heat from the biogas enrichment process, will be sufficient to cover these needs.

The estimated project investments (CAPEX) amounted to 14.2 million EUR, including VAT and customs duties **(Table 8.2).** The lion's share of the investments (43.4%) falls on the biogas production complex. The specific investment in the biogas production complex is 2185 EUR per kW of equivalent electrical capacity of the biogas cogeneration unit, which corresponds to the average price level on the market for installations of a similar scale. Significant components of the investments are also the biogas enrichment complex to biomethane (16.2%), the CO_2 liquefaction complex (10.4%), and the ensiling unit (11.4% in total).

Table 8.1. Calculated indicators for biogas yield and feedstock composition.

Index	Unit	Mixture, total	Feedstock:			
			Winter rye silage	Pig manure	vetch-oat mixture silage (30%/70%)	Maize silage
Assumed biochemical potential of methane yield (BMP)	nm^3CH_4/t DOM	**328.6**	340.0	360.0	340.0	350.0
	nm^3CH_4/t	**114.6**	93.8	12.2	93.8	113.9
Biogas	nm^3/t DOM	**581.3**	618.2	553.8	618.2	636.4
Efficiency	%	**95.0**	95	95	95	95
Production of CH_4	nm^3CH_4/day	**16 206**	6 122	2 867	3 061	4 155
	nm^3CH_4/y	**5 915 203**	2 234 673	1 046 520	1 117 292	1 516 718
Production of biogas	nm^3/day	**28 664**	11 132	4 411	5 566	7 555
	nm^3/y	**10 462 181**	4 063 042	1 610 031	2 031 440	2 757 669
Production of CO_2	nm^3CO_2/day	**12 171**	4 898	1 500	2 449	3 324
% CH_4	%	**56.5**	55	65	55	55
%CO_2	%	**42.5**	44.0	34.0	44.0	44.0
Total nitrogen content	kg N/t	**3.7**	5.4	2.8	6.2	4.5
C : N	-	**16.6**	25.6	5.7	21.6	34.4

Table 8.2. CAPEX of the project.

Components of the investments	Total, EUR	Share of the total
TOTAL	**14 222 304**	**100.0%**
Machinery and equipment	**8 360 040**	**58.8%**
Construction and mounting	**5 045 029**	**35.5%**
Other	**817 235**	**5.7%**
Biogas production complex	6 179 005	43.4%
Machinery and equipment for ensiling and silage transportation to the biogas plant	351 000	2.5%
Silage storage	1 263 511	8.9%
Biogas cogeneration plant	859 974	6.0%
Back-up biomass boiler plant	155 506	1.1%
Biogas to biomethane upgrading complex	2 309 954	16.2%
CO_2 liquefaction complex	1 485 498	10.4%
Biomethane supply into gas-transport system (main and backup gas compressors, 5 km gas pipe, gas accounting unit, gas chromatograph)	1 172 070	8.2%
Machinery and equipment for CO_2 logistics	195 077	1.4%
Connection to power grid	68 987	0.5%
Machinery and equipment for digestate handling	61 724	0.4%
Designing	120 000	0.8%

The total annual operating expenses (OPEX) are estimated at 2.36 million EUR including VAT **(Table 8.3)**, which is 16.6% of the CAPEX. The main project expenditures are related to the purchase, supply and transportation of feedstock (61.7% in total).

The basic tariffs and prices adopted in the financial model are given in **Table 8.4.** The basic exchange rate is 47.13 UAH/EUR.

The assessment of the possible price for biomethane was made on the basis of data from biomethane traders, taking into account the estimated carbon footprint of such biomethane.

The calculation of GHG emission reductions was carried out in accordance with RED II provisions, in particular the methodology for calculating emission reductions set out in Annex VI B (biomass fuels). When calculating GHG emission reductions, one of the permitted approaches was applied, namely a combination of estimated values and disaggregated default values. The disaggregated default values were used partially for manure and maize silage. The estimated GHG emission reductions for each type of feedstock (raw materials) are given in **Table 8.5.**

As can be seen from the calculation results, all types of feedstocks (raw materials) provide the required level of GHG emission reduction, which is 65% for transport fuels. The averaged total emissions (E) for the entire final product (BIOMETHANE) amount to (-13.00) gCO_{2eq}/MJ.

The project generates revenue from the sale of 43,599 MWh of biomethane, 5,620 t/y of liquefied carbon dioxide and 128,249 t/y of digestate. The total revenue is estimated at 4.865 million EUR/y excluding VAT. The main revenue, about 80.6% at the adopted prices, is generated from the sale of biomethane; another 15.4% of the revenue is generated from the sale of carbon dioxide, and only 4% from digestate.

Table 8.3. OPEX of the project.

Components of operating expenses	Total, EUR/y	Share of the total
OPEX, TOTAL	**2 358 495**	**100.0%**
Feedstock	**1 247 296**	**52.9%**
Feedstock logistics	**208 332**	**8.8%**
Operating expenses	**342 243**	**14.5%**
Target product logistics	**464 102**	**19.7%**
Labour cost	**96 522**	**4.1%**
Feedstock	1 247 296	52.9%
Feedstock logistics	208 332	8.8%
Biogas production	143 756	6.1%
Combined heat and power production by the biogas cogeneration plant	94 273	4.0%
Maintenance of the back-up biomass boiler plant	31 711	1.3%
Upgrading of biogas to biomethane	131 889	5.6%
CO_2 liquefaction	37 137	1.6%
Liquified CO_2 logistics	107 911	4.6%
Biomethane logistics	273 679	11.6%
Digestate handling	82 512	3.5%

Table 8.4. Basic tariffs and prices adopted in the financial model (excluding VAT).

Index	Unit	Value
TARGET PRODUCTS		
Biomethane price	EUR/MWh*	90
Liquefied CO_2 price	EUR/t	133
Digestate price	EUR/t	1.5
FEEDSTOCK		
Winter rye silage	EUR/t	17.82
Pig manure	EUR/t	0
Vetch-oat mixture silage	EUR/t	23.87
Maize silage	EUR/t	20.95
ENSILING AND SILAGE LOGISTICS		
Winter rye silage	EUR/t	3.45
Vetch-oat mixture silage	EUR/t	3.45
Maize silage	EUR/t	3.14
TARGET PRODUCT LOGISTICS		
Liquefied CO_2	EUR/(t•km)	0.05
Biomethane: tariff for the point of entry into Ukraine's gas-transport system	UAH/(1000 m^3/day)	464.37
Biomethane: tariff for the entry and exit points at the interstate connections	EUR/(1000 m^3/day)	25.66

* 1 MWh of biomethane energy content = about 100.28 nm^3 CH_4

Table 8.5. Total emissions for the target products by feedstock type, g CO_{2eq}/MJ of the final product (biomethane).

Components of emission assessment	Feedstock:			
	Silage of winter rye green mass	Silage of vetch-oat mixture	Wet manure	Maize silage
Emissions from extraction and cultivation of raw materials [eec,n+etd,n+el,n-esca,n]	7.63	10.45	0.00	18.10
Credits for digestate	0.00	0.00	-147.50	0.00
Bonus eB (restored degraded land), g CO_{2eq}/MJ	0.00	0.00	0.00	0.00
Emissions from processing (ep)	17.76	17.76	17.76	17.76
Emissions from transport and distribution of the final product (etd, product)	4.60	4.60	4.60	4.60
Emissions from the product in use (eu)	0.36	0.36	0.36	0.36
Emission savings from CO_2 capture and replacement (eccr)	-34.66	-34.66	-34.66	-34.66
Total emissions (E) for the final product (BIOMETHANE)	-4.32	-1.49	-159.44	6.15
Potential for GHG emission reduction for the final product, %	104.59%	101.59%	269.62%	93.45%

Table 8.6 shows the adopted terms of financing the project. The share of borrowed funds is assumed to be 60% at 8.0% per annum. The depreciation period is assumed to be 15 years for equipment, and 50 years for buildings. The inflation factor is not taken into account in the financial model. The results of the assessment of the main financial indicators are presented in **Table 8.7.**

The discounted payback period is 7.8 years with an IRR of 20%, which allows us to consider this project concept, given the adopted calculation parameters, to be quite attractive for investment.

Sensitivity analysis of the IRR indicator from the sales price of the main target products shows that the project profitability is significantly affected by the selling price of biomethane **(Fig. 8.1),** and to a lesser extent by the selling price of liquefied CO_2 **(Fig. 8.2).**

Table 8.6. Project financing conditions.

Index	Unit	Value
Interest rate	%	8.0%
Delayed loan payment	years	1
Lending term	years	7
Corporate tax rate	%	18%
Discount rate	%	10%
Equity capital	%	40%

Table 8.7. Project cost-effectiveness indicators.

Indicator	Unit	Value
Investments (CAPEX), including:	million EUR	14.22
Borrowed funds		8.53
Own funds		5.69
Operating expenses (OPEX), including:	million EUR/y (excluding VAT)	1.98
Feedstock		1.21
Operating expenses		0.29
Target product logistics		0.39
Revenue		4.87
Biomethane into gas-transport system		3.92
Liquefied CO_2		0.75
Digestate		0.19
Net present value (NPV)	million EUR	**5.78**
Internal return rate (IRR)	%	**19.9%**
Profitability index (PI)	-	**0.41**
Simple payback period (SPP)	years	**5.9**
Discounted payback period (DPP)	years	**7.8**

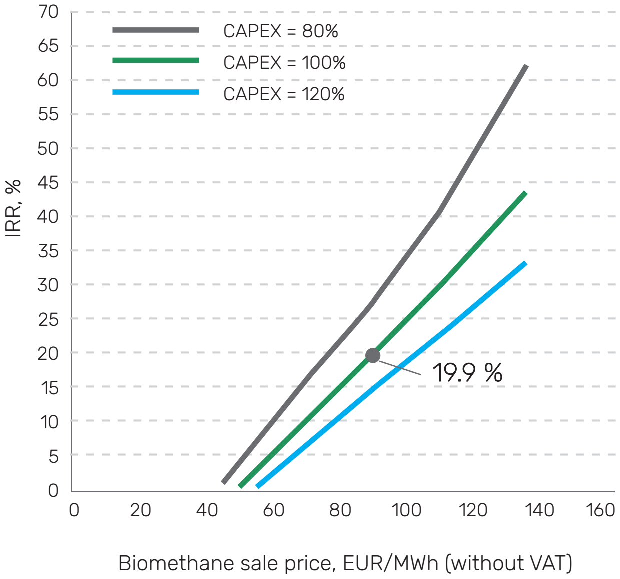

Fig. 8.1. Dependence of IRR on biomethane sale price (EUR/MWh without VAT)

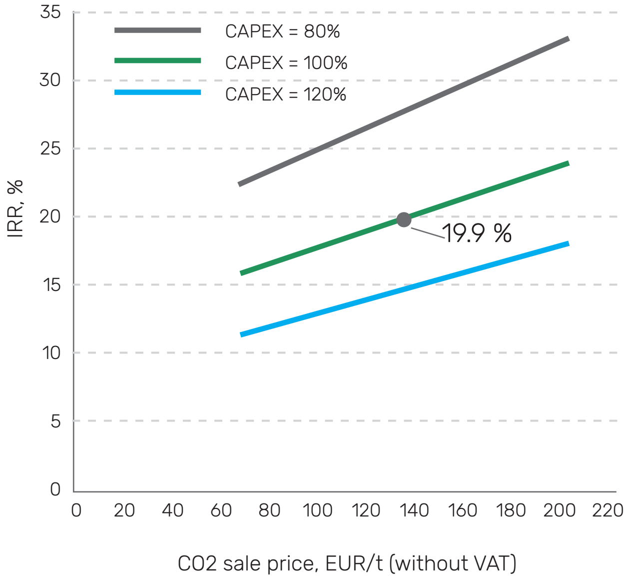

Fig. 8.2. Dependence of IRR on liquefied CO_2 sale price (EUR/t without VAT)

The above analysis shows that the project is also sensitive to an increase in CAPEX. Thus, with the increase in CAPEX by 20%, the project may be on the verge of investment attractiveness with a discounted payback period of 10.3 years and an IRR of 14.8%. Also, a decrease in the sale price of biomethane by only 10% to 81 EUR/MWh leads to an increase in the payback period to 9.7 years with an IRR of 15.7%.

Therefore, the project is quite sensitive to changes in key economic parameters. The key to the successful implementation of such projects may be to guarantee a satisfactory sale price of biomethane for the long term and to find sales markets for liquefied carbon dioxide with higher profitability. Reducing investments will also make the project more economically feasible; however, the probability of a significant (by 15-20%) reduction of investments is assessed as low.

An alternative concept for this project could be the production of electricity from biogas with sale to the grid (on the DAM or under bilateral agreements) or for the enterprise's own needs. At the same time, with the operation of CHP in a uniform mode and the supply of electricity 24/24, the cost of the project could be reduced to 10.5 million EUR, and operating costs by 13%. To achieve a similar level of profitability, the electricity price should be no lower than 18 euro cents per 1 kWh. This price, however, greatly exceeds the recent levels of prices on DAM in Ukraine.

Assessment of biomethane production potential from intermediate and cover crops in Ukraine

SECTION 9

The use of **cover/intermediate crops is** a promising direction for a significant increase in the volume of biomethane production. The potential for biomethane production from such crops in Ukraine can be estimated at **9.23** bcm CH_4/y (**7.89** Mtoe/y). This estimate corresponds to the **conservative** approach, according to which it is assumed that **20%** of the sown area is allocated for growing cover/intermediate crops with the average yield of these crops at the level of **5** t d.m./ha and the biogas yield of **570** m^3/t d.m. **(Table 9.1)**.

The estimated potential for biomethane production from cover/intermediate crops (**9.23** bcm CH_4/y) is the largest component (**47%**) of the total potential for biomethane production from different feedstocks in Ukraine. Other major components of the potential are biomethane from post-harvest crop residues (4.37 bcm CH_4/y, 22%) and biomethane from the silage of maize as an energy crop (3.00 bcm CH_4/y, 15%) **(Table 9.2, Fig. 9.1)**.

Then, we will assess the potential of intermediate crops for biomethane production at the regional level of Ukraine. The methodology of this assessment takes into account regional climatic features, such as the sum of effective temperatures above 50°C and the amount of precipitation by month, which are determined by the relevant climatic data – the average temperature of the months of the year and the amount of precipitation from the web portal https://weatherandclimate.com/ukraine. It is assumed that to obtain an intermediate crop yield, the basic sum of active temperatures above 50°C during the growing season should be more than 600°C[88,89], and 350 litres of water are used to form 1 kg of dry matter[90].

88 Kosolap M.P. Presentation on «Cover and green manure crops after harvesting», 22.08.2024.

89 https://agro-business.com.ua/agro/ahronomiia-sohodni/item/397-syderatsiia-nevidiemna-skladova-biolohichnoho-zemlerobst-va.html

90 https://www.agronom.com.ua/vyroshhuvannya-gibrydno-go-zhyta/

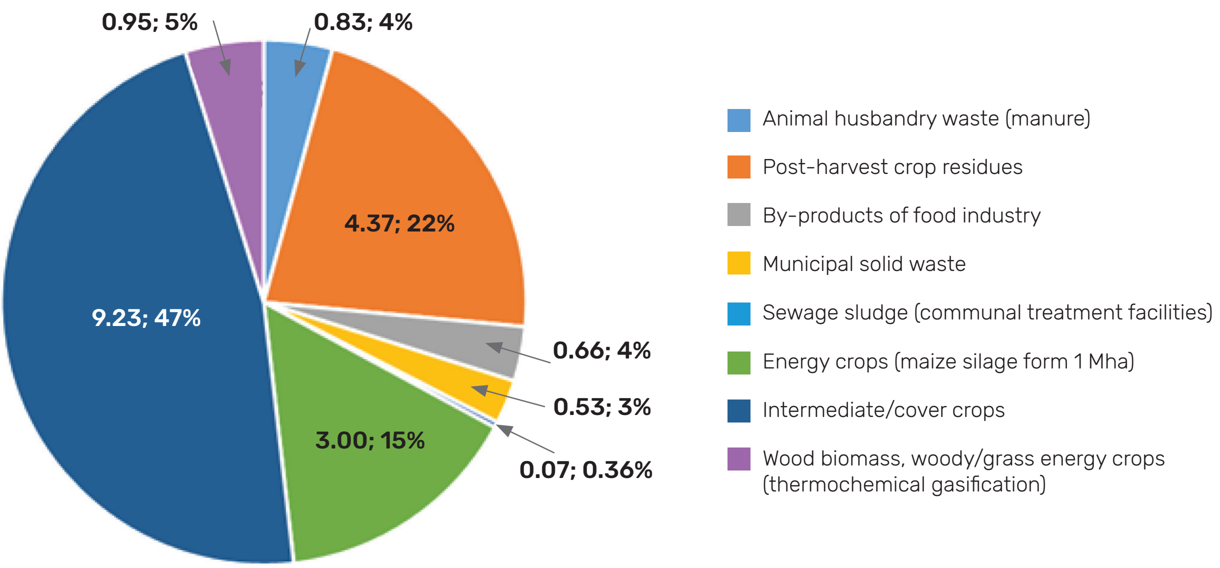

Fig. 9.1. Structure of the economic potential of biomethane production in Ukraine, bcm CH_4/y.

Table 9.1. Methodology for the assessment of biomethane production from cover/intermediate crops in Ukraine.

Parameter	Value	Comment
Sown area, Mha (I)	28.4	Data for 2021.
Share of the sown area intended for growing cover/intermediate crops (II), %	20	Assumed considering data of the study on «The Role of Sequential Cropping and Biogasdoneright™ in Enhancing the Sustainability of Agricultural Systems in Europe» (2021)[54]. A description of the study is presented in Chapter 5 of the Analytical Note.
Average yield of cover/intermediate crops, t d.m./ha/y (III)	5	
Yield of biogas from cover/intermediate crops, m^3/t d.m. (IV)	570	
Concentration of biomethane in biogas (V), %	57	According to the figure from the biomethane potential assessment by Gas for Climate (2022)*.
Potential of biomethane production from cover/intermediate crops, bcm/y (I× II/100 × III × IV × V/100)	9.23	The conservative approach assessment. Higher input data (area under cover/intermediate crops and their yield) will result in higher potential.

* Biomethane production potentials in the EU (Gas for Climate, 2022).
https://gasforclimate2050.eu/wp-content/uploads/2023/12/Guidehouse_GfC_report_design_final_v3.pdf

Table 9.2. Assessment of biomethane production potential in Ukraine[1)].

Types of feedstocks for biomethane production	Theoretical potential, bcm CH_4/y	Potential available for energy (the economic potential)		
		Share of the theoretical potential, %	bcm CH_4/y	Mtoe/y
Animal husbandry waste (manure)	1.04	80	0.83	0.71
Post-harvest crop residues	16.79	26	4.37	3.8
By-products of food industry	1.69	39	0.66	0.56
Municipal solid waste	0.70	75	0.53	0.45
Sewage sludge (communal treatment facilities)	0.07	100	0,07	0,06
Energy crops (maize silage form 1 Mha)	3.00	100	3.00	2.57
Intermediate/cover crops	**9.23**	**100**	**9.23**	**7.89**
Wood biomass, woody/grass energy crops[2)]	9.51	10	0.95	0.82
BIOMETHANE, total	**42.03**	**47**	**19.64**	**16.86**

1) Excluding temporarily occupied territories of Ukraine as of 2021.
2) 10% of the theoretical potential of wood biomass (fuel wood, logging residues, wood processing waste, deadwood, wood from protective forest belts, pruning of orchards/vineyards) and woody/grass energy crops (willow, poplar, miscanthus) is allocated to biomethane production through thermochemical gasification of biomass.

The basic sown area of intermediate crops is taken as 20% of the sown area of agricultural crops for the 2021 harvest. At the same time, the area is divided into 50% for winter intermediate crops and 50% for post-harvest crops. Based on climatic data, a reassessment of the potential areas for growing winter intermediate crops and post-harvest crops was carried out for individual regions, and the potential yield of green mass for biomethane production was assumed in tons of dry matter **(Table 9.3)**. For the Odesa and Donetsk regions, given the insufficient amount of precipitation during the growing season of winter intermediate crops (up to 240 mm from mid-August to April), it is assumed that they will be sown on 5% of the sown area. Due to the lack of precipitation during the growing season of post-harvest crops, their cultivation is not considered in Donetsk, Zhytomyr, Mykolaiv, Odesa and Kherson regions. In addition, due to the low moisture supply, the cultivation of intermediate crops in the Autonomous Republic of Crimea was not taken into account.

Similar to the potential assessment for Ukraine as a whole, the specific biogas yield is 570 m^3/t d.m. intermediate crops; the content of biomethane in biogas is 57% (see **Table 9.1**). The map of the specific potential of biomethane production from intermediate crops in Ukraine's regions is presented in **Fig. 9.2.**

The total potential by region is in line with the results of the assessment of biomethane production potential in Ukraine as a whole – **9.23** bcm CH_4/y. The largest potential of intermediate crops for biomethane is concentrated in regions with large sown areas: Kharkiv, Dnipropetrovsk and Poltava oblasts. At the same time, a higher specific yield of biomethane can be obtained in regions with higher precipitation: Ivano-Frankivsk, Lviv, Rivne, Ternopil, Khmelnytskyi and Chernivtsi oblasts. It should be noted that for some individual territories of the regions, one set of climatic data is accepted without taking into account their regional climatic conditions, therefore the obtained assessment results are approximate. Given this, for a more accurate justification of the implementation of projects for growing intermediate crops and producing biomethane from them, it is necessary to use more differentiated local data.

Fig. 9.2. The economic specific potential of biomethane production from intermediate crops in Ukraine's regions, m^3 CH_4/ha of sown area of agricultural crops in the region.

Table 9.3. Assessment of the potential of biomethane production from intermediate crops in Ukraine's regions.

Regions (oblasts)	Area under intermediate crops, 1000 ha		Approximate yield of intermediate crops, t d.m./ha		Biomethane amount, million m^3 CH_4/y
	winter crops	post-harvest crops	winter crops	post-harvest crops	
Vinnytsia	165	165	7.0	3.5	564
Volyn	61	61	8.0	3.5	229
Dnipropetrovsk	197	197	7.0	3.5	673
Donetsk	52	–	5.2	–	88
Zhytomyr	115	–	6.0	–	225
Zakarpattia	17	17	9.0	4.5	76
Zaporizhzhia	171	171	8.0	3.5	640
Ivano-Frankivsk	38	38	9.0	5.0	174
Kyiv	119	119	8.0	3.5	445
Kirovohrad	171	171	7.0	3.5	582
Luhansk	86	86	8.0	3.5	320
Lviv	71	71	9.0	5.0	321
Mykolaiv	160	–	6.0	–	312
Odessa	92	–	5.2	–	156
Poltava	173	173	8.0	3.5	647
Rivne	62	62	9.0	5.0	282
Sumy	121	121	9.0	3.5	491
Ternopil	84	84	9.0	5.0	382
Kharkiv	182	182	8.0	3.5	681
Kherson	148	–	6.0	–	288
Khmelnytskyi	121	121	9.0	5.0	548
Cherkasy	122	122	7.0	3.5	415
Chernivtsi	31	31	9.0	5.0	140
Chernihiv	135	135	9.0	3.5	550
Total					**9229**

Conclusions and recommendations

Intermediate and cover crops as feedstock have considerable potential for energy production. Fast growth, generally low soil requirements, absence of competition with main crops that are used for food production, and high susceptibility to ensiling, which makes possible long-term storage, are features that favour the use of this biomass in the energy sector. In addition, a possible reduction of the energy industry's carbon footprint as a result of the consumption of renewable energy is a significant advantage of using intermediate and cover crops for biogas production. This effect is noticeably manifested when the fermentation residues, rich in organic matter and more stable than untreated aboveground biomass, are returned to the soil as a source of nutrients and starting components for the formation of humus.

In Ukraine, so far, intermediate and cover crops have been grown for further use as green manure or for feed production. Expansion of the area under these crops and their integration into biomethane supply chains, with nutrients returned to the soil with digestate, presents a new perspective for sustainable bioenergy and agriculture. The usage of intermediate and cover crops for biomethane production emphasizes an innovative approach, which requires a thorough analysis of feasible opportunities and prerequisites for successful implementation within Ukraine's context.
The obtained biomethane can be consumed domestically as a replacement for natural gas and fossil motor fuels (first of all, compressed natural gas and diesel), as well as exported.

Ukraine has gained considerable experience in cultivating intermediate crops for feed production, which can also be used to grow feedstock for bioenergy, in particular, for the production of biogas and biomethane. Correct alternation of a scientifically substantiated set of crops in combination with progressive methods of soil treatment, fertilization, and maximum inclusion of intermediate crops in crop rotations make it possible to intensively use the land, increase its fertility, and improve the physical properties of the soil. To plan the cultivation of intermediate and cover crops, in addition to their biological interaction with forecrops and aftercrops in crop rotation and their impact on soil fertility, it is important to determine the periods when the fields are free from main crops, but at the same time, there are favourable agroclimatic conditions for plant vegetation.

In Ukraine, the following crops can be used as intermediate crops for biomass production in the current year and subsequent biogas/biomethane production: spring cereals (after early preceding crops), corn (early-maturing hybrids under favourable conditions), sorghum, and vetch. For early biomass harvesting in the following year for similar bioenergy use, the next crops can be considered: winter intermediate crops such as green rye (KWS Propower, KWS Magnifico), triticale (Veleten), winter wheat, and winter barley (at early stages of development). Furthermore, other types of intermediate and cover crops are also being explored. Among these, amaranth is promising due to its drought resistance, resilience, and ability to quickly build up significant biomass for obtaining green mass intended for further biogas and biomethane production. Soufflet Agro Ukraine has published a reference book on cover crops, which contains characteristics of 21 plants from the Asteraceae, Watercress, Brassica, Legume, Flax and Buckwheat families. This reference book can be used when planning the introduction of cover crop cultivation in Ukraine.

The use of cover and intermediate crops is a promising direction for a significant increase in the volume of biomethane production. The potential for biomethane production from such crops can be estimated at 9.23 bcm CH_4/y (7.89 Mtoe/y) in Ukraine. This estimate corresponds to the conservative approach, according to which it is assumed that 20% of the sown area is allocated for growing cover/intermediate crops with an average yield of 5 t d.m./ha and a biogas yield of 570 m^3/t d.m. The estimated potential for biomethane production from cover/intermediate crops is the largest component (47%) of the total potential for biomethane production from different feedstocks in Ukraine. Other major components of the potential are biomethane from post-harvest crop residues (4.37 bcm CH_4/y, 22% of the total) and biomethane from the silage of maize as an energy crop (3.00 bcm CH_4/y, 15%).

The largest potential of intermediate/cover crops for biomethane is concentrated in Ukraine's regions with large sown areas: Kharkiv, Dnipropetrovsk and Poltava oblasts. At the same time, a higher specific yield of biomethane can be obtained in regions with higher precipitation: Ivano-Frankivsk, Lviv, Rivne, Ternopil, Khmelnytskyi and Chernivtsi oblasts. It should be noted that for some individual territories of the regions, one set of climatic data is accepted without taking into account their regional climatic conditions, therefore the obtained assessment results are approximate. Given this, for a more accurate justification of the implementation of projects for growing intermediate/cover crops and producing biomethane from them, it is necessary to use more differentiated local data.

The performed feasibility study of the project on biomethane production from intermediate and cover crops shows that all the considered types of feedstocks provide the required level of GHG emission reduction, which is 65% for transport fuels (fulfilment of RED III requirement). The averaged total emissions for the entire final product (biomethane) amount to (-13.00) gCO_{2eq}/MJ. The discounted payback period is 7.8 years at an IRR of 20%, which allows considering this project concept, given the adopted calculation parameters, to be sufficiently attractive for investment. The IRR sensitivity analysis from the sale prices of the main target products shows that the profitability of the project is significantly affected by the sale price of biomethane, and to a lesser extent, by the sale price of liquefied CO_2. The performed analysis shows that the project is also sensitive to an increase in CAPEX. Thus, the project is quite sensitive to changes in key economic parameters. The key to the successful implementation of such projects may be to guarantee a satisfactory long-term biomethane sale price and to find more profitable markets for liquefied carbon dioxide. Reducing investment in the project will also make it more economically stable; however, the probability of a significant (15-20%) reduction in investments is estimated to be low.

Further research is needed to exploit the potential of intermediate/cover crops for bioenergy more effectively. Genetic engineering tools can be revolutionary for the industry, especially their application to improve the digestibility of biomass and increase its starch content. Optimizing the biomass supply chain is critical for scaling up the production system. Improving the efficiency of biomass conversion into biogas and biofuels requires improvements and the creation of new technologies.

Ukraine can potentially capture up to 20% of the European biomethane market, produce over 20 bcm of biomethane a year and attract up to 40 billion EUR of investment in this sector. Biomethane from intermediate and cover crops, which is the subject of the Analytical Note, may contribute by about 46% (9.2 bcm/y) to this total amount. For the development of domestic biomethane production, it is important to create prerequisites for the rational use of existing and prospective resources of sustainable biomass feedstock.

Annex 1. List of typical crops that are cultivated as intermediate and cover crops in different parts of the world and directions of their additional application

Source: Catch and Cover Crop Biomass Bioconversion into Energy[1]

Family	Species	Application/Function	Distribution
Asteraceae (alt. Compositae)	**Niger, Niger seed** (Guizotia abyssinica)	Soil improver, fodder; source of oil	Africa: Ethiopia (n) Africa (cult., natur.) Asia (cult. natur.) Australia (cult.) South. Europe (natur.)
	Sunflower (Helianthus annuus L.)	Fodder; honey production, oil production, ornamental, human food	North. America (n) Widely cult.
Boraginaceae	**Lacy phacelia, purple tansy** (Phacelia tanacetifolia Benth.)	Soil improver: cover crops; honey production; ornamental function; phytosanitary function	North America (n), Australia (natur.), Europe (natur.)
	White mustard (Sinapis alba)	Soil improver (deep root system): cover crops; fodder; source of lipids; medicine herbs; phytosanitary function	Europe, North Africa, West Asia
	Fodder radish, Oilseed radish (Raphanus sativus)	Soil improver (deep and bulky root system), cover crop; fodder; phytosanitary function	Widely cultivated
Brassicaceae (alt. Cruciferae)	**Camelina, false flax** (Camelina sativa L.)	Soil improver: cover crop, green manure, source of oil; fodder	Asia (n), Europe (n), North America (n); Widely naturalize
	Turnip, field mustard, colbaga (Brassica rapa L.)	Soil improver: cover crop, human food; fodder	Widely cultivated
	Rape, rapeseed, winter canola (Brassica napus L.)	Soil improver: cover crop; fodder	Widely cultivated

1 Scholarly Community Encyclopaedia https://encyclopedia.pub/entry/54759

	Cowpea, field pea (Vigna unguiculata L. Walp)	Soil improver: green manure, cover crop; catch crop; forage; human food	Africa (n), Widely cultivated
	Sunn hemp, Indian hemp (Crotalaria juncea L.)	Soil improver: green manure, cover crop; forage; catch crop, nitrogen-fixing, fibre production	Asia (n), South Africa, Cultivated throughout tropics
	Yellow lupine (Lupinus luteus L.)	Soil improver: cover and catch crops; fodder; forage; medicine herbs	North Africa (n), South Europe (n), Australia (cult.), West Asia (natur.), South Africa (natur.)
	Narrowleaf lupin, narrow-leaved lupin, blue lupin (Lupinus angustifolius)	Soil improver: catch crop; fodder; forage	North Africa (n), West Asia (n), South Europe (n), Australia (cult.)
	White lupine (Lupinus albus L.)	Soil improver; cover crop; fodder; forage; ornamental function	Asia (n), Europe (n), Widely cultivated
	Alfalfa, lucerne (Medicago sativa L.)	Soil improver, cover crop, fodder	Africa (n), Asia (n), Europe (n), Widely cultivated
	Common vetch (Vicia sativa L.)	Soil improver: catch crop; fodder; forage	Africa (n), Asia (n), Europe (n), Widely cultivated
	Fodder vetch, hairy vetch, winter vetch (Vicia villosa Roth.)	Soil improver: catch crop; fodder; forage (but can be toxic to horses)	Africa (n), Asia (n), Europe (n), Widely cultivated
Fabaceae (alt. Leguminosae)	**Faba bean, fava bean, broad bean** (Vicia faba L.)	Soil improver: catch crop, cover crop	Widely cultivated
	Seradela, French serradella (Ornithopus sativus Brot.)	Soil improver: catch crop; forage	North Africa (n), South Europe (n), Australia (cult.), Europe (cult.), Africa (natur.)
	Egyptian clover, berseem clover (Trifolium alexandrinum L.)	Soil improver: catch crop; forage	Africa (cult.), Asia (cult.), Australia (cult.), Europe (cult.), North America (cult.)
	Reversed clover, Persian clover (Trifolium resupinatum L.)	Soil improver: catch crop; forage; fodder	Africa (n), Asia (n), Europe (n), Widely cultivated
	White clover (Trifolium repens L.)	Soil improver: catch crop; forage	Africa (n), Asia (n), Europe (n), Widely cultivated in temperate regions
	Red clover (Trifolium pratense L.)	Soil improver: catch crop; forage; fodder; honey production; food additive	Africa (n), Asia (n), Europe (n), Widely cultivated and naturalized in temperate regions
	Crimson clover (Trifolium incarnatum)	Soil improver: catch crop; forage; fodder; honey production	Africa (n), Asia (n), Europe (n), Widely cultivated in temperate regions
	Pea, field pea (diverse Pisum sativum L.)	Soil improver: catch crop; human food	Africa (n), Asia (n), Europe (n), Worldwide cultivated

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