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The Role of Agriculture in Climate Change Mitigation—A Polish Example

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Abstract: Biomass, a basic product of agriculture, is one of the main sinks of carbon in global cycle. Additionally, it can be used as a renewable source of energy, leading to depletion in CO_2 emissions. The paper presents the results of estimations on the current and potential share of catch crop cultivation in climate change mitigation, in Poland, where the agricultural sector plays a significant economic role. The estimation of CO_2 assimilation in biomass was performed on the basis of our own data on yields of commonly used catch crops, obtained in randomly selected 80 farms in Poland, and the content of carbon in the biomass. Calculation of energy potential of the biomass was conducted, assuming its conversion into biogas, on the basis of our own data on catch crop yields and the literature data on their biomethane potentials. The results have shown that catch crops in Poland, which are cultivated to an area of 1.177 mln ha sequestrate 6.85 mln t CO_2 yr^{-1}. However, considering the total area of fields used for spring crop cultivation, it is possible to increase the sequestration to 18.25 mln t CO_2 yr^{-1}, which constitutes about 6% of the annual emission of CO_2 in Poland. Biomethane yields per hectare of particular crops ranged from 965 to 1762 m^3 CH_4 ha^{-1}, and were significantly lower compared to maize, which is commonly in use in biogas plants. However, due to high biomethane potential and favorable chemical composition, catch crops can be a valuable co-substrate for the feedstocks with a high C:N ratio. The potential recovery of energy produced from aboveground biomass of catch crops harvested in Poland during the year is 6327 GWh of electricity and 7230 GWh of thermal energy. Thus, it is advisable to promote catch crops on a wide scale due to substantial environmental benefits of their cultivation.

Keywords: climate change; catch crops; carbon dioxide sequestration; bioenergy

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1. Introduction

An increase in the concentration of greenhouse gases (GHGs) in the atmosphere is unquestioned phenomenon. According to IPCC reports [1,2] it results from increased emission of these gases from anthropogenic sources. One of the most important greenhouse gases (GHGs) is carbon dioxide (CO_2), which is responsible for 56.4% of the greenhouse effect.

Global annual emissions of CO_2 are continuously growing: from 9.3 mL t CO_2 in 1751 (at the beginning of the Industrial Age) through 28.1 mln t CO_2 in 1800; 198.7 mln t CO_2 in 1850; 1.95 Gt CO_2 in 1900; 5.79 Gt CO_2 in 1950; 30.2 Gt CO_2 in 2000 to 39.9 Gt CO_2 in 2020 [3,4]. Growing CO_2 emissions from anthropogenic sources are responsible for the increase in CO_2 concentration in the atmosphere from about 277 ppm in 1751 through 283 ppm in 1800, 285 ppm in 1850, 296 ppm in 1900, 311 ppm in 1950, 368 ppm in 2000, 391 ppm in 2010, 402 ppm in 2015, and to 418 ppm in 2020 [5].

Human activity, mostly electricity, heat production, transport, and cement production, but also agriculture and the changes in the land use (mainly deforestation) are considered to be the main reasons of the GHG emissions. Agriculture, forestry, and other land use release ca. 24% of total global amount of GHGs and are located just behind the electricity and heat production sector (25%) [6]. The ever-growing demand for energy, food and tangible goods does not give rise to optimism in terms of reducing GHGs concentrations, unless the effective, universally acceptable methods of GHGs emission reduction or capture from the atmosphere in particular sectors of human activities are implemented.

While taking the action to mitigate the climate change, it would be helpful to analyze the global natural CO_2 fluxes. There are four important global natural CO_2 fluxes in the terrestrial ecosystems:

- CO_2 absorption by plants through photosynthesis;
- CO_2 emissions as a result of organisms and plants respiration and decomposition of biomass;
- CO_2 absorption by oceans;
- CO_2 emissions by degassing of ocean water.

Photosynthesis is responsible for absorbing about 451 Gt CO_2 yr^{-1} and covering it into biomass. Simultaneously 435 Gt CO_2 yr^{-1} is emitted from terrestrial ecosystems as a result of organisms' and plants' respiration and decomposition of biomass [2]. Oceans are the second most important terrestrial ecosystem which absorbs about 293 Gt CO_2 yr^{-1} and simultaneously emits about 278 Gt CO_2 yr^{-1} through degassing [1,7]. As a major remedial measure, ecological organizations recommend limiting the use of fossil fuels as a source of energy. However, the one-sided approach to only reducing the CO_2 emissions through decreasing the use of fossil fuels by replacing it, for example with biomass, often leads to creation of socio-economic problems [8–10]. Negative examples are production of biodiesel from the oil obtained from coconut palms grown in Indonesia on the land acquired by burning off tropical forests or the production of ethanol from corn [11,12]. Promotion of biofuels was based on the assumption that the amount of CO_2 emitted during biofuels combustion is equal to the amount absorbed by plants from the atmosphere in photosynthesis process. Although this statement is true, it does not account for additional energy used during cultivation, harvesting and processing plants into biofuels. Moreover, such assumption omits the fact that in order to create a plantation, another ecosystem was destroyed—such as tropical forest or peatland—which would absorb greater amounts of CO_2 from the atmosphere. These reasons for GHGs emission are included in the "land use changes" [13].

While the use of plant biomass as a source of energy is widely recommended for mitigation of CO_2 emissions [14,15], the potential role of whole agriculture in mitigation of CO_2 concentration in the atmosphere is not sufficiently recognized. However, an increase in CO_2 absorption by plants in the photosynthesis process by only about 9.4% would allow the complete neutralization of the whole annual anthropogenic CO_2 emissions [16]. This allows the supposition that agricultural activity consisting in cultivation of cover and catch crops is a potential way to decrease the CO_2 concentration in the atmosphere.

Historically, agriculture has traditionally been based on natural methods and fertilizers, catch crop and fallow application, and crop rotation have been widely used, which has resulted in biodiversity. Over time, the use of some traditional practices was significantly reduced or replaced by other systems to maximize yields and profits, disregarding respect for the environment [17,18]. Such an attitude was particularly visible in the policy of many countries in Central and Eastern European, even in the 1980s and 1990s, sometimes leading to corruption in the agro-industrial sector [19]. These practices were implemented and not only on large farms. Many individual farmers departed from traditional farming methods, opting for a simpler and more effective increase in plant yields through the use of mineral fertilization.

These transformations resulted in a number of unfavorable environmental transformations, including soil and ground water contamination, climate change, as well as the alarming depletion of organic matter in soil. About 45% of the mineral soil in Europe is classified as having low or very low organic carbon content (0 to 2%) [20], while the soil in southern Europe has significantly lesser carbon content [21]. It is commonly known that soil organic matter determines the quality of the soil, and directly influences the greenhouse effect, as the carbon released from humic compounds migrates to the atmosphere.

Attempts are being made to remedy the long-term omissions in the environmental impact of agriculture. One of the tools used for this purpose are programs supporting sustainable agriculture, focused on ecological production of healthier food, accompanied by reducing one's environmental footprint. These actions are driven by socio-economic and technological forces but also supported by public policies, such as the Common Agricultural Policy (CAP) realized in European Union [22]. Supporting the practices contributing to increase the biodiversity, mitigation the climate changes, and limiting soil degradation are the main aims of this program. However, the research of [23] showed that adopted programs do not meet the expectations. That can be explained by the low interest in increasing the share of field margins, buffer strips, and fallow lands, which are the most beneficial actions according to the ecologists. However, because of long-term exclusion of land from cultivation, these practices can be applied in agriculture only to a limited extent and farmers are interested mainly in implementation of catch crops and green covers [24]. The purpose of using catch crops is to prevent a decrease in soil productivity by changing its properties, mainly increasing nitrogen resources, as a result of introducing plant biomass into them, which constitute an additional crop, between successive plantings of main crops [25–28].

Wide-spreading of cover and catch crops cultivation can make a significant contribution to reduction of the CO_2 concentration in the atmosphere by carbon immobilisation in biomass and in soil humic substances, and additionally, could provide a source of valuable substrate for biofuels production, using the biological or thermochemical technologies.

There are many studies on the impact of the catch crops on soil productivity, chemical properties and nitrogen budget [29–32], but a little is known about the share of catch crops in the carbon budget and their potential in green energy production, although, in recent years, the European Union has begun to examine the scale and motives of farmers to use catch and cover crops in selected regions in some EU countries: Spain; Romania; France, and the Netherlands [33]. However, the analysis does not relate to the value of carbon absorption or the share the catch crop biomass in energy production.

In our multi-faceted studies, we attempted to estimate the significance of catch crops cultivation in Poland, where agriculture plays an important role, as arable land accounts for approx. 44% of the country's area [34]. The aim of the study was to assess the carbon sequestration potential in the biomass of catch crops cultivated in Poland and to estimate the energy potential contained in the above-ground biomass of these plants when used for biogas production.

2. Materials and Methods

2.1. Estimation of Biomass Yield and Carbon Sequestration

The calculations of potential CO_2 sequestration in catch crops in Poland were conducted on the basis of the data given in Statistical Yearbooks of Agriculture of the years 2005, 2012, and 2018 [35–37], and the results of surveys conducted among Polish farmers (2017–2018), and the research data given in the relevant literature. The real and theoretical possibilities of increasing the share of catch crops cultivated in Poland in binding atmospheric carbon were estimated taking into account the results of the analysis of the trend in catch crops acreage changes in Poland in the recent years [35–37] and the available area of spring crop in Poland in 2018 [37]. The obtained values of potential annual CO_2 absorption in plant biomass were compared with the annual CO_2 emissions in Poland noted in 2018 [38].

The yields of carbon dioxide sequestration (Y_{CO2}, t CO_2 ha^{-1}) in catch crops were calculated on total dry biomass yields of catch crops (t ha^{-1}).

The data on the catch crop biomass yields (Y_b) were obtained in 2018. Samples of the biomass were taken out from 80 farms in Poland (selected randomly from among farmers cultivating catch crops). The samples were taken from the most popular cultivated catch crops in Poland: white mustard (*Sinapis alba* L.); tansy phacelia (*Phacelia tanacetifolia* L.); red clover (*Trifolium pretense* L.); winter rye (*Secale cereale* L.); winter vetch (*Vicia villosa* Roth.); narrow-leafed lupine (*Lupinus angustifolius* L.), mixtures of: yellow lupine (*Lupinus luteus* L.) with serradella (*Ornithopus sativus* Brot.), oats (*Avena sativa* L.) with spring vetch (*Vicia sativa* L.) and field pea (*Pisum sativum subsp. arvense* (L.) Asch.); spring vetch (*Vicia sativa* L.) with field pea (*Pisum sativum subsp. arvense* (L.) Asch.) At the agronomically optimal harvest date of the particular catch crop plant, the samples of plant material were collected from an identical area (1.0 m^2) of each cover-cropped plot in order to determine total biomass yield (aboveground parts and roots). Samples were taken at 2 randomly selected places in each plot, within a 0.50 × 1.00 m frame. The collected samples were segregated into above and belowground fractions and dried under laboratory conditions at a temperature of 40 °C to determine the dried weight. Next, the yields of particular biomass fractions were calculated (Y_b, t ha^{-1}). The carbon (C) content in plant tissues was determined for each fraction [39] and expressed as CO_2 content (by multiplying the value of C content ×3.67). The CO_2 sequestration efficiency was calculated taking into account the biomass yield of particular catch crops (whose dry matter was between 85 and 88%, depending on the plant species) and the carbon content in biomass expressed as a CO_2 basis (t CO_2 ha^{-1}). Then, annual CO_2 sequestration (t CO_2 $ha^{-1} \cdot yr^{-1}$) was calculated based on the yield of the individual plants (Y_b, t ha^{-1}).

2.2. Estimation of Biomethane Yield of Catch Crop Biomass

Potential production of biomethane (Y_{CH4}, m^3 CH_4 ha^{-1}) obtained from the dry weight of biomass harvested from 1 hectare of the crop area was calculated on the approximate value of biomethane potential (BMP, m^3 CH_4 t^{-1}), estimated on the basis of literature data and the values of biomass yield (Y_b, t ha^{-1}) of each crop [40]. Assuming the cultivation area of each crop types, estimated on the basis of statistical data [41], own surveys, and the potential production of biomethane (Y_{CH4}) obtained for each crop, the total annual amount of biomethane production (Q_{CH4}, mln m^3 CH_4 yr^{-1}) was calculated.

2.3. Statistical Analysis

Analysis of variance (ANOVA) was used to statistical elaboration of the data, while Tukey's test was applied to determine Honest Significant Difference (HDS) values at $p <$ 0.05. For the results presented in Tables 1 and 2 the following parameters were calculated: SD—standard deviation and (r)—coefficient correlation between the dry biomass of catch crop (plants + roots) and carbon content in biomass (plants + roots). The analysis was done by using Statistica PL 13.3.

Table 1. Biomass yields and carbon dioxide sequestration by catch crops cultivated in Poland.

Catch Crops	Catch Crops Type	Biomass Yield, Y_b (t ha^{-1})		Average CO_2 Sequestration in Biomass Y_{CO2} (t CO_2 ha^{-1})		
		In Above-Ground Biomass	In Below-Ground Biomass	In Above-Ground Biomass	In Below-Ground Biomass	Total
White mustard	stubble crop	3.94–4.58 a	0.12–0.14 a	6.56 a ± 0.39 **	0.20 a ± 0.04	6.76 a ±0.43
Tansy phacelia	stubble crop	3.61–4.35 a	0.07–0.09 a	6.13 a ± 0.27	0.12 a ± 0.03	6.25 a ± 0.30
Yellow lupine + serradella	stubble crop	3.20–3.60 b	0.27–0.33 b	5.24 b ± 0.21	0.77 b ± 0.13	6.01 a ± 0.34
Oats + spring vetch + field pea	stubble crop	3.04–3.40 b	0.14–0.18 a	4.96 b ± 0.19	0.25 a ± 0.08	5.21 b ± 0.27
Red clover	undersown crop	2.48–2.90 c	0.06–0.08 a	4.14 c ± 0.16	0.11 a ± 0.02	4.25 c ± 0.18
Winter rye	winter cover crop	3.62–4.52 a	0.12–0.14 a	6.27 a ± 0.25	0.20 a ± 0.04	6.47 a ± 0.29
Spring vetch + field pea	stubble crop	2.98–3.94 b	0.18–0.24 b	5.33 b ± 0.22	0.65 b ±0.12	5.98 a ± 0.34
Winter vetch	winter cover crop	2.78–3.16 c	0.11–0.13 a	4.57 b ± 0.18	0.18 a ± 0.06	4.75 c ± 0.24
Narrow-leafed lupine	stubble crop	2.39–2.89 c	0.26–0.32 b	4.07 b ± 0.13	0.45 b ± 0.14	4.52 c ± 0.27
$HSD_{(0.05)}$	-	0.35	0.07	0.59	0.09	0.76

The mean values within a column followed by different letters (a,b ...) are significantly different; ** SD—standard deviation.

Table 2. Total annual sequestration of CO_2 by catch crops cultivated in Poland.

Catch Crops	Area (ha)	Total Annual CO_2 Sequestration (mln t CO_2 yr^{-1})	Predicted Total Annual CO_2 Sequestration Assuming 30% Increase in Catch Crop Area (mln t CO_2 yr^{-1})	Predicted Total Annual CO_2 Sequestration Assuming Total Potential Area for Catch Crop Cultivation (mln t CO_2 yr^{-1})
White mustard	225,000 a *	1.52 a ± 0.11 **	1.98 a ± 0.17	4.05 a ± 0.28
Tansy phacelia	188,000 b	1.18 b ± 0.07	1.53 b ± 0.13	3.14 b ± 0.21
Yellow lupine + serradella	163,000 b	0.98 b ± 0.05	1.27 b ± 0.10	2.61 c ± 0.17
Oats + spring vetch + field pea	150,000 b	0.78 b ± 0.04	1.02 b ± 0.08	2.08 c ± 0.15
Red clover	113,000 c	0.48 c ± 0.03	0.62 c ± 0.05	1.28 d ± 0.09
Winter rye	106,000 c	0.69 b ± 0.04	0.89 d ± 0.07	1.84 d ± 0.12
Spring vetch + field pea	100,000 c	0.60 b ± 0.03	0.78 d ± 0.06	1.60 d ± 0.09
Winter vetch	69,000 d	0.33 d ± 0.02	0.43 e ± 0.04	0.88 e ± 0.11
Narrow-leafed lupine	63,000 d	0.29 d ± 0.02	0.37 e ± 0.03	0.77 e ± 0.07
Total	1177,000	6.85	8.88	18.25
$HSD_{(0.05)}$	35.2	0.17	0.19	0.24

* The means values within a column followed by different letters (a,b . . .) are significantly different; ** SD—standard deviation.

3. Results and Discussion

Six species of plants cultivated in monocultures and three mixture cultures of catch crops were taken into consideration in this study (Table 1). These plants belong to the catch crops commonly used by farmers in Central and Eastern Europe [25]. The popularity of these crops results from their short growing period (fast growth rate) and good adaptation to climatic and soil conditions. An important factor which determines the crop selection is the aim of its cultivation. Catch crops most frequently are used as green manure (the biomass is mixed with soil by plowing), mulch (the plants are cut in autumn and left on the field surface to early spring) undergoing slow mineralization [42,43] or as a fodder for animals. Most of the catch crops under examination were cultivated as a stubble crop, which is sown in the second half of summer, after harvesting the early main crop. Two of them were used as a winter crop, which is sown in autumn after the main crop is harvested, and harvested in the spring of the following year, and only one was cultivated as an undersown crop, which is sown in spring simultaneously with the main crop or during its growing season and remaining after its harvest until autumn of the same year [44].

The yields of biomass of particular crops cultivated in Poland and yields of CO_2 sequestration in their biomass are presented in Table 1.

The lowest CO_2 sequestration in the above-ground biomass (4.07 t CO_2 ha^{-1}) was observed in case of for narrow-leaf lupine, and the highest (6.56 t CO_2 ha^{-1}) for white mustard. Sequestration of CO_2 in the below-ground biomass was significantly smaller than in above-ground parts of the plants. The lowest value of this parameter (0.11 t CO_2 ha^{-1}) was found in case of red clover and the highest one (0.77 t CO_2 ha^{-1}) in the case of the mixture of yellow lupine with serradella. Taking into account total sequestration, the most efficient was white mustard, having absorbed 6.76 t CO_2 ha^{-1}, while the lowest sequestration 4.52 t CO_2 ha^{-1} was shown by narrow-leafed lupine.

The analysis of statistical data [35–37] shows that the acreage of catch crops in Poland is still growing. In 2005, the acreage of these crops amounted to 700 thousand hectares, in 2012 it increased to about 860 thousand hectares, and in 2019 it reached the value of ca. 1230 million hectares. It can be related to the law regulations according to which the farmers using more than 15 ha of arable land are required to provide at least 5% of the area as ecological focus areas (EFA) which are the part of the CAP. Cultivation of catch crops is one of the ways to fulfill this obligation. The area of catch crops in Poland is dominated by stubble crops, which constitute about 75% of the total amount. The other types of crops: winter cover crops and undersown crops constitute 15% and 10% of the total area of catch crops, respectively.

Our research (Table 2) shows that four species of plants clearly dominate in the catch crops in Poland, another three species are moderately popular, and the other two species are not very popular. About 6% of the area of catch crops is covered by "other species" that have low popularity among the farmers in Poland (a single species corresponds to less than 1% of crops). Our further calculations did not take into account the area covered by this group of plants, assuming that the area covered by catch crops in Poland is 1177 million ha. It was calculated that the catch crops growing in this area sequester 6.85 million t CO_2 annually. The characteristics of the annual sequestration of CO_2 by the catch crops cultivated in Poland are depicted in Table 2.

Assuming that the current trend of popularity of individual catch crops among Polish farmers will be maintained, it can be stated that it is possible to increase the area of crops by 30% in the next 10 years. It will increase the area of catch crops up to approximately 1530 million ha and the annual sequestration of CO_2 to 8.88 million t CO_2 yr^{-1}. This seems to be a realistic forecast, especially with greater promotion of such activity. However, not all the carbon sequestration potential of the Polish farmland is currently used. The catch crops can be applied on the fields where spring crops, i.e., cereals, potatoes, and vegetables, are cultivated. These areas were estimated to be 3136 mln t in 2018. Taking into account that 1230 million ha was occupied by catch crop cultivation in 2018 [41], ca. 1900 mln ha (potential increase of 150%) are still potentially available for use for carbon sequestration purpose. This makes it possible to enhance the CO_2 absorption by a further 9.37 million t CO_2 annually up to 18.25 mln t CO_2 annually. For comparison, total annual CO_2 emissions in Poland in 2018 were 305.75 mL ton CO_2 [19] and total agricultural GHGs emissions in Poland expressed as an equivalent of CO_2 were 30.05 mln t [41]. Thus, catch crops can retain ca. 6% of the annual emission of CO_2 in Poland and can compensate for over 50% of the national GHGs emissions from agriculture. Additionally, absorption of carbon in catch crops corresponds to 20% of the amount of carbon contained in the biomass of cereals (wheat, rye, barley, oats, triticale), which are the dominate crops cultivated in Poland [41]. Our previous studies [45] showed that cereals cultivated in Poland absorb 23.8 mln t of carbon annually which is equal to 87.3 mln t of CO_2.

The potential increase in the available area for catch crops cultivation in Poland is multiply higher than in cases of other countries. For example, the value of these parameters, estimated on the base of the total area where cereals, protein and industrial crops are cultivated, in the Overijssel region in Denmark is 90%, but in some of Spanish, Romanian and French regions is only below 20% [33]. Such different values are related to the popularity of catch crops in the considered regions. In France, where catch crops are very popular [33], the possibilities for increasing their cultivation area are less than in countries where these practices are less used.

The forecast of the scale of CO_2 sequestration due to catch crop cultivation in Poland may be even more favorable, taking into account the focus on the cultivation of the most efficient species, i.e., white mustard, tansy phacelia, winter rye, mixtures of spring vetch with field pea or oats with spring vetch and field pea (which entails the highest parameters of CO_2 sequestration) (Table 1).

The main purpose of catch crops using (soil enrichment or green biomass production) should be taken into account when selecting the plant species. When the production of green biomass (as fodder or energy source) is more important than soil improvement, species with high aboveground carbon retention are recommended. For these plants, the total carbon sequestration is strongly correlated with the above-ground yield of biomass (Table 3). The strongest significant correlation between the amount of above-ground biomass of catch crops and the CO_2 sequestration was observed in cases of white mustard, tansy phacelia and spring vetch mixed with field pea. On the other hand, there is lower dependence in the case of below-ground biomass—only in the case of legumes or their mixtures with cereals (producing high root biomass) is the correlation coefficient statistically significant (Table 3).

Table 3. Correlation coefficients (r) between above and below-ground biomass yields and CO_2 sequestration in the biomass.

Catch Crop	Above-Ground Biomass	Below-Ground Biomass
White mustard	0.80 *	0.45
Tansy phacelia	0.77 *	0.40
Yellow lupine + serradella	0.59 *	0.54 *
Oats + spring vetch + field pea	0.65 *	0.55 *
Red clover	0.52 *	0.33
Winter rye	0.61 *	0.29
Spring vetch + field pea	0.77 *	0.52 *
Winter vetch	0.42	0.46
Narrow-leafed lupine	0.57 *	0.57 *

* significant correlation coefficient (0.05).

The absorption of carbon in plant biomass cannot be considered as the sufficient way to reduce the concentration of CO_2 in the atmosphere. However, increasing the production of any type of biomass leads to an increase in the amount of carbon absorbed from the atmosphere and contributes to lowering its concentration in the air, mitigating the greenhouse effect. Moreover, the biomass of catch crops, also the above-ground one, usually remains in the field, and a significant part of carbon included in the plant tissues is incorporated into the soil humic substance. These compounds are hardly biodegradable and highly persistent, remaining in the soil even for over 100 years [46].

However, the assessment of the net soil sequestration of biomass carbon is difficult, because this phenomenon depends on many factors, including physical, chemical and biological soil properties, climatic conditions, land use and management [47] as well as the chemical composition of biomass. These factors influence which part of the biomass remaining in the soil will be transformed into humic compounds or mineralized [48–50].

Significant differences in properties of the biomass of shoots and roots determine the rate and pathways of the conversions. For example [51] estimated that the root biomass is more efficiently converted into persistent organic compounds in the soil than the biomass of the aboveground parts. A humification coefficient which refers to the part of organic matter that is converted to the humic substance for roots is 0.42, while for above-ground crop residues it is only 0.22.

The biomass of catch crops which is used as green fertilizer improves the quality of the soil and increases the yields of main agricultural crops used to production of foods or fodders. However, shoot biomass can be also applied as a raw material for the production of biofuels through anaerobic digestion or thermal processes. The use of the biomass for biogas production is very beneficial from the environmental point of view, because it provides the fuels with low impact on the environment. Additionally, digestate still plays a role in carbon sequestration because it constitutes a source of exogenous soil organic matter.

Some researchers emphasize the advantages of use the catch crop biomass, especially the legumes for biogas production. The study in [52,53], which examined the sorgum which can be used as a catch crop, indicated the possibility of increasing the biomethane yield per hectare, even to a value similar for maize, which is commonly used in biogas plants in CEE. They found the biomethane yield of sorgum biomass to be even up to 6500 m^3 ha^{-1}. The yields of biomethane per hectare calculated for particular catch crops cultivated in Poland obtained in our study (Table 4) are not in line with this observation. The value of this parameter for particular crops ranged from 965 m^3 CH_4 ha^{-1} (which was the lowest value) to 1762 m^3 CH_4 ha^{-1} (which was the highest one). The average value of biomethane production from biomass of catch crops was 1382 m^3 CH_4 ha^{-1}. This value is a few times lower in comparison with the methane yields obtained from maize, that is between 7500 and 10,200 m^3 CH_4 ha^{-1} [54].

There is no doubt that catch crops cannot be compared with maize in terms of suitability for biogas production, due to the significantly lower annual biomass yield (which was found even at 21 t ha^{-1} at full sunlight on the fields in Southwest Germany) [55]. Although the biomethane amount produced during anaerobic decomposition of 1 ton of dry biomass of some catch crops (Table 4) is even higher than in case of maize, which ranged from 262 to 318 m^3 t^{-1} of dry weight of maize silage [56,57]. The highest potential of biomethane of 313 m^3 CH_4 t^{-1} of dry biomass was found in the case of red clover, while the lowest one was 222 m^3 biogas t^{-1} biomass for white mustard. Therefore, it can be stated that this type of biomass can complement the base of the feedstock used in this renewable energy sector.

Catch crops, especially legumes, such as clovers, peas, lupines, vetches have low C:N ratios which usually range from 8 to 15 [58,59]. Thus, the biomass of these crops can balance the high value of this parameter observed in the case of maize raw biomass or silage, the commonly used feedstock in biogas plants, which ranges from 29 to 48 [60–63]. Besides the nitrogen content, the advantage of catch used using in biogas production refers to high content of micronutrients which are necessary for activity of microorganisms growing in anaerobic digester [64], leading to an increase in biogas production. The results of the study of Fahlbusch et al. [64] showed that faba bean, amaranth, and ryegrass have a higher concentration of essential trace elements for the microorganisms responsible for biogas production than maize, triticale, or winter rye intercropped with vetch. The researchers also emphasize the other benefits of catch crops, such as enrichment of biodiversity on the field and improvement of soil quality due to application of the residual product of biogas production to the soil as a source of macronutrient and trace elements.

Table 4. Estimated biomethane potential and yield of biomass of catch crops cultivated in Poland.

Catch Crops	Biomethane Potential, BMP (m^3 t^{-1} of Dry Biomass)	Calculated Biomethane Yield per Hectare, Y_{CH4} (m^3 ha^{-1})	Total Potential Amount of Biomethane Produced from aAbove Ground Biomass, Q_{CH4} (mln m^3 yr^{-1})
White mustard	222 [1]	1456	328
Tansy phacelia	234 [2]	1434	270
Yellow lupine + serradella	237 [3]	1242	202
Oats + spring vetch + field pea	292 [4] (averaged)	1448	217
Red clover	313 [5]	1296	146
Winter rye	281 [2]	1762	187
Spring vetch + field pea	301 [6] (averaged)	1604	160
Winter vetch	270 [7]	1234	85
Narrow-leafed lupine	237 [7]	965	61
Average:		1382	-
Total:		-	1657

[1] [65]: assuming CH_4 concentration in biogas at 50%. [2] [66] [3] [67]: yellow lupine 237; no data found for serradella (both belong to Fabaceae). [4] [65]: oats 256 m^3/t of dry biomass; [67] vetch 270 m^3/t of dry biomass; [68] peas 351 m^3/t of dry biomass. [5] [69]: assuming vs. content 92%. [6] [67]: vetch 270 m^3/t of dry biomass; [69] peas 351 m^3/t of dry biomass. [7] [67].

Assuming that all the above-ground biomass will be used as feedstock in digestion chambers, the total potential amount of biomethane produced from the above-ground biomass is estimated to be 1657 mln m^3 yr^{-1}, with the highest share of white mustard and tansy phacelia (20 and 16%, respectively) and the lowest one in case of winter vetch and narrow-leafed lupine (5 and 4%, respectively).

Assuming the efficiency of biogas conversion to energy at the level achieved by typical cogeneration systems (CHP) amounts to 40% electric energy and 45% thermal energy, potential recovery of electrical energy is 2.1 kWh_{el} and thermal energy is 2.4 kWh_t from 1 m^3 of biogas containing approx. 55% CH_4. Thus, 6327 GWh of electricity and 7230 GWh of thermal energy can be recovered from the biogas produced from the entire above ground biomass of catch crops collected in Poland during the year (which is estimated on 3012.7 million m^3 assuming the CH_4 concentration in biogas of 55%). For comparison, the total annual volume of biogas produced in 28 agricultural biogas plants operating in Poland in 2013 was 112.4 million m^3, of which 227.89 GWh_{el} yr^{-1} and 246.56 GWh_t yr^{-1} were produced, while the total annual volume of biogas produced in 116 agricultural biogas plants operating in Poland in 2020 was 325.4 million m^3, of which 689.12 GWh_{el} yr^{-1} were recovered [70] and about 780 GWh_t yr^{-1} (estimated value, as the law regulations applicable from 2015 on renewable energy sources have abolished the obligation of producers to provide information about amount of heat generated from agricultural biogas. The total biogas volume obtained in biogas plants in 2020 corresponds to 11% of the total potential volume of biogas produced annually from biomass of aboveground catch crops cultivated in Poland). This value shows how large the energy potential contained in the catch crops' biomass is.

Environmental and practical advantages and catch crops should be recognized and supported by programs promoting green energy production, as well as rural development, which is the second pillar of the European Union's Common Agricultural Policy (CAP). Increasing the production of catch crop biomass for energy purposes helps to achieve the long-term goals of this program, such as achieving sustainable management of natural resources, actions to limit climate change, achieving balanced territorial development of rural economies and communities, including the creation of new jobs in the sector of production of raw materials for energy purposes or their processing.

4. Conclusions

The interest in catch cropping as a way to increase atmospheric CO_2 sequestration has been growing recently. This is of great importance in the context of the global warming phenomenon.

Our estimation has shown that all catch crops cultivated in Poland sequester 6.85 mln t CO_2 ha^{-1}. However, taking into account that the potential of cultivating these plants in Poland is not sufficiently exploited, it can be said that an additional 2 million hectares of fields could be used for catch cropping in the future, which will make it possible to increase the CO_2 sequestration over 2.5 times. The predicted extent of CO_2 sequestration may be even more favorable when cultivation of the most efficient species (in terms of carbon sequestration), such as: white mustard, tansy phacelia, winter rye, spring vetch and field pea mixture, oats, spring vetch and field pea mixture, are applied.

The wide spreading of catch crop cultivation has other advantages as well. The biomass can be used as green fertilizer which improves the quality of soil and thus improves the yields of the main agricultural crops contributing to the increased safety of the food supply, as valuable fodder for animals, and a renewable source of energy, that can be gained by conversion of crop biomass to biofuels such as biomethane or syngas, in anaerobic digestion or thermal processes. The results of our estimation showed that potential production of energy from biogas generated from aboveground biomass of catch crops annually harvested in Poland is a few times higher than the energy obtained from the total volume of biogas produced in this time in all the biogas plants operating in Poland, which indicates a significant, unused profitable source of renewable energy.

Our estimations were based on data collected selectively from several dozen farms in Poland, statistical and literature data. Thus, our results are approximated. The uncertainties are related to the determination of the area occupied by individual types of plants, the impact of soil diversity and microclimatic conditions on the biomass yield, as well as the determination of the methanogenic potential of catch crop biomass. However, the obtained results indicate that even with these limitations of calculations, it is worth considering the cultivation of catch crops not only as a way to improve soil quality and carbon sequestration, but also as a new source of renewable energy with high availability.

The future research in this area should be focus on optimization of catch crop selection in order to obtain the highest yields in various climatic and soil conditions. It could be assumed that, if the farmers had focused only on highly-yielding and low-water demanding species of catch crops, with low-water requirement, the scale of sequestration, and especially the potential effect of obtained energy, would be greater. Additionally, the future studies should also cover the carbon budget related to the catch crop production and applications, including assimilation of CO_2 in catch crop biomass, humification of organic matter in soil, following biomass ploughing under ('soil as a CO_2 bank'), carbon emission during energy production from biogas obtained from catch crop biomass, and accumulation of carbon introduced to the soil with residuals after anaerobic digestion of catch crop biomass.

Taking into account the high worldwide demand for energy, unstable and uncertain fossil fuels sources as well as the concern over global climate change, greater attention should be paid to the increase in the role of agriculture in climate change mitigation and providing raw materials for renewable energy production. Increasing the area of sowing catch crops in typically agricultural regions of Central and Eastern Europe may be an effective and relatively cheap way to mitigate adverse climate changes. However, the role of agriculture in climate change mitigation is potentially significant but the knowledge and awareness of the society in this regard are unsatisfactory. Dissemination of catch crops cultivation requires the re-education of farmers and the application of mechanisms of their financial and advisory support. However, to improve the quality of the environment due to the decrease in the CO_2 concentration in the atmosphere and increase in carbon sequestration in soil, such investments are necessary.

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References

1. IPCC. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013; p. 1535.
2. IPCC. AR6 Synthesis Report: Climate Change. Available online: https://www.ipcc.ch/report/sixth-assessment-report-cycle/ (accessed on 1 May 2021).
3. Le Quéré, C.; Andrew, R.M.; Friedlingstein, P.; Sitch, S.; Hauck, J.; Pongratz, J.; Pickers, P.A.; Korsbakken, J.I.; Peters, G.P.; Canadell, J.G.; et al. Global Carbon Budget. *Earth Syst. Sci. Data* **2018**, *10*, 2141–2194. [CrossRef]
4. Friedlingstein, P.; O'Sullivan, M.; Jones, M.W.; Andrew, R.M.; Hauck, J.; Olsen, A.; Peters, G.P.; Peters, W.; Pongratz, J.; Sitch, S.; et al. Global Carbon Budget. *Earth Syst. Sci. Data* **2020**, *12*, 3269–3340. [CrossRef]
5. Ritchie, H.; Roser, M. CO_2 and Greenhouse Gas Emissions. Available online: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions (accessed on 1 May 2021).
6. IPCC. 2014 Summary for Policymakers. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Edenhofer, O., Pichs-Madruga, Y., Sokona, E., Farahani, S., Kadner, K., Seyboth, A., Adler, I., Baum, S., Brunner, P., Eickemeier, B., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014; Available online: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_summary-for-policymakers.pdf (accessed on 1 February 2021).
7. Ciais, P.; Gasser, T.; Paris, J.D.; Caldeira, K.; Raupach, M.R.; Canadell, J.G.; Patwardhan, A.; Friedlingstein, P.; Piao, S.L.; Gitz, V. Attributing the increase in atmospheric CO2 to emitters and absorbers. *Nat. Clim. Chang.* **2013**, *3*, 926–930. [CrossRef]
8. Sztumski, W. Reflection on the Human Living Environment in Connection with Sustainable Development. *Probl. Ekorozwoju* **2021**, *16*, 39–44. [CrossRef]
9. Pawłowski, A. The Sustainable Revolution. *Problemy Ekorozwoju/Problem. Sustain. Dev.* **2009**, *4*, 65–76.
10. Udo, V.; Pawłowski, A. Human Progress Towards equitable Sustainable Development: A Philosophical Exploration. *Problemy Ekorozwoju/Problem. Sustain. Develop.* **2009**, *4*, 23–44.
11. Fargione, J.; Hill, J.; Tilman, D.; Polasky, S.; Hawthorne, P. Land Clearing and the Biofuel Carbon Debt. *Science* **2008**, *319*, 1235–1238. [CrossRef]

12. Searchinger, T.; Heimlich, R.; Houghton, R.A.; Dong, F.; Elobeid, A.; Fabiosa, J.; Tokgoz, S.; Hayes, D.; Yu, T.-H. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science* **2008**, *319*, 1238–1240. [CrossRef]
13. Rudel, T.K.; Coomes, O.T.; Moran, E.; Achard, F.; Angelsen, A.; Xu, J.; Lambin, E. Forest transitions: Towards a global understanding of land use change. *Glob. Environ. Chang.* **2005**, *15*, 23–31. [CrossRef]
14. Canadell, J.; Schulze, E.D. Global potential of biospheric carbon management for climate mitigation. *Nat. Commun.* **2014**, *5*, 5282. [CrossRef]
15. Favero, A.; Massetti, E. Trade of woody biomass for electricity generation under climate mitigation policy. *Resour. Energy Econ.* **2014**, *36*, 166–190. [CrossRef]
16. Pawlowski, L.; Litwińczuk, Z.; Zhou, G. *The Role of Agriculture in Climate Change Mitigation*; CRC Press: Boca Raton, FL, USA, 2020; pp. 1–135.
17. Stoate, C.; Báldi, A.; Beja, P.; Boatman, N.; Herzon, I.; van Doorn, A.; de Snoo, G.; Rakosy, L.; Ramwell, C. Ecological impacts of early 21st century agricultural change in Europe—A review. *J. Environ. Manag.* **2009**, *91*, 22–46. [CrossRef] [PubMed]
18. Pe'Er, G.; Bonn, A.; Bruelheide, H.; Dieker, P.; Eisenhauer, N.; Feindt, P.H.; Hagedorn, G.; Hansjürgens, B.; Herzon, I.; Lomba, Â.; et al. Action needed for the EU Common Agricultural Policy to address sustainability challenges. *People Nat.* **2020**, *2*, 305–316. [CrossRef] [PubMed]
19. Creţan, R.; O'Brien, T. Corruption and conflagration: (in)Justice and protest in Bucharest after the Colectiv fire. *Urban Geogr.* **2020**, *41*, 368–388. [CrossRef]
20. Louwagie, G.; Gay, S.H.; Burrell, A. *Final Report on the Project Sustainable Agriculture and Soil Conservation (SoCo)*; JRC Scientific and Technical Reports Luxembourg; European Commission; Joint Research Centre: Luxembourg, 2009.
21. Zdruli, P.; Jones, R.J.A.; Montanarella, L. *Organic Matter in the Soils of Southern Europe European Soil Bureau Technical Report Luxembourg*; Publications Office of the European Union: Luxembourg, 2004.
22. Hodge, I.; Hauck, J.; Bonn, A. The alignment of agricultural and nature conservation policies in the European Union. *Conserv. Biol.* **2015**, *29*, 996–1005. [CrossRef]
23. Pe'Er, G.; Zinngrebe, Y.; Moreira, F.; Sirami, C.; Schindler, S.; Müller, R.; Bontzorlos, V.; Clough, D.; Bezák, P.; Bonn, A.; et al. A greener path for the EU Common Agricultural Policy. *Science* **2019**, *365*, 449–451. [CrossRef]
24. Pe'Er, G.; Zinngrebe, Y.; Hauck, J.; Schindler, S.; Dittrich, A.; Zingg, S.; Tscharntke, T.; Oppermann, R.; Sutcliffe, L.M.; Sirami, C.; et al. Adding Some Green to the Greening: Improving the EU's Ecological Focus Areas for Biodiversity and Farmers. *Conserv. Lett.* **2017**, *10*, 517–530. [CrossRef]
25. Żuk-Gołaszewska, K.; Wanic, M.; Orzech, K. The role of catch crops in in the field plant production—A review. *J. Elementol.* **2018**, *24*. [CrossRef]
26. Myers, R.; Watts, C. Progress and perspectives with cover crops: Interpreting three years of farmer surveys on cover crops. *J. Soil Water Conserv.* **2015**, *70*, 125A–129A. [CrossRef]
27. Kołodziejczyk, M.; Antonkiewicz, J.; Kulig, B. Effect of living mulches and conventional methods of weed control on weed occurrence and nutrient uptake in potato. *Int. J. Plant Prod.* **2017**, *11*, 275–284. [CrossRef]
28. Harasim, E.; Kwiatkowski, C.; Staniak, M. Effect of catch crops and tillage systems on some chemical properties of loess soil in a short-term monoculture of spring wheat. *J. Elementol.* **2019**, *25*, 35–43. [CrossRef]
29. Doltra, J.; Olesen, J.E. The role of catch crops in the ecological intensification of spring cereals in organic farming under Nordic climate. *Eur. J. Agron.* **2013**, *44*, 98–108. [CrossRef]
30. Komainda, M.; Taube, F.; Kluß, C.; Herrmann, A. Effects of catch crops on silage maize (*Zea mays* L.): Yield, nitrogen uptake efficiency and losses. *Nutr. Cycl. Agroecosyst.* **2018**, *110*, 51–69. [CrossRef]
31. Sałata, A.; Pandino, G.; Buczkowska, H.; Lombardo, S. Influence of Catch Crops on Yield and Chemical Composition of Winter Garlic Grown for Bunch Harvesting. *Agricculture* **2020**, *10*, 134. [CrossRef]
32. De Notaris, C.; Rasmussen, J.; Sørensen, P.; Olesen, J.E. Nitrogen leaching: A crop rotation perspective on the effect of N surplus, field management and use of catch crops. *Agric. Ecosyst. Environ.* **2018**, *255*, 1–11. [CrossRef]
33. Smit, B.; Janssens, B.; Haagsma, W.; Hennen, W.; Adrados, J.; Kathage, J. *Adoption of Cover Crops for Climate Change Mitigation in the EU*; Kathage, J., Perez Dominguez, I., Eds.; Publications Office of the European Union: Luxembourg, 2019; ISBN 978-92-76-11312-6. [CrossRef]
34. Statistics Poland Environment. 2019. Available online: https://stat.gov.pl/en/topics/environment-energy/environment/environment-2019,1,11.html (accessed on 22 May 2021).
35. Dmochowska, H. (Ed.) *Statistical Yearbook of Agriculture 2005*; GUS: Warsaw, Poland, 2005. Available online: https://stat.gov.pl/obszary-tematyczne/roczniki-statystyczne/roczniki-statystyczne/maly-rocznik-statystyczny-2005-r,1,6.html?contrast=default (accessed on 20 January 2021).
36. Ziółkowska, E. (Ed.) *Statistical Yearbook of Agriculture 2012*; GUS: Warsaw, Poland, 2012. Available online: https://stat.gov.pl/en/topics/statistical-yearbooks/statistical-yearbooks/statistical-yearbook-of-agriculture-2012,6,7.html (accessed on 20 January 2021).
37. Rozkrut, D. (Ed.) *Statistical Yearbook of Agriculture 2018*; GUS: Warsaw, Poland, 2018. Available online: https://stat.gov.pl/download/gfx/portalinformacyjny/en/defaultaktualnosci/3328/6/13/1/statistical_yearbook_of_agriculture_2018.pdf (accessed on 1 May 2021).

38. IEA, Poland. Available online: https://www.iea.org/countries/poland (accessed on 1 May 2021).
39. Tyurin, I.V. A new modification of the volumetric method of determining soil organic matter by means of chromic acid. *Pochvovedenie* **1931**, *5–6*, 36–47.
40. Hakl, J.; Fuksa, P.; Habart, J.; Šantrůček, J. The biogas production from lucerne biomass in relationto term of harvest. *Plant Soil Environ.* **2012**, *58*, 289–294. [CrossRef]
41. Statistics Poland. Production of Agricultural and Horticultural Crops in 2018: Warsaw, Poland 2019. Available online: https://stat.gov.pl/download/gfx/portalinformacyjny/en/defaultaktualnosci/3332/2/3/1/production_of_agricultural_and_horticultural_crops_in_2018_.pdf (accessed on 1 May 2021).
42. Kristensen, H.L.; Thorup-Kristensen, K. Root Growth and Nitrate Uptake of Three Different Catch Crops in Deep Soil Layers. *Soil Sci. Soc. Am. J.* **2004**, *68*, 529–537. [CrossRef]
43. Morris, N.; Miller, P.; Orson, J.H.; Froud-Williams, R. The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment—A review. *Soil Tillage Res.* **2010**, *108*, 1–15. [CrossRef]
44. Thomas, F.A.; Archambeaud, M. (Eds.) *Les Couverts Végétaux: Gestion Pratique de l'interculture*; Agricole: Paris, France, 2013.
45. Pawłowski, L.; Pawłowska, M.; Cel, W.; Wang, L.; Li, C.; Mei, T. Characteristic of carbon dioxide absorption by cereals in Poland and China. Gospodarka Surowcami Mineralnymi. *Min. Resour. Manag.* **2019**, *35*, 165–176. [CrossRef]
46. Prusty, B.A.K.; Azeez, P.A. Humus: The Natural Organic Matter in the Soil System. *J. Agric. Res. Dev.* **2004**, *1*, 1–12.
47. Franzluebbers, A.J. Organic residues, decomposition. In *Encyclopedia of Soils in the Environment*; Hillel, D., Hatfield, J.L., Powlson, D.S., Rosenzweig, C., Scow, K.M., Singer, M.J., Sparks, Eds.; Academic Press: Amsterdam, The Netherland, 2004; pp. 112–118.
48. Jongen, M. Effects of Elevated Carbon Dioxide on Plant Biomass Production and Competition in a Simulated Neutral Grassland Community. *Ann. Bot.* **1998**, *82*, 111–123. [CrossRef]
49. Wang, H.; Prentice, I.C.; Keenan, T.F.; Davis, T.W.; Wright, I.J.; Cornwell, W.K.; Evans, B.J.; Peng, C. Towards a universal model for carbon dioxide uptake by plants. *Nat. Plants* **2017**, *3*, 734–741. [CrossRef] [PubMed]
50. Cheng, L.; Zhang, N.; Yuan, M.; Xiao, J.; Qin, Y.; Deng, Y.; Tu, Q.; Xue, K.; Van Nostrand, J.D.; Wu, L.; et al. Warming enhances old organic carbon decomposition through altering functional microbial communities. *ISME J.* **2017**, *11*, 1825–1835. [CrossRef] [PubMed]
51. Bonten, L.T.C.; Elferink, E.V.; Zwart, K. BioESoil Version 0.Tool to Assess Effects Of Bio-Energy on Nutrient Losses and Soil Organic Matter. Manual and Background Document. Available online: https://www.wur.nl/upload_mm/5/c/e/0b7fdda3-1deb-4eed-9e67-dc2aace480de_BioESoil-Manual.pdf (accessed on 1 May 2021).
52. Wannasek, L.; Ortner, M.; Amon, B.; Amon, T. Sorghum, a sustainable feedstock for biogas production? Impact of climate, variety and harvesting time on maturity and biomass yield. *Biomass Bioenerg.* **2017**, *106*, 137–145. [CrossRef]
53. Stinner, P.W.; Deuker, A.; Schmalfuß, T.; Brock, C.; Rensberg, N.; Denysenko, V.; Trainer, P.; Möller, K.; Zang, J.; Janke, L.; et al. Perennial and Intercrop Legumes as Energy Crops for Biogas Production. In *Legumes for Soil Health and Sustainable Management*; Springer Science and Business Media LLC: Berlin/Heidelberg, Germany, 2018; pp. 139–171.
54. Amon, T.; Amon, B.; Kryvoruchko, V.; Machmüller, A.; Hopfner-Sixt, K.; Bodiroza, V.; Hrbek, R.; Friedel, J.; Pötsch, E.; Wagentristl, H.; et al. Methane production through anaerobic digestion of various energy crops grown in sustainable crop rotations. *Bioresour. Technol.* **2007**, *98*, 3204–3212. [CrossRef]
55. Schulz, V.S.; Munz, S.; Stolzenburg, K.; Hartung, J.; Weisenburger, S.; Mastel, K.; Möller, K.; Claupein, W.; Graeff-Hönninger, S. Biomass and Biogas Yield of Maize (*Zea mays* L.) Grown under Artificial Shading. *Agriculture* **2018**, *8*, 178. [CrossRef]
56. Dach, J.; Pulka, J.; Janczak, D.; Lewicki, A.; Pochwatka, P.; Oniszczuk, T. Energetic Assessment of Biogas Plant Projects Based on Biowaste and Maize Silage Usage. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *505*, 012029. [CrossRef]
57. Smurzyńska, A.; Dach, J.; Kozłowski, K.; Mazurkiewicz, J.; Woźniak, E.; Boniecki, P.; Kupryaniuk, K.; Janczak, D.; Brzoski, M. Relevant biogas substrate—maize silage vs slaughterhouse waste. In Proceedings of the 8th International Conference on Information and Communication Technologies in Agriculture, Food & Environment, Chania, Crete, Greece, 21–24 September 2017; Available online: http://ceur-ws.org/Vol-2030/HAICTA_2017_paper21.pdf (accessed on 23 May 2021).
58. Clark, A. *Managing Cover Crops Profitably*, 3rd ed.; Sare: Maryland, MD, USA, 2007; pp. 1–248.
59. Wendling, M.; Büchi, L.; Amossé, C.; Sinaj, S.; Walter, A.; Charles, R. Influence of root and leaf traits on the uptake of nutrients in cover crops. *Plant Soil* **2016**, *409*, 419–434. [CrossRef]
60. Varol, A.; Ugurlu, A. Comparative evaluation of biogas production from dairy manure and co-digestion with maize silage by CSTR and new anaerobic hybrid reactor. *Eng. Life Sci.* **2017**, *17*, 402–412. [CrossRef] [PubMed]
61. Szlachta, J.; Prask, H.; Fugol, M.; Luberański, A. Effect of Mechanical Pre-Treatment of the Agricultural Substrates on Yield of Biogas and Kinetics of Anaerobic Digestion. *Sustainability* **2018**, *10*, 3669. [CrossRef]
62. Dinca, I.; Voicu, G.; Ferdes, M.; Toma, L.; Voicea, I. Anaerobic digestion of animal manure and maize silage in pilot plant for biogas production. *U.P.B. Sci. Bull. Ser. B* **2016**, *78*, 71–80.
63. Chomczyńska, M.; Zdeb, M. The Effect of Z-ion Zeolite Substrate on Growth of *Zea mays* L. as Energy Crop Growing on Marginal Soil. *J. Ecol. Eng.* **2019**, *20*, 253–260. [CrossRef]
64. Fahlbusch, W.; Hey, K.; Sauer, B.; Ruppert, H. Trace element delivery for biogas production enhanced by alternative energy crops: Results from two-year field trials. *Energy Sustain. Soc.* **2018**, *8*, 38. [CrossRef]

65. Peu, P.; Picard, S.; Girault, R.; Labreuche, J.; Béline, F.; Dabert, P. Catch crops for agricultural biogas production, case study for *Brassicaceae* sp. Available online: https://www.oieau.org/eaudoc/oai/Catch-crops-agricultural-biogas-production-case-study-Brassicaceae-sp (accessed on 1 May 2021).
66. Herrmann, C.; Idler, C.; Heiermann, M. Biogas crops grown in energy crop rotations: Linking chemical composition and methane production characteristics. *Bioresour. Technol.* **2016**, *206*, 23–35. [CrossRef] [PubMed]
67. Pabón-Pereira, C.; Hamelers, H.; Matilla, I.; Van Lier, J. New Insights on the Estimation of the Anaerobic Biodegradability of Plant Material: Identifying Valuable Plants for Sustainable Energy Production. *Processes* **2020**, *8*, 806. [CrossRef]
68. Braun, R. Anaerobic digestion—A multifaceted process for energy, environmental management and rural development. In *Improvement of Crop Plants for Industrial End Users*; Ranalli, P., Ed.; Springer: Berlin, Germany, 2007; pp. 307–334.
69. Wang, G.; Schmidt, J.E. Biogas production from energy crops and agriculture residues: A review. In *Biogas Production from Energy Crops and Agriculture Residues*; Ris0 DTU National Laboratory for Sustainable Energy: Roskilde, Denmark, 2010; pp. 1–90.
70. National Support Centre for Agriculture (KOWR). Biuletyn Informacji Publicznej Krajowego Ośrodka Wsparcia Rolnictwa. Dane dotyczące działalności wytwórców biogazu rolniczego w latach 2011–2020 (Data on the Activity of Agricultural Biogas Producers in 2011–2020). Available online: https://bip.kowr.gov.pl/informacje-publiczne/odnawialne-zrodla-energii/biogaz-rolniczy/dane-dotyczace-dzialalnosci-wytworcow-biogazu-rolniczego-w-latach-2011-2020 (accessed on 2 June 2021). (In Polish)