Catch and Cover Crop Biomass Bioconversion into Energy

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cover crops | catch crops | biomass | renewable energy sources | climate neutrality

1. Characteristics and Spatial Distribution of Catch and Cover Crops

Catch and cover crops are defined as crops sown in pure or mixed sowings between two main crops [1]. A short vegetation period is a key feature of these plants [2]. Depending on the sowing date, one can distinguish stubble catch crops sown after harvesting the main crop at the end of summer and harvested or ploughed in the fall of the same year or left in the field until spring; winter crops sown after harvest at the end of summer and harvested in the spring of the following year; and undersowing catch crops, plants that tolerate shade well, which are sown together with the main crop and after harvesting and left in the field until autumn [3]. The biomass of these plants is used in various ways on farms. It can be used for forage purposes—directly grazed (forage) or processed to fodder in a form of hay or silage; introduced into the soil to improve its chemical properties and its structure (soil improver), for example, as a source of nutrients and organic matter after direct ploughing; or left in the field as a form of mulch after previous mowing or damage by frost. It can also play a protective role in relation to the soil surface, preventing water or wind erosion, or protect nitrogen resources in the soil by incorporating it and retaining it in the biomass in the period after the harvest of the main crop plants [4][5][6]. The latter function is fulfilled by plants with increased nitrogen fixation efficiency (expressed in a low C:N ratio) belonging to the *Fabaceae* family, such as peas, lupins, seradela, vetch, clover, alfalfa). Through the symbiosis with nitrogen-fixing bacteria growing inside the root nodule cells of these plants, atmospheric nitrogen becomes available to plants and may be incorporated into their biomass [7][8]. Thanks to the production of specific root secretions, many CCC plants have a phytosanitary effect, which involves stimulating the development of beneficial soil microflora and microfauna and limiting the development of pathogens and pests [9][10][11]. In addition, introducing additional plant species, especially mixtures, between the main crops increases biodiversity.

In agricultural practice, many plants are in use that, when grown between the main crops, improve the properties of the soil and contribute to increasing its fertility and yields. **Table 1** summarizes the types of plants used as CCCs in the world that are most frequently mentioned in the literature.

Table 1. Typical plants cultivated as cover or catch crops in different parts of the world, and their additional applications (main sources [12][13]).

Family	Species	Application/Function	Distribution	References with Regard to Use as CCC
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.)	[14][15][16]
	Sunflower (*Helianthus annuus* L.)	Fodder; honey production, oil production, ornamental, human food,	North. America (n) Widely cult.	[15]
Boraginaceae	Lacy phacelia, purple tansy (*Phacelia tanacetifolia* Benth.)	Soil improver: cover crops; honey production; ornamental function; phyto sanitary function	North America (n) Australia (natur.) Europe (natur.)	[15][16][17][18][19][20]
Brassicaceae (alt. *Cruciferae*)	White mustard (*Sinapis alba*)	Soil improver (deep root system): cover crops; fodder; source of lipids; medicine herbs; phytosanitary function	Europe North. Africa West. Asia	[18][19][21][22][23]
	Fodder radish, Oilseed radish *(Raphanus sativus)*	Soil improver (deep and bulky root system), cover crop; fodder; phytosanitary function	Widely cult.	[16][18][24]
	Camelina, false flax *(Camelina sativa* L.)	Soil improver: cover crop, green manure, source of oil; fodder	Asia (n) Europe (n), North America (n) Widely natur.	[14]
	Turnip, field mustard, colbaga (*Brassica rapa* L.)	Soil improver: cover crop, human food; fodder	Widely cult.	[18][24]
	Rape, rapeseed, winter canola (*Brassica napus* L.)	Soil improver: cover crop; fodder	Widely cult.	[24][25]

Family	Species	Application/Function	Distribution	References with Regard to Use as CCC
Fabaceae (alt. *Leguminosae*)	Cowpea, field pea (*Vigna unguiculata* L. Walp)	Soil improver: green manure, cover crop; catch crop; forage; human food	Africa (n) Widely cult.	[26][27]
	Sunn hemp, Indian hemp (*Crotalaria juncea* L.)	Soil improver: green manure, cover crop; forage; catch crop, nitrogen-fixing, fiber production	Asia (n) South Africa Cult. throughout tropics	[26][28]
	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.)	[29][30]
	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.)	[31]
	White lupine (*Lupinus albus* L.)	Soil improver; cover crop; fodder; forage; ornamental function	Asia (n) Europe (n) Widely cult.	[32]
	Alfalfa, lucerne (*Medicago sativa* L.)	Soil improver, cover crop, fodder	Africa (n) Asia (n) Europa (n) Widely cult.	[33][34][35]
	Common vetch (*Vicia sativa* L.)	Soil improver: catch crop; fodder; forage	Africa (n) Asia (n) Europe (n) Widely cult.	[14][15][16][23][36][37]
	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 cult.	[18][38][39]
	Faba bean, fava bean, broad bean *(Vicia faba* L.)	Soil improver: catch crop, cover crop	Widely cult.	[18][29][37]
	Seradela, French serradella	Soil improver: catch crop; forage	North. Africa (n) South. Europe	

Family	Species	Application/Function	Distribution	References with Regard to Use as CCC
	(Ornithopus sativus Brot.)		(n) Australia (cult.) Europa (cult.) Africa (natur.)	
	Egyptian clover, berseem clove (*Trifolium alexandrinum* L.)	Soil improver: catch crop; forage	Africa (cult.) Asia (cult.) Australia (cult.) Europa (cult.) Northern America (cult.)	[18][37]
	Reversed clover, Persian clover *(Trifolium resupinatum* L.)	Soil improver: catch crop; forage; fodder	Africa (n) Asia (n) Europa (n) Widely cult.	[40]
	White clover (*Trifolium repens* L.)	Soil improver: catch crop; forage;	Africa (n) Asia (n) Europa (n) Widely cult. in temperate regions	[23]
	Red clover (*Trifolium pratense* L)	Soil improver: catch crop; forage; fodder; honey production, food additive	Africa (n) Asia (n) Europa (n) Widely cult. and natur. in temperate regions	[22][25][35][41]
	Crimson clover *(Trifolium incarnatum)*	Soil improver: catch crop; forage; fodder; honey production	Africa (n) Asia (n) Europa (n) Widely cult. in temperate regions	[29][31][41]
	Pea, field pea (diverse *Pisum sativum* L.)	Soil improver: catch crop; human food	Africa (n) Asia (n) Europa (n) Worldwide (cult.)	[15][25][31][37][39]
Poaceae (alt. *Gramineae*)	Black oat, lopsided oat, bristle oat (*Avena strigose*)	Soil improver: cover crop, green manure; forage; fodder; source of oil used in cosmetics	Europe (n) South America (cult.) South. part of	[14][16][26]

Family	Species	Application/Function	Distribution	References with Regard to Use as CCC
			North America (cult.) South Africa (cult.)	
	Common oat (*Avena sativa* L.)	Soil improver: cover crop; human food; fodder; forage	Widely cult.	[25][26][35][39]
	Rye, common rye, winter rye, stooling rye (*Secale cereale*)	Soil improver: cover crop, green manure, human food; forage; fodder	Asia (n) Europa (n) Widely cult.	[18][26][31]
	Triticale (*Triticale* A. Müntzing)	Soil improver: cover crop, green manure; forage, human food	Europe (cult.) Asia (cult.) South Africa (cult.)	[26][35]
	Italian millet, foxtail millet (*Setaria italica* L.)	Forage, fodder, cover, green manure	South. Asia (n) Asia (cult.) Africa (cult.) South. Part of North America (cult.or natur.)	[26][39]
	Finger millet *(Eleusine coracana* L. Gaertn.)	Cover, human food, fodder	Asia (cult.) South Africa (cult)	[26][28]
	Pearl millet, bajra (*Pennisetum glaucum)*	Soil improver: cover crops, erosion control; forage; fodder; human food; ornamental	Asia (cult.) Africa (cult.) North America (cult.)	[26][28][37][42]
	Japanese millet, white millet (*Echinochloa esculenta)*	Soil improver: cover crop; fodder; forage; human food	Africa (cult.) Asia (cult.) North America (cult.) South America (cult.)	[42]
	Westerwold ryegrass, Italian ryegrass (*Lolium multiflorum* Lam.)	Soil improver: cover crop, erosion control; fodder; forage	Africa (n) Asia (n) Europa (n) North. America (natur.)	[41][43][44][45]

Looking at the information given in **Table 1**, many of the plants used as cover or catch crops, for example, common vetch, hairy vetch, common oat and common buckwheat, are cultivated in various regions of the world, while some,

Family	Species	Application/Function	Distribution	References with Regard to Use as CCC
	Perennial ryegrass, English ryegrass (*Lolium perenne* L.)	Soil improver: cover crop, erosion control; fodder; forage	Africa (n) Asia (n) Europa (n) North, America (natur.) South. America (natur.) Australasia (natur.)	[41][45][46]
[51]	Meadow fescue, English bluegrass (*Festuca pratensis* Huds.)	Soil improver: cover crop, erosion, forage	[48][49][50] Africa (n) Asia (n) Europa (n) Widely natur.	[45]
[52]	Orchard grass, cocksfoot [53] (*Dactylis glomerata* L.)	Soil improver: cover crop; fodder; forage; ornamental	Africa (n) Asia (n) Europa (n) North. America (cult.) Australasia (natur.) South. America (natur.) [51]	[33][41]
Polygonaceae	Common buckwheat (*Fagopyrum esculentum* Moench)	Soil improver: cover crops, green manure; human food; forage; fodder; honey production	Asia (n) Widely cult. and natur.	[14][16][18][38] [54][55][56]

Abbreviations: n—native, cult.—cultivated, natur.—naturalized.

climate, one can use mixtures of cowpea, foxtail millet and sunflower as well as mixtures of various combinations of plants such as: millet, triticale, red clover and fodder radish [57][58].

The wide variety of plant species that are adapted to different habitat conditions allows the most favorable CCC species for a given climatic and soil zone to be found. However, particular plant species differ in terms of biomass composition, which can influence their suitability for energy production, especially via biochemical processes.

2. Features of Catch and Cover Crops (CCCs) Biomass Important Because of Biochemical Conversion into Biofuels

Biomass of catch and cover crops (CCCs), similarly to the other types of biomass, can be used as a source of energy after conversion into biofuels, such as biomethane, alcohol, bio-oil and biohydrogen (via biochemical, chemical or thermochemical processes) or directly after combustion. The application of appropriate bifunctional catalytic materials (e.g., Bronsted–Lewis acid), which allow biofuels and chemicals to be produced from lignocellulosic biomass, offer the great opportunities [59]. The choice of the method for converting biomass into energy depends largely on the dry matter content of the raw material. Biological methods, such as methane fermentation, can be used when the moisture content of the feedstock allows intensive development of microorganisms and is not less than 60% dry weight (d.w.) (in the case of dry anaerobic digestion systems) or over 85% (in the case of wet anaerobic digestion systems). However, direct combustion of biomass is justified when the moisture is low, e.g., for straw it is recommended that it is not higher than 25% [60]. Thermochemical methods are instead recommended for dry biomass. When biomass is converted by widely known processes such as pyrolysis (under anoxygenic conditions) or gasification (under oxygen-deficient conditions), the water content should be in the range of 10–20% d.w. in the case of gasification [61], and 15–35% d.w. in the case of pyrolysis [62]. However, a high moisture content does not exclude the possibility of using biomass for the production of biofuels in thermochemical processes. Hydrothermal conversion processes such as hydrothermal liquefaction (HTL), hydrothermal carbonization (HTC) and hydrothermal gasification HTG (supercritical water gasification) allow the conversion of wet biomass into biofuels, such as bio-crude oil, hydrochar and a mixture of combustible gases, respectively. These processes are carried out at temperatures of 100–700 °C and high pressures of 5–40 MPa in a liquid media or hot supercritical water [63]. However, technologies based on these processes are not yet widely used at a technical scale. Thus, in the case of wet biomass biological methods, such as anaerobic digestion, are still preferable. Additionally, well-known technology and the possibility of it using in on a small scale, e.g., on large agricultural farms, are an important arguments for the use of these methods.

The water content of the raw biomass of CCCs varies significantly depending on many factors, among them, plant species and growth stage. Research conducted on corn by [64] in a Mediterranean climate showed that the highest dry matter content, approx. 54% of d.w., was observed in the phase of maturity, while the dry matter content in biomass harvested at the end of the vegetative stage was about 15%. According to the study of Piskier [65], the content of total solids in the corn straw was still high and varied between 40 and 55%. A significant increase in dry matter content from 26.1 to 38.5% d.w. between the early dent and black layer stages of corn growth was observed by Rabelo et al. [66]. Changes in dry matter content in phacelia (*Phacelia tanacetifolia*) biomass between pre-flowering and end-flowering phases ranged from 32.6 to 54.6% d.w. [67]. Tekeli et al. [68] found that the dry matter content in Persian clovers increased from 6.8 to 12.2% d.w. between the stages of pre-bud and full-bloom.

The results of these studies show that the raw biomass of CCC plants is characterized by high water content even in the later stages of development, such as full-bloom, which indicates its greater suitability for being processed into biofuels using biological methods. If one chooses such methods, there is no need to remove water. Therefore, preparing biomass is less energy-intensive and expensive than preparing it for processing in thermochemical processes, such as pyrolysis and gasification, which require preliminary partial dewatering [69].

However, when choosing biochemical methods, an important feature of biomass is its high biodegradability, which determines the high efficiency of the conversion of chemical energy contained in organic compounds into useful forms of energy. Biodegradability depends on the chemical composition of organic matter, which in turn depends on such factors as the plant species, part of plant, growth stage, harvest time, climate conditions, soil properties and fertilization. Biomass with a high content of non-structural and water-soluble carbohydrates, as well as a low content of lignin, is highly biodegradable [70][71]. Microorganisms can degrade the labile fraction of organic substrates, avoid resistant molecules (e.g., lignin) and produce stabilized metabolites [72][73]. A high lignin content not only reduces biogas production due to difficult biodegradability of this compound, but also due to the reduction in the hydrolysis of cellulose by creating a physical barrier for cellulases and reducing their availability because of the sorption of these enzymes on lignin [74]. As shown in the data presented in **Table 2**, the lignin content in the raw biomass of plants used as cover crops ranges from 1.42 to 20% d.w., which shows its significantly different biodegradability. Chaves et al. [75] examined grass and legume and found that lignin content in perennial ryegrass (*Lolium perenne*) varied from 2.38 to 4.35%, while in white clover (*Trifolium repens*), red clover (*Trifolium pratense*) and lucerne (*Medicago sativa*), it was 5.87, 6.23 and 6.12% d.w., respectively.

The chemical composition of biomass varies significantly depending on the stage of plant growth. A decrease in the content of crude protein was observed in phacelia biomass between the pre-flowering and end-flowering phases, from 19.8 to 14.8% d.w., and crude fat, from 2.8 to 1.4% d.w. At the same time an increase in the contents of acid detergent fiber (ADF) and neutral detergent fiber (NFD) was observed, from 28.6 to 32.3% d.w. and 39.0 to 45.0% d.w., respectively [67]. Tekeli et al. [68] stated that the content of crude protein in Persian clovers between the stages of pre-bud and full-bloom decreased from 20.7 to 17.9% d.w., while the content of crude cellulose increased from 14.5 to 17.8% d.w.

For comparison, according to Wojcieszak et al. [76], the content of lignin unsuitable for biogas production in various parts of corn (cobs, leaves, stalks, husks), which is a popular substrate used for biogas production in Europe, collected 5–6 months after sowing, ranged from 13.1 to 20.1% d.w. However, corn intended for silage production should be harvested earlier, which translates into a lower lignin content in the biomass. Nowicka et al. [77] claimed that the lignin content in the corn silage they tested was 2.6% d.w., while the content of polysaccharides, which after hydrolysis can be processed by microorganisms, was 20.1% and 14.6% d.w. in the case of cellulose and hemicellulose, respectively.

Table 2. Contents of cellulose, hemicellulose and lignin in biomass of selected cover crops.

Species	Cellulose (% d.w.)	Hemicellulose (% d.w.)	Lignin (% d.w.)	References
Grasses	37.85	27.33	9.65	[78]
Grass silage	34.15	24.27	2.78	[79]
Sunflower (*Helianthus annuus* L.)	34.06	5.18	7.72	[78]
Fodder radish *(Raphanus sativus* L.), flowering stage	8.5	17.6	9.43	[80]
Fodder radish *(Raphanus sativus* L.), maturation stage	18.99	14.54	10.63	
Pearl millet (*Pennisetum glaucum),* flowering stage	22.44	29.87	4.7	
Pearl millet (*Pennisetum glaucum),* maturation stage	12.96	27.64	10.56	

Species	Cellulose (% d.w.)	Hemicellulose (% d.w.)	Lignin (% d.w.)	References
Orchard grass, cocksfoot (*Dactylis glomerata* L.)	52.3	42.9	6.6	[81]
Abruzzi rye (*Secale cereal* L.)	25.26	25.17	2.56	[82]
Black oat (*Avena Strigosa* Schreb)	46.2	27.84	9.12	[83]
Black oat (*Avena strigosa* Schreb)	25.17	20.82	1.77	[82]
Winter barley (Hordeum vulgare L.).	19.36	20.88	1.42	[82]
Field (winter) pea (*Pisum sativum* L.) different varieties	26.8–38.7	5.1–11.8	l.d.	[84]
Field (winter) pea (*Pisum sativum* L.) 17 different genotypes	20.3–36.16	9.18–10.8	4.86–10.2	[85]
Crimson clover (*Trifolium incarnatum*)	26–61.3		4.5–8.0	[83]
Crimson clover (*Trifolium incarnatum*)	17.33	12.65	3.37	[86]
Crimson clover (*Trifolium incarnatum*)	25.58	9.53	3.35	[82]
Crimson clover (*Trifolium incarnatum)*	29.1–36.88 *	10.8–11.12 *	7.5–10.10 *	[85]
Hairy vetch (*Vicia villosa* Roth)	26.84–33.53	10.84–11.63	8.3–11.2	[87]
Hairy vetch (*Vicia villosa* Roth)	28.4	10.12	7.57	[83]
Hairy vetch (*Vicia villosa* Roth)	27.24	14.29	4.86	[82]
Common vetch (*Vicia sativa* L.).	13.4	25.8	7.3	[88]
White lupine (Lupinus albus L.) silage	40.34	13.6	7.63	[89]
Broad bean (Vicia faba L.) silage	28.12	18.59	7.22	[89]
Switchgrass (*Panicum virgatum*)	39.5–45	20.3–31.5	12–20	[90]

Considering the data given in **Table 2**, it can be stated that cellulose dominates in crude fiber fraction, reaching up to 50% d.w., while the content of lignin in CCC biomass is usually lower than 10% d.w. Late harvest usually leads to an increase in the lignin content in CCC biomass, causing a decrease in biodegradability. Thus, the time of plant harvesting is a very important factor that influences the biomass' suitability for biogas production.

l.d.—lack of data; * values grown with harvest timings

Other important chemical properties indicating the suitability of plant biomass for energy use in biochemical conversion processes are related to the content of carbon and nitrogen and the mutual ratio of these parameters C/N, as well as the content of macroelements such as P, K, Ca, Mg and numerous microelements, which influence the functioning of microorganisms responsible for the biodegradation process of biomass.

The carbon content in the dry matter of catch crops in the aboveground part usually ranges from 40 to 50% [91][92]. The nitrogen concentration in plant biomass varies depending on the species, ranging from 13.6 to 52 g N kg dry d.w.$^{-1}$ in the biomass of brassicas and grasses, respectively. Higher concentrations of nitrogen, from 43 to 84 g N kg of d.w.$^{-1}$, are found in legumes [32][92]. Kwiatkowski et al. (2019) [20] found the nitrogen content in the biomasses of white mustard and lacy phacelia to be 38.6–39.321 g N/kg dry d.w.$^{-1}$ and 2.74–3.21 g N kg d.w.$^{-1}$, respectively. Studies carried out in France and Denmark showed that the total nitrogen amount in catch crops' biomass harvested on 1 hectare ranged from 10 to 171 kg N ha^{-1} for legumes, and from 9 to 89 kg N ha^{-1} for non-legumes, while the C:N ratio ranged widely, from 9 to 40, thus sometimes going beyond the range considered optimal for microorganisms' growth, which is estimated to be between 20 and 35 [93][94]. According to the study of Szwarc et al. [79], the C:N ratio of grass silage was ca. 23.

The concentrations of other important nutrients in the catch crops' biomasses, belonging to grasses, legumes and brassicas, were: phosphorus—2–8.2 g kg d.w.$^{-1}$, potassium—15–52.8 g kg d.w.$^{-1}$, magnesium—0.9–4 g kg d.w.$^{-1}$ [20][32], calcium—21.4–26.6 g kg d.w.$^{-1}$ [20] and sulfur—1–9 kg d.w.$^{-1}$ [32]. An excessive content of sulfur in biomass poses a threat to the proper course for both the biochemical and thermal methods of biomass conversion into energy. In the case of anaerobic digestion, problems are related to the production of H_2S, which inhibits the growth of microorganisms [95]. The solution is to modify the composition of the substrate so that the optimal value of C:S in the feedstock is over 40 [96]. In the case of combustion, the high content of sulfur in the fuel leads to SO_2 production. In general, the content of sulfur in plant biomass is low [97].

3. Energy Potential of CCC Biomass Converted into Biogas

The basis for the economic assessment of the suitability of plant biomass for use in the energy sector is the value of energy that can be produced from biomass harvested per hectare of crop area per year (MJ ha^{-1} yr^{-1}). This value is calculated based on the yield of the raw material (Mg ha^{-1} yr^{-1}), which is an energy carrier, and its energy value (MJ Mg^{-1}). In the case of the methane fermentation process, the measure of the suitability of CCC biomass for biogas production is its specific methane yield or biomethane potential, which is the volume of methane obtained per mass unit of substrate (m^3 CH_4 Mg^{-1}) and biomass yield obtained per hectare per year (Mg ha^{-1} yr^{-1}). On this basis, the methane yield per hectare per year (m^3 CH_4 ha^{-1} yr^{-1}) is calculated. Assuming the lower heating value of methane (35.8 MJ Nm^{-3}), the energy of biomass per mass unit or cropping area unit is estimated.

According to Möller and Müller [98], during anaerobic fermentation, up to 95% of the carbon contained in the substrate is converted into gaseous components of biogas (CH_4 and CO_2). In the case of energy catch crops examined by Bareha et al. [91], the amount of carbon converted into biogas during this process ranged from 43 to 74%, while in the case of animal manure, it is 36–41%. The degree of conversion depends on many factors, including the content of water-soluble organic compounds, polysaccharides, lignin, C:N ratio, the kind of biomass pretreatment, e.g., grinding or ensiling, and the operational conditions of anaerobic digestion.

Th value of the specific methane yield of the aboveground biomass of different CCC plants is similar. According to Graß et al. [99], the methanogenic potential of the biomass of plant species, such as turnip rape, rye, winter pea, maize, sorghum and sunflower cultivated in different combinations in double-cropping systems in Germany harvested in the vegetative phase, only slightly differed among the particular species. Thus, the yield of biomass was a key factor determining the potential of these plants for biogas production in the fermentation process. The similarity of the specific methane yield values is also indicated by the data presented in **Table 3**.

Table 3. Specific methane yields of selected catch and cover crop biomass.

Crop	Part of the Plant	Methane Yield (m^3 $Mg^{-1}VS$)	Reference
White mustard (*Sinapis alba)*	Tops	352	[100]
Oil seed rape (*Brassica napus* spp. *oleifera*)	Straw	420	[101]
Radish (*Raphanus sativus)*	Shoots	293–304	[102]
Rape (*Brassica napus arvensis)*	Tops	334	[100]
Rape (*Brassica napus)*	Not reported	340	[103]
Winter rye (*Secale cereale montanum)*	Straw	360	[101]
Rye (*Secale cereale)*	Whole plants	140–275	[67]
Triticale (*Triticale)*	Whole plants	212–286	[67]
Triticale (*Triticale)*	Whole plants	396	[104]
Faba bean (*Vicia faba)*	Straw	440	[105]
Faba bean (*Vicia faba)*	Whole plants	387	[106]
Ryegrass (*Lolium* sp.)	-	410	[103]
Ryegrass (*Lolium* sp.)	-	490	[84]
Clover (*Trifolium* sp.)	Vegetative stage	210	[107]
Clover (*Trifolium* sp.)	Flowering stage	140	[107]
Grass hay	-	350	[107]
Oat	-	260	[107]
Lupine (*Lupinus polyphyllus)*	Whole plants	310–360	[100]
Vetch oat (*50% Vicia sativa)*	Whole plants	400–410	[100]

Crop	Part of the Plant	Methane Yield (m^3 Mg^{-1}VS)	Reference
Red clover (*Trifolium pratense)*	Whole plants	310–320	[100]
Red clover (*Trifolium pratense)*	Whole plants	238–293	[108]
Red/white clover–ryegrass *Trifolium pratense*, *Trifolium repens* L., *Lolium perenne* L.)	Whole plants	281–315	[108]
Corn	Corn stover	256 ± 15	[109]

40 to 490 ... literature ... [67] ... dition, the results of the studies of Molinuevo-Salces et al. [8], carried out in Denmark on 10 types of catch crops (single species: white mustard, yellow lupin, oil seed radish, lupin, bean; mixed species: white mustard and common vetch, oil seed rape and winter vetch, perennial rye and Persian clover, winter ryegrass and winter vetch, triticale and winter vetch) were comparable with the values given above. The methane potential was between 229 and 450 m^3 Mg^{-1} VS, and its highest values were obtained in the case of a mixture of rapeseed and winter vetch (399–415 m^3 Mg^{-1} VS), and oilseed radish (368–450 m^3 Mg^{-1} VS) cultivated in one of the locations tested in the study (Holstebro), while the lowest values were obtained in the case of white mustard (239–252 m^3 Mg^{-1} VS), regardless of the location of the crops. The biomethane potential of the raw biomass of CCCs usually does not differ from the potential of raw corn biomass, which is 256 ± 15 m^3 Mg^{-1} VS [109].

A serious limitation in the energetic use of the biomass of plants is the difficulty in maintaining its chemical properties for a long time. The biomasses of CCC plants harvested in the low-maturity phase, useful for biogas production, have a high water content, and are low in their resistance to biodegradation during storage. This is an unfavorable feature when taking into account the efficiency of methane production because it leads to carbon losses before the process of organic matter conversion into biogas. However, research indicates that this problem can be dealt with by the use of ensiling, commonly practiced as a method of preserving plant biomass for animal feed. This process involves the transformation of organic matter in the fermentation process carried out by lactic acid bacteria [110]. During the process, organic matter is lost. However, as reported by Borreani et al. [111] based on the results of their literature review, these losses may vary widely from 1 to 34% depending on the process conditions. According to Villa et al. [112], a properly conducted ensiling process allows for the conservation of up to 93% of the gross energy of biomass. The process leads to a change in the chemical composition that is beneficial for methanogens, which involves the production of organic acids that are easily accessible to them. According to Franco et al. [113], the most preferable features of feedstock subjected to ensiling are the high content of accessible carbohydrates, low buffering capacity and low moisture. The research conducted by Van Vlierberghe et al. [114] showed that the high moisture in CCC biomass leads to the production of leachate, and thereby causes losses in the amount of valuable substrates for biogas production. Their study confirmed that the addition of co-substrates with a high water retention capacity, such as bio-waste and manures, allows the organic matter losses to be limited and the high biogas potential of the silage to be maintained.

Herrmann et al. [115] showed that the reference values of the methane yields of silages of different crop species, such as Italian ryegrass, fodder radish, phacelia, annual ryegrass, spring barley, rapeseed, buckwheat, alfalfa, clover/grass mixtures, alfalfa/grass mixture, oat/fodder vetch mixture, mustard, Bokhara clover and buckwheat/phacelia mixture, related to maize silage, ranged from 57 to 109%, and the lowest value was observed in the case of the alfalfa/grass mixture, and the highest one in the case of the oat/fodder vetch and clover/grass mixtures. The mean methane yield of maize silage determined in this study was 354.6 m^3 Mg^{-1} VS. Hutňan [116] found a lower value for the specific methane yield of maize silage, which was in the range 206–283 m^3 Mg^{-1} VS.

In Europe, aboveground catch biomass rarely exceeds 5 Mg d.w. ha^{-1} [32]. The biomass yield of CCCs can vary depending on crop species, soil properties and climatic conditions. According to Hansen et al. [32], the production of biomass in Denmark remains highly variable, and it ranges from 3 to 15 Mg d.w. ha^{-1} for summer energy crops, and from 2 to 16 Mg d.w. ha^{-1} for winter energy crops. According to their observations, it was difficult to obtain a dense and uniform cover in the summer season due to the lack of water in the soil, while the low number of sunny days was the limiting factor in autumn.

Many studies have been conducted to maximize CCC biomass yield, e.g., by modification in the selection of the plants used in double-cropping systems in order to increase their potential in energy production [99][104][107][117][118].

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