agronomy

MDPI

Article

Digestate Application Methods and Rates with Regard to Greenhouse Gas Emissions and Crop Conditions

Jaroslav Korba [1], Petr Šařec [1], Václav Novák [1,*], Pavel Brož [2], Antonín Dolan [3] and Martin Dědina [4]

[1] Department of Machinery Utilization, Faculty of Engineering, Czech University of Life Sciences Prague, 165 00 Prague, Czech Republic; korba@tf.czu.cz (J.K.); psarec@tf.czu.cz (P.Š.)
[2] Department of Agricultural Machines, Faculty of Engineering, Czech University of Life Sciences Prague, 165 00 Prague, Czech Republic; brozp@tf.czu.cz
[3] Department of Technology and Cybernetics, Faculty of Agriculture and Technology, University of South Bohemia, 370 05 Ceske Budejovice, Czech Republic; dolan@zf.jcu.cz
[4] Research Institute of Agricultural Engineering, 161 01 Prague, Czech Republic; martin.dedina@vuzt.cz
* Correspondence: novakvaclav@tf.czu.cz

Abstract: Digestate is commonly used as a liquid organic fertilizer, as it contains nutrients that are important for plant growth and thus help reduce usage of mineral fertilizers. Since the digestate application leads to the release of greenhouse gases (GHGs) into the atmosphere, it is necessary to find a suitable application method and fertilizer rate with minimal gas emissions while providing sufficient nutrients to crops. The aim of this study was to investigate the relationship between selected GHGs and ammonia (NH_3) release into the atmosphere and different rates of digestate applied, i.e., 0, 10, 20, 30, and 40 m^3 ha^{-1}. Two digestate incorporation methods were used, i.e., a disc application unit (D) and strip-till (S). The fluxes, i.e., methane (CH_4), ammonia, and carbon dioxide (CO_2), were monitored using the wind tunnel method. Crop growth and potential nutrient utilization by silage maize were assessed through stand condition monitoring by the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI) using remote sensing. Under the given conditions, the digestate rates and the compared application methods had significant effects on the level of fluxes. The rate of digestate was confirmed to affect the yield of silage maize. The yield increased by more than 8% when using the disc applicator. Based on our results, it is advisable to apply digestate by strip-till technology at rates of approximately 20 m^3 ha^{-1}.

Keywords: flux; remote sensing; yield; disc application unit; strip-till

Citation: Korba, J.; Šařec, P.; Novák, V.; Brož, P.; Dolan, A.; Dědina, M. Digestate Application Methods and Rates with Regard to Greenhouse Gas Emissions and Crop Conditions. *Agronomy* **2024**, *14*, 336. https://doi.org/10.3390/agronomy14020336

Academic Editor: José L. S. Pereira

Received: 20 December 2023
Revised: 2 February 2024
Accepted: 5 February 2024
Published: 6 February 2024

1. Introduction

One of the causes of climate change and global warming is greenhouse gas (GHG) emissions, especially of carbon dioxide and methane. Climate change has occurred in the past, but the present changes are more marked and rapid than before. These changes can have an adverse effect on our environment [1,2]. This especially increases the pressure on industries that obtain energy from fossil fuels, such as for instance oil or gas, which are often located in politically unstable regions. With respect to sustainability, the European Commission has established a plan to increase the required proportion of energy from renewable sources. This aim is described by the revised Directive EU/2023/2413, which entered into force on 20th November 2023 [3]. Biogas produced in agriculture can contribute to this effort, although using land for non-food purposes is often considered controversial [4]. However, the number of biogas plants in the Czech Republic has increased significantly in the last decade, as this method of electricity production has been promoted [5].

Anaerobic digestion involves the transformation of organic materials without access to air and produces biogas and digestate [6]. Digestate is mostly used in agriculture as a liquid organic fertilizer, because it contains nutrients that are easily accessible by plants.

Although the quality of digestate is influenced by many factors, it is primarily affected by the feedstock that is used for biogas production [7]. Digestate contains a large amount of macronutrients (N, P, K) and trace elements [8,9]. Digestate constitutes nutrients/substances that have been stabilized by prior treatments and are easily degradable or mineralized by microbes, making nutrients easily available for plant uptake [10].

The application of digestate instead of slurry has several advantages; for example, it reduces smell, increases veterinary safety, reduces the presence of harmful microorganisms and weed seeds, and results in reduced CO_2 and CH_4 fluxes [11,12]. It was also reported that the lower fluxes of these gases are due to the anaerobic digestion (AD) process, where labile carbon is transformed into biogas, and the resulting product in the form of digestate contains less substrate and therefore has less potential for the production of these emissions [13]. In addition, digestate has lower CO_2 and CH_4 emissions compared to other organic fertilizers. However, NH_3 emissions are typically greater for digestate than for manure or slurry [14].

Nutrients from digestate can leach into surface- and groundwater and escape as gaseous emissions into the air. The amount of nutrient losses can be significantly influenced by the method of application to the soil [15]. Broadcast spreading of slurry using splash plates (SPs) is being replaced by precision spreading equipment that enables accurate application by a band spreader (e.g., trailing hose and trailing shoe) or by direct injection into the soil, thus reducing ammonia emissions via volatilization from field-applied slurry or digestate. The most effective approaches in terms of the abatement of ammonia emissions compared to broadcasting are the closed-slot shallow or deep injections. Compared to SPs, closed-slot injection reduces ammonia emissions by 23 to 94% [16,17], while deep injection reduces these by 95 to 99% [18].

The digestate rates focused on in this analysis showed an increase in the oilseed rape yield depending on the dose applied [19]. Another study [20] verified that digestate can be used as a fertilizer on grasslands with no significant effect on the nutritive value, and that fodder safety will not be compromised by digestate fertilization in repetitive higher doses of 40 m^3 ha^{-1}. Digestate can partially replace the use of mineral fertilizers. The nitrogen contained in digestate is largely in the form of ammonium. Not only ammonium nitrogen, but other elements contained in the fertilizer are subject to losses to the atmosphere [21]. The gases monitored in this experiment are greenhouse gases. Methane is the second most important greenhouse gas after carbon dioxide [22,23].

Methods for measuring greenhouse gas emissions from livestock production are well established, but methods for measuring them after fertilizer application to fields are not uniform. There are several different methods for measuring emissions in the field. One of the oldest techniques is the use of static passive chambers. These chambers capture the gases that are released from the soil, which can then be sampled and subsequently analyzed. A more advanced method is the employment of dynamic chambers, where the monitored gas is drawn into an analyzer and then returned to the chamber. Other approaches include using wind tunnels to measure emissions, where the difference in composition of the incoming and outgoing air is monitored [24]. Compared to the chambers described above, the results from wind tunnels are not affected by the possible emerging microclimate of the monitored area [25]. The wind tunnel method is especially appropriate for monitoring ammonia flux [26].

The concentrations of gases that are released after digestate application, which are measured above the surface, decrease with time [27]. In addition, these concentrations are also affected by the soil moisture and temperature, porosity, and bulk density. The origin as well as the state (raw, solid, liquid, composted) of the digestate also has an impact on emissions. The greatest emissions can be observed with the raw digestates, while lower emissions are emitted with the liquid ones [28]. The timing of digestate application does not affect the overall annual emissions, but it does shift emissions to the non-growing season for fall applications and to the growing season for spring applications [29]. Hence, it is advisable to start measurements immediately following fertilizer application. In the search for the optimum dose, the smallest release of GHGs into the air should be balanced with sufficient plant nutrition.

In this experiment, two methods of digestate application, carried out prior to silage maize sowing, were compared. The aim of this study was to evaluate (i) the conventional closed-slot injection by disc application and (ii) a unit with deep injection performed by soil conservation strip-till application. Different rates of digestate were applied by both methods, with the aim of choosing the method and rate resulting in low gas emissions from the applied fertilizer. Crop status assessment during the growing season was included to ensure that the recommended rate provides sufficient nutrition to the plants, thus avoiding any potential yield loss. The hypotheses to be verified are as follows: (a) GHG and NH_3 emissions increase with rising digestate rates, (b) strip-till application leads to lower emissions compared to the shallower incorporation method; and (c) higher digestate rates lead to better vegetation conditions and improved yields.

2. Materials and Methods

In two consecutive years, 2021 and 2022, field trials were established, focusing on different rates and application methods of digestate prior to maize sowing near the village of Čechtice in the Central Bohemia Region, Czech Republic. In 2021, the measurements were carried out on a slightly sloping plot of Locality A (49.6051642 N, 15.0814217 E), with an average altitude of 540 m above sea level. In 2022, the experiment was repeated on a flat plot, Locality B (49.6359539 N, 15.0302989 E), at 525 m above sea level. According to the United States Department of Agriculture assessment, the soil texture of both fields was sandy loam [30]. Table 1 presents selected chemical parameters that attained similar values for both localities.

Table 1. Chemical characteristics (mean ± st. dev.) of experimental fields.

Soil Property	Locality A—2021	Locality B—2022
Total carbon (%)	4.24 ± 0.68	4.17 ± 0.65
Total nitrogen (%)	0.40 ± 0.06	0.41 ± 0.06
C/N ratio (-)	10.36 ± 0.59	10.09 ± 0.55
K ($mg \cdot kg^{-1}$)	349 ± 99.33	357 ± 98.54
Ca ($mg \cdot kg^{-1}$)	2708.5 ± 502.38	2626.05 ± 542.85
Mg ($mg \cdot kg^{-1}$)	315.29 ± 45.55	312.37 ± 47.36
P ($mg \cdot kg^{-1}$)	35.90 ± 9.99	34.16 ± 9.5
pH (-)	6.64 ± 0.18	6.78 ± 0.21

Digestate was made at a farm's biogas plant that processes mainly maize silage and cow slurry. Before the filling of the application tanker, a mixed sample was taken for laboratory analysis each year from the storage facility where the digestate had been homogenized. Table 2 shows the chemical composition of the applied digestate and the resulting calculated amounts of key nutrients that were supplied, with respective digestate rates that were set by the application tanker. Dry matter (DM) in digestate attained 6%, and digestate density reached 980 to 990 kg m^{-3}. The lowest digestate rate of 10 m^3 ha^{-1} supplied total nitrogen (N_{tot}) at 18 kg ha^{-1}, the highest rate of 40 m^3 ha^{-1} at over 92 kg ha^{-1}. The composition of the digestate applied on the experimental localities differed. This was the case particularly for organic carbon, whose content was more than 50% higher in 2022 in Locality B, and for total nitrogen content, which was higher by 24.4% again in 2022 compared to 2021. Nitrogen that was accessible to plants amounted to around 50% of the total nitrogen. Concerning laboratory chemical analysis of digestate, pH was determined by potentiometry, $C_{organic}$ by gravimetric method, and N_{tot}, P, and K were determined by Atomic Absorption Spectrometry.

Table 2. Composition of digestate and nutrient doses for respective digestate application rates on the experimental localities.

Year	pH	$C_{organic}$	N_{tot}	P	K	$N_{inorganic}$	N/NO_3	N/NH_4
					(g kg^{-1} DM)			
2021	8.34	79.52	31.52	8.34	68.63	8.33	1.80	6.53
2022	9.07	122.70	39.20	8.69	65.21	8.37	6.03	2.34
	Digestate rate				(kg ha^{-1})			
2021	0 m^3 ha^{-1}	0	0	0	0	0	0	0
	10 m^3 ha^{-1}	46.76	18.53	4.90	40.35	4.90	1.06	3.84
	20 m^3 ha^{-1}	93.52	37.07	9.81	80.71	9.80	2.12	7.68
	30 m^3 ha^{-1}	140.27	55.60	14.71	121.06	14.70	3.18	11.52
	40 m^3 ha^{-1}	187.03	74.14	19.62	161.42	19.60	4.24	15.36
2022	0 m^3 ha^{-1}	0	0	0	0	0	0	0
	10 m^3 ha^{-1}	72.15	23.05	5.11	38.34	4.92	3.55	1.38
	20 m^3 ha^{-1}	144.30	46.10	10.22	76.69	9.84	7.09	2.75
	30 m^3 ha^{-1}	216.44	69.15	15.33	115.03	14.76	10.64	4.13
	40 m^3 ha^{-1}	288.59	92.20	20.44	153.37	19.69	14.18	5.50

Two digestate application and incorporation techniques were used separately in each locality, i.e., one using disc application and the other using a strip-till application unit. Figure 1 shows the application units used. In both cases, they linked to the self-propelled tanker VREDO VT4556 (Vredo, Dodewaard, The Netherlands). The farm where the experiment took place grows rye for silage as a pre-crop for maize. Strip-till application was chosen as a soil conservation technology that is suitable for reducing soil erosion, especially on sloping land. The depth of digestate incorporation of the strip-till unit was set by the coulter behind which the application was carried out and by positioning relative to the crumbling rollers and to the pairs of support wheels. The disc application unit had tools that were spaced at 25 cm. The depth of digestate incorporation was determined by the depth of soil processing by the disc working tools. This depth was adjusted relative to the crumbling roller that moved over the soil surface. The disc application unit incorporated digestate to approximately 12 cm of depth while cultivating the soil surface area evenly. The strip-till unit incorporated digestate to 16 to up to 30 cm of depth, while cultivating only 30 cm wide soil strips, with their centers spaced 75 cm apart. In the year 2021, in Locality A, the width of the variants for the disc applicator was 24 m, with a length of 100 m. For the variants with strip-till employed, the width was 12 m, and the length was 200 m. The application of the digestate took place on 25 May 2021, approximately one week after the harvesting of rye for silage. Four days after the application, maize for silage (MARCAMO, FAO 190, 120,000 plats per hectare) was sown. In the year 2022, in Locality B, the dimensions of the variants for the disc, as well as for the strip applicator, were the same, i.e., a width of 12 m and a length of 200 m. The application of the digestate took place on 23 May 2022, approximately two weeks after the harvest of rye for silage. In the day following the digestate application, maize for silage (MARCAMO, FAO 190, 120,000 plats per hectare) was sown. Each year, the application was carried out by both methods in four variants differing in rates, i.e., 10, 20, 30, and 40 m^3 ha^{-1}. The fifth variant was considered a control, where only the soil was cultivated by the unit, without any fertilizer applied.

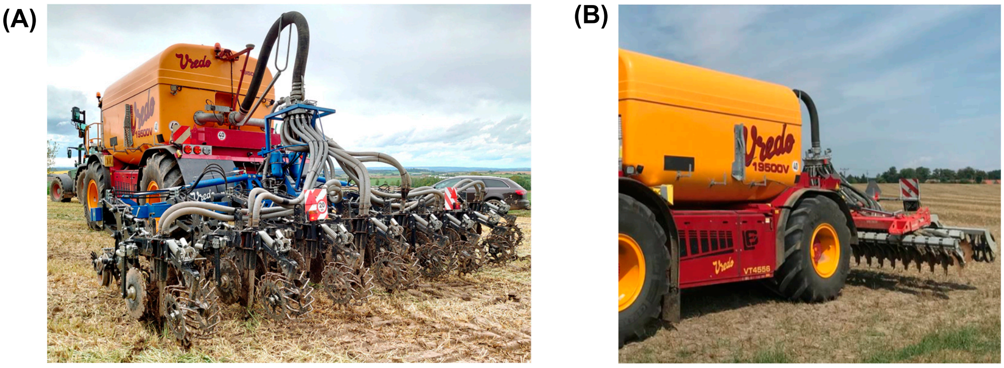

Figure 1. Digestate application units used: (**A**) strip-till application unit, (**B**) disc application unit.

As mentioned in the introduction, the wind tunnel method was used, as it was the most suitable, in particular for measuring the flux of ammonia. Emissions were measured immediately after the application of the digestate, since concentrations are reported to decrease with the time interval from application. The monitored gases were NH_3, CO_2, and CH_4. The INOVA 1412 (INNOVA Air Tech Instruments, Ballerup, Denmark) was used to monitor gases, supplemented by a multiplexer INOVA 1309 (INNOVA Air Tech Instruments, Denmark) to allow for simultaneous measurements on all the variants. Wind tunnels were placed on each variant of the experimental plot to capture the fluxes. Special tubes led from them, which conducted the analyzed air to the gas analyzer. The concentrations in the air entering the wind tunnel and in the air leaving the wind tunnel were measured. The fluxes of the monitored gases were determined from the differences between the measured values at the outlet and the inlet. The wind tunnel dimensions were 50 × 35 cm. Apart from gas analyzer intake tubes, the inlet opening was fitted with an anemometer, an outlet with an adjustable fan providing the required constant airflow rate. The air flow speed through the tunnel inlet opening reached approximately 0.7 m s^{-1}. A thermometer was placed inside to record the temperature during the measurement. The wind tunnels were moved to a different position of the respective variants after one hour, and three repetitions, i.e., three positions of a wind tunnel per variant, were performed in total. At each wind tunnel position, the fluxes of monitored gases were measured repeatedly at least 5 times per hour, thus providing 15 flux measurements per variant as a minimum. All measured data were continuously stored on a PC. Flux, "J", was calculated based on mass per unit area per unit time (µg m^{-2} min^{-1}) using Equation (1) [31]:

$$J = \frac{v \cdot A_t \cdot (C_{out} - C_{in})}{A_s}, \tag{1}$$

where "v" is the average air velocity in the wind tunnel (m min^{-1}), "A_t" is the cross-sectional area of the ventilation openings (m^2), "C_{out}" is the concentration of the monitored gases in the outcoming air (µg m^{-3}), "C_{in}" is the concentration of the monitored gases in the incoming air (µg m^{-3}), and "A_S" is the area of the wind tunnel footprint (m^2). The calculated concentrations were then converted to fluxes released per minute. In the case of the strip-till, the flux values had to be recalculated to account for the fact that the digestate was not applied evenly, but in strips. Dixon's Q test was used for identification and rejection of outliers at a probability level of 0.05.

Satellite data of Sentinel-2 (European Space Agency; ESA) were used for crop status evaluation. The use of Sentinel-2 mission data is well suited to agricultural practice, as it provides free high spatial and temporal resolution data from most regions of the world [32]. Therefore, five cloud-less images were selected with spatial resolutions of 10 m·px^{-1}. Crop status was derived from (a) the Normalized Difference Vegetation Index (NDVI), as one of the most common vegetation indexes that are used for local-scale management purposes as an direct indicator of plant health and growth [33,34] and (b) the Normalized Difference

Water Index (NDWI), which is sensitive to the water content of the plants [35], as is shown in Table 3. The data were processed using Google Earth Engine (Google LLC, San Francisco, CA, USA) qGIS (Open Source Geospatial Foundation), and STATISTICA (TIBCO, Palo Alto, CA, USA). Yields can be predicted by long-term monitoring of crop stands using remote sensing [36].

Table 3. Vegetation indices used for crop stand assessment.

Normalized Difference Vegetation Index	NDVI	$\frac{NIR-RED}{NIR+RED}$	[37]
Normalized Difference Water Index	NDWI	$\frac{NIR-SWIR}{NIR+SWIR}$	[38]

Yield measurements were carried out by randomly selecting ten 1 m^2 plots in each experimental variant where maize plants were hand-harvested and weighed; then, the dry weight of each sample was determined. The maize was harvested on 20th October in Dough stage—BBCH 85. The plant was cut 25 cm above the ground, as it would have been when harvested using a forage harvester. Plant heights were measured from the ground surface to the plant apex in two terms. Statistical analysis of data was performed using Statistica 12 software. Significant differences in fluxes, NDVI, NDWI, maize dry matter (DM) yields, and crude protein (CP) in DM among investigated variants were determined through factorial (factors: locality; digestate rate; application method) analyses of variance (ANOVA) and Tukey's HSD post-hoc tests with a 95% confidence interval. Simple linear regression for gas fluxes, maize dry matter (DM) yields, and crude protein (CP) in DM was performed in order to analyze their dependance on the digestate application rate.

3. Results

Figure 2 shows monthly the precipitation rates and average monthly temperatures in 2021 and 2022, as well as long-term average temperatures and monthly average precipitation rates from 1961 to 1999. With regard to precipitation in the year of 2021, February through April were below average, while May and June were above average, followed by two average precipitation months. The end of the corn growing season was markedly below average. Concerning temperatures, June and July were above average, while the rest of the maize growing season was average in this respect. In terms of precipitation, the 2022 season was below average compared to the long-term normal. Noteworthy precipitation was observed in August, when the rainfall was two times higher. However, that month was preceded by an extremely droughty July. The monthly average temperature in 2022 was 1.2 °C higher than in 2021 and 1.9 °C above the long-term average. The total annual rainfall was 610 mm in 2021 and 681 mm in 2022, while the long-term average is 715 mm.

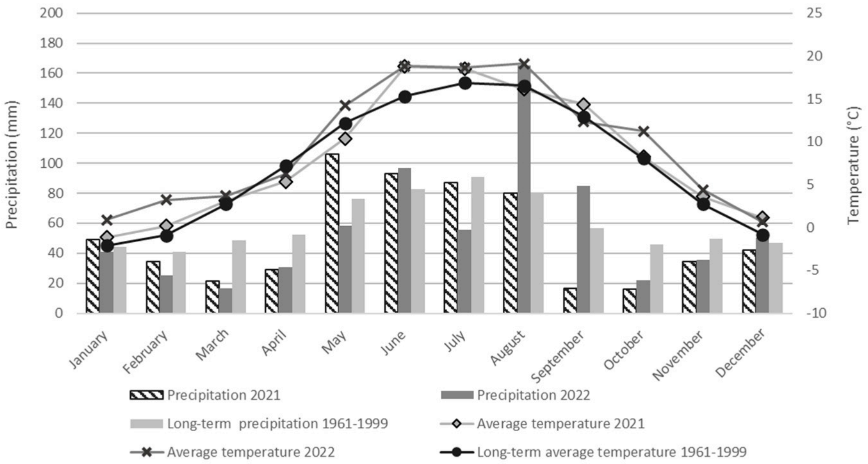

Figure 2. Monthly precipitation and average temperatures on the experimental localities, as well as long-term averages.

3.1. GHG Fluxes

In Figure 3, three monitored fluxes of selected GHGs and ammonia are presented according to the locality, application method, and digestate rate. The factorial (locality; digestate rate; application method) ANOVA was employed to analyze the data. With only locality taken as a factor, the fluxes of all three gases in question, i.e., ammonia, carbon dioxide, and methane, demonstrated significant differences. In Locality A in 2021, the average fluxes of NH_3 (124.05 $\mu g\ m^{-2}\ min^{-1}$), of CO_2 (10,119.64 $\mu g\ m^{-2}\ min^{-1}$), and of CH_4 (390.47 $\mu g\ m^{-2}\ min^{-1}$) attained significantly lower values compared to Locality B in 2022, with respective values of 1265.13 $\mu g\ m^{-2}\ min^{-1}$, 73,800.03 $\mu g\ m^{-2}\ min^{-1}$, and 2601.08 $\mu g\ m^{-2}\ min^{-1}$. These differences, in the case of NH_3 flux amounting to more than ten times, were to a certain extent caused by the above-mentioned significant differences in temperatures. Generally, there is a reported relationship between flux and temperature. Interannual differences in digestate composition, particularly with regard to organic carbon and total nitrogen, might have been another important aspect (see Table 3). Considering solely the factor of application method, all three gas fluxes proved, again, significantly different. With the strip-till application unit used, the average fluxes of NH_3 (469.21 $\mu g\ m^{-2}\ min^{-1}$), of CO_2 (22,113.60 $\mu g\ m^{-2}\ min^{-1}$), and of CH_4 (908.18 $\mu g\ m^{-2}\ min^{-1}$) attained significantly lower values compared to those attained by the disc application unit, with respective values of 618.03 $\mu g\ m^{-2}\ min^{-1}$, 45,070.31 $\mu g\ m^{-2}\ min^{-1}$, and 1500.81 $\mu g\ m^{-2}\ min^{-1}$. These differences, in the case of NH_3 flux amounting to more than 1.3 times to 2 times of CO_2 and in the case of CH_4 to more than 1.6 times, were most likely caused by better digestate incorporation into the soil, particularly by its greater depth. With only the digestate rate taken into consideration, the exact same patterns of significant differences were observed for the means of NH_3 and CH_4 fluxes. The highest digestate rates of 30 and 40 $m^3\ ha^{-1}$ produced significantly higher average fluxes (for NH_3, 894.71 and 1277.79 $\mu g\ m^{-2}\ min^{-1}$, respectively; for CH_4, 3245.29 and 1316.62 $\mu g\ m^{-2}\ min^{-1}$, respectively) than the control and lower digestate rates of 10 and 20 $m^3\ ha^{-1}$ (for NH_3, 161.38, 221.05, and 188.47$\mu g\ m^{-2}\ min^{-1}$, respectively; for CH_4, 309.58, 603.07, and 567.83 $\mu g\ m^{-2}\ min^{-1}$, respectively). For CO_2, the flux of the control variant without digestate application (11,719.84 $\mu g\ m^{-2}\ min^{-1}$) differed significantly from all the variants with digestate applied, i.e., with the rates of 10, 20, 30, and 40 $m^3\ ha^{-1}$ (29,801.96, 39,289.57, 37,743.43, and 49,775.34 $\mu g\ m^{-2}\ min^{-1}$, respectively). The only other significant difference was verified between the lowest rate of 10 $m^3\ ha^{-1}$ and the highest one of 40 $m^3\ ha^{-1}$.

Figure 3A presents ammonia fluxes with regard to the locality, digestate rate, and application method. Significant differences were found among the higher digestate rates of 30 and 40 $m^3\ ha^{-1}$, applied both using a disc and strip-till unit in Locality B in 2022, and all the other variants. Moreover, within the higher rates of the year 2022, the NH_3 flux, measured after a rate of 30 $m^3\ ha^{-1}$ applied using a disc unit, significantly exceeded the one measured after a rate of 40 $m^3\ ha^{-1}$ applied using a strip-till unit; the NH_3 flux measured after a rate of 40 $m^3\ ha^{-1}$, applied again using a disc unit, significantly exceeded those that were measured after rates of 30 and 40 $m^3\ ha^{-1}$ applied using a strip-till unit. Therefore, in Location B in 2022, NH_3 fluxes that were higher on average by up to 80% could be observed when the disc applicator was employed.

Figure 3B demonstrates carbon dioxide fluxes. In 2022, significantly higher fluxes could be observed for all the rates, i.e., 10, 20, 30, and 40 $m^3\ ha^{-1}$, when digestate was applied using the disc unit. With regards to the strip-till unit, significant differences, i.e., higher average values, were verified for rates of 10 and 40 $m^3\ ha^{-1}$ in 2022 compared to the variants with lower digestate rates in the year of 2021, specifically to 0, 10, 20, and 30 $m^3\ ha^{-1}$ treated using the strip-till unit and to 0 and 10 $m^3\ ha^{-1}$ treated using the disc unit. Overall, CO_2 fluxes attained on average 48% higher values in 2021, and 182% higher values in 2022 when the disc applicator was employed compared to the strip-till unit.

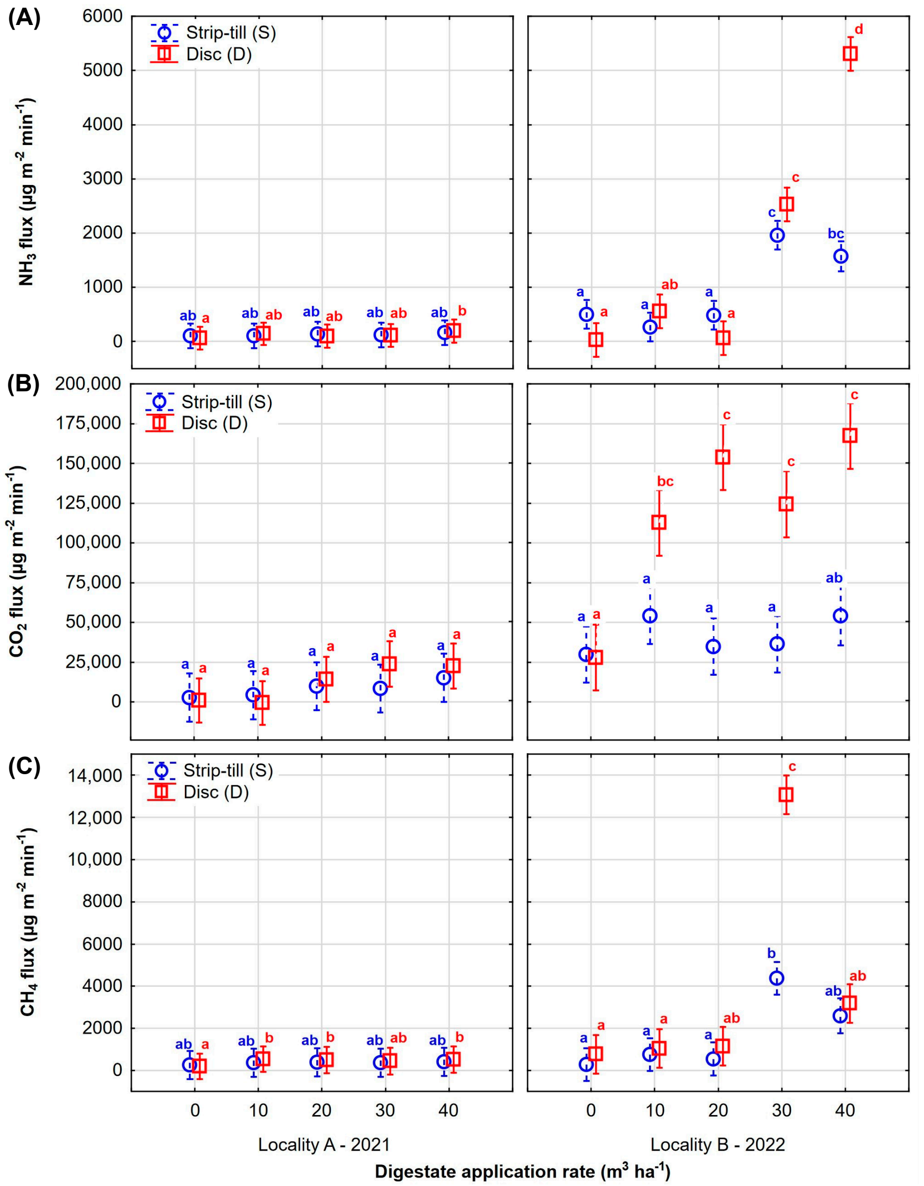

Figure 3. Flux values of measured gases, (**A**) ammonia, (**B**) carbon dioxide, and (**C**) methane, for different methods and rates of digestate application in the experimental localities; vertical bars denote 0.95 confidence intervals; lower case letters denote significant differences within each experimental locality separately.

Figure 3C, which describes methane fluxes, presents relationships that are mostly similar to the ammonia fluxes described above. Significant differences were found among a higher digestate rate of 30 m^3 ha^{-1}, applied using a disc unit in Locality B in 2022 and all the other variants. The other higher digestate rate variants of 2022, i.e., 30 m^3 ha^{-1} applied by a strip-till unit and 40 m^3 ha^{-1} applied both by strip-till and disc units, demonstrated significantly higher methane fluxes than all the variants of Location A in 2021 and than some of the lower-rate variants of Location B in 2022. Overall, CH_4 fluxes attained on average 23% higher values in 2021 and 126% higher values in 2022 when the disc applicator was employed compared to the strip-till unit.

In the case of ammonia and methane, fluxes increased with an increasing digestate rate, although significant differences were found solely among the highest rates of 30 and 40 m^3 ha^{-1} in Locality B in 2022, when a higher temperature and digestate composition favored emissions, compared to the variants from 2021 and also compared to the control 0 and lower rates from 2022. With carbon dioxide, any dose that was applied using the disc unit in 2022 produced a significantly higher flux. The difference between the application methods proved significant for all three fluxes in question. The results suggested lower flux values of the strip-till method compared to the disc one.

Figure 4 presents the simple linear regression for the relationships between the monitored fluxes and the digestate application rates. Since the result of ANOVA of all the three fluxes suggested significant differences regarding the factor of locality, as well as that of application method, the linear regression was completed for both factors separately. In all the cases, the flux values increased with an increasing digestate rate, but in Locality A in 2021, the increase was more gradual for both application methods. In 2022, the flux values of all the monitored gases demonstrated a steeper increase, particularly concerning the disc application method. R-squared surpassed 0.5 solely in the case of ammonia flux after digestate having been applied using a disc unit in 2022 (see Figure 4A).

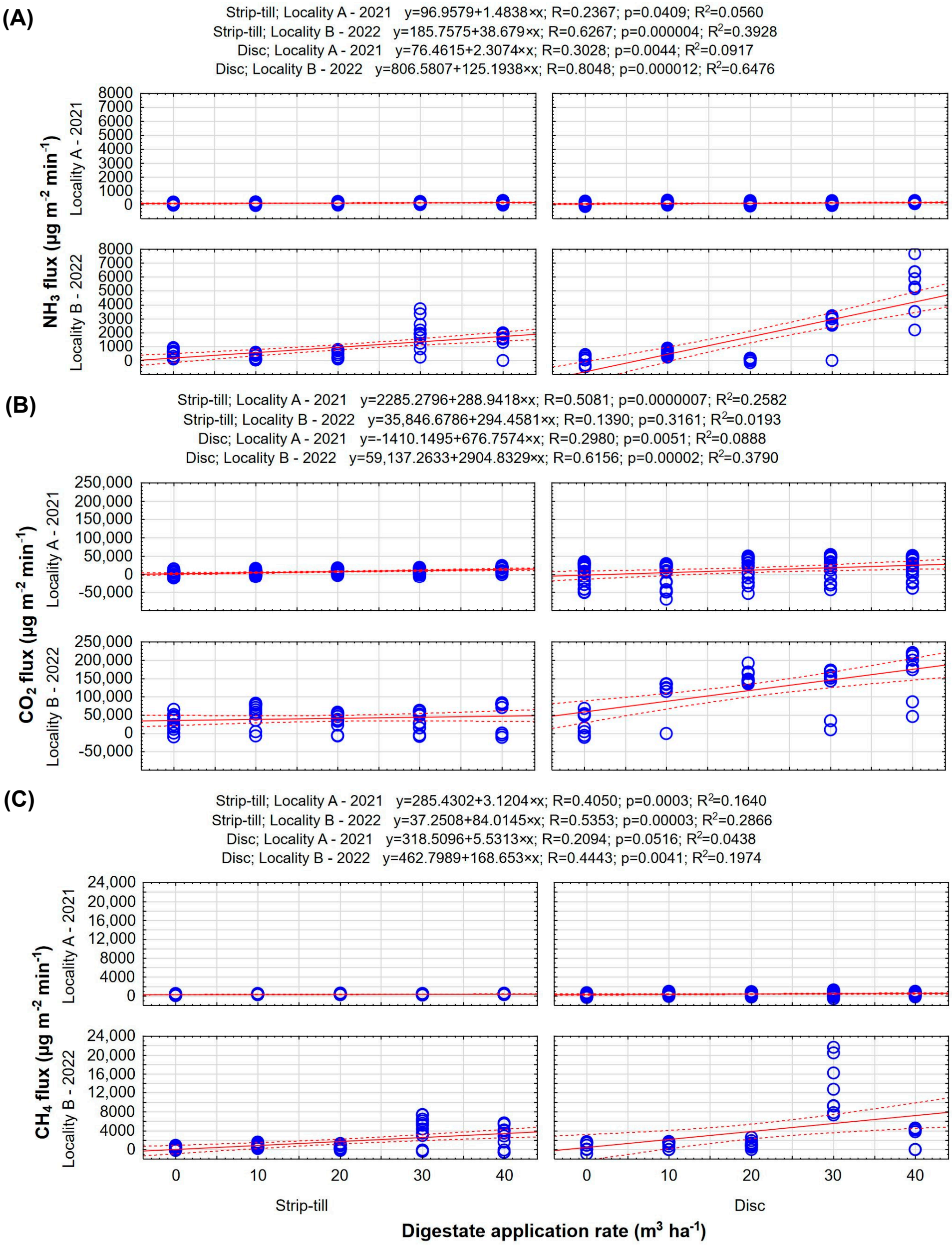

Figure 4. Linear regression analysis of flux values of measured gases on digestate application rates, (**A**) ammonia, (**B**) carbon dioxide, and (**C**) methane, for different methods of digestate application in the experimental localities; dotted regression bands denote confidence at 0.95 level.

3.2. Remote Sensing

Figure 5 provides the vegetation indexes of individual variants (digestate rate and application method) during the years of 2021 and 2022. In the 2021 season, Figure 5A indicates that maize reached the mature stage after 24 July 2021, when NDVI (see Figure 5A) values became considerably higher than on previous dates. The NDWI (see Figure 5B) represents the potential water stress during the monitored period. Differences in vegetation index values among application treatments at the beginning of the tillering phase for the control treatments may indicate plot inhomogeneity. In the early growth phase, the variants with strip-till application of digestate showed higher index values. This difference evened out on 24 July 2021. On the other hand, on the subsequent date, the variants with the fertilizer being applied by disc applicator attained significantly higher vegetation index values. At the end of the season, the index values of all the variants leveled off relative to the previous terms. With the factorial (digestate rate; application method) ANOVA, however, the last term of 5 September 2021 demonstrated significant differences in both factors separate as well as combined. The strip-till method demonstrated a higher NDVI, whereas the disc method demonstrated significantly higher values of the NDWI. The latter was the case for all the digestate rates, i.e., 0, 10, 20, and 30, except for the highest rate of 40. There were no apparent indications of higher indexes with increased digestate rates. This may be due to the nutrient stock in the soil after the pre-crop. In the 2022 season, although no statistically significant differences in the NDVI were observed between strip-till and disc (see Figure 5A), statistically significant differences were noted between a rate of 0 and all other rates. Despite maize being sown on 24 May 2022, the first cloud-free image from the Sentinel-2 satellite was acquired on 17 July 2022. The crop growth appeared to be relatively inconsistent during this period. On the subsequent two dates, 8 and 16 August 2022, vegetation was nearly consistent, except for variant 0S. The most recent available satellite image before harvest indicated a decrease in the NDVI index. Regarding the NDWI index in 2022 (see Figure 5B), no statistically significant differences were observed among application units or rates. High NDWI index values indicate sufficient water availability for plants, especially in August when the extreme rainfall occurred.

Overall, there was no evidence of a statistically significant difference between application methods on vegetation indices (NDVI and NDWI) over the study period. However, statistically significant differences were observed for the NDVI between doses of 0 and 10; 10 and 20; 10 and 40; and 30 and 40. For the NDWI, a statistically significant difference was observed between a dose of 40, demonstrating the lowest value, and all the other doses.

3.3. Maize Yield

Figure 6A presents the results for silage maize yields during the monitored periods. Generally, higher yields were observed when the disc applicator was used. Although there were no statistically significant differences between the application methods within each season, the overall difference for both years was statistically significant. Yields increased with the digestate rate in both years. However, a statistically significant difference was observed only between the 0 and 20–40 m^3 ha^{-1}, as well as between the 10 and 30–40 m^3 ha^{-1}.

In terms of crude protein (see Figure 6B), no statistically significant differences could be observed apart from differences with respect to localities, i.e., to years.

Figure 7 presents the simple linear regression for the relationships between the yields, the crude protein contents, and the digestate application rates. Since the result of the ANOVA of silage maize yields suggested significant differences regarding the factor of locality, as well as that of application method, the linear regression was completed for both factors separately. Concerning yields, their values increased with increasing digestate rate, although R-squared varied only from 0.2252 (for strip-till in 2022) to up to 0.5854 (for strip-till in 2021). The crude protein content only changed gradually, and in Locality B in 2022, it even slightly decreased with higher digestate rates. R-squared did not exceed 0.0740.

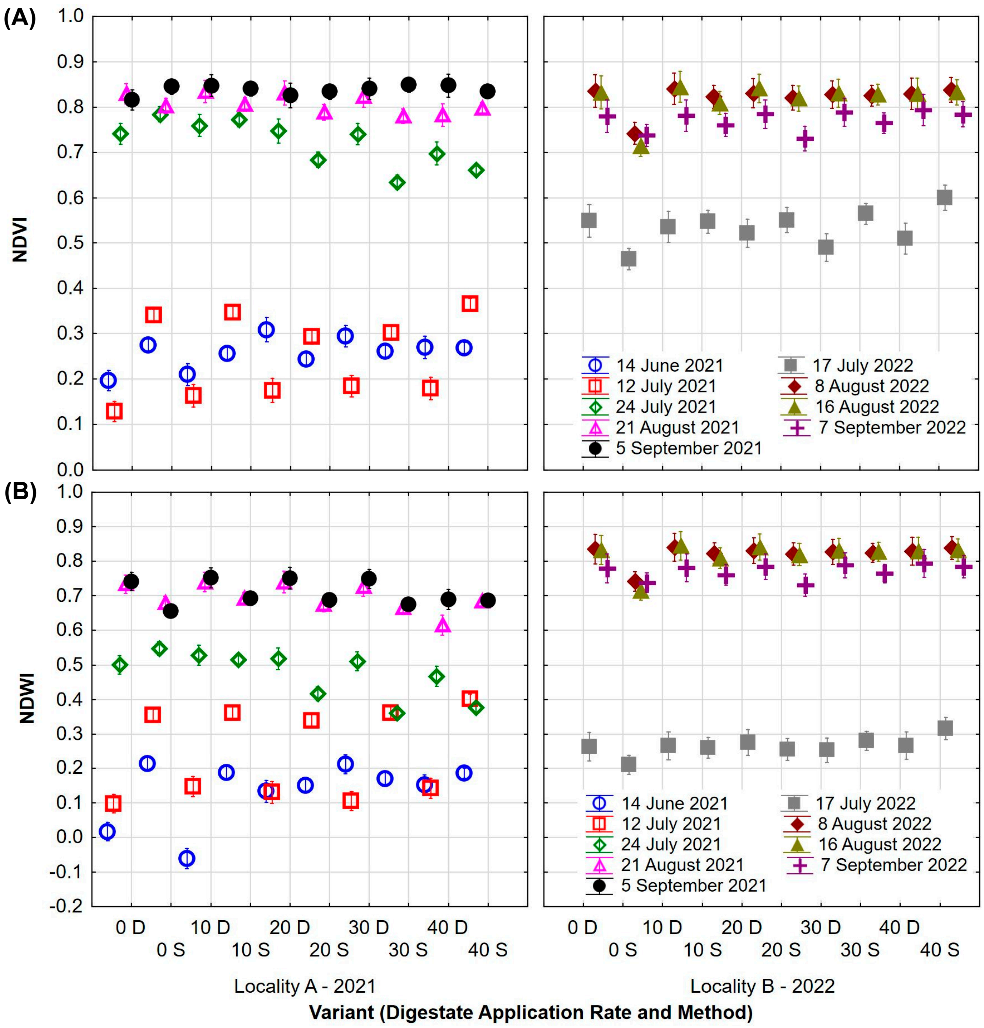

Figure 5. Indexes of individual variants (digestate rate and application method) in the experimental localities at given dates: (**A**) NDVI, (**B**) NDWI; vertical bars denote 0.95 confidence intervals.

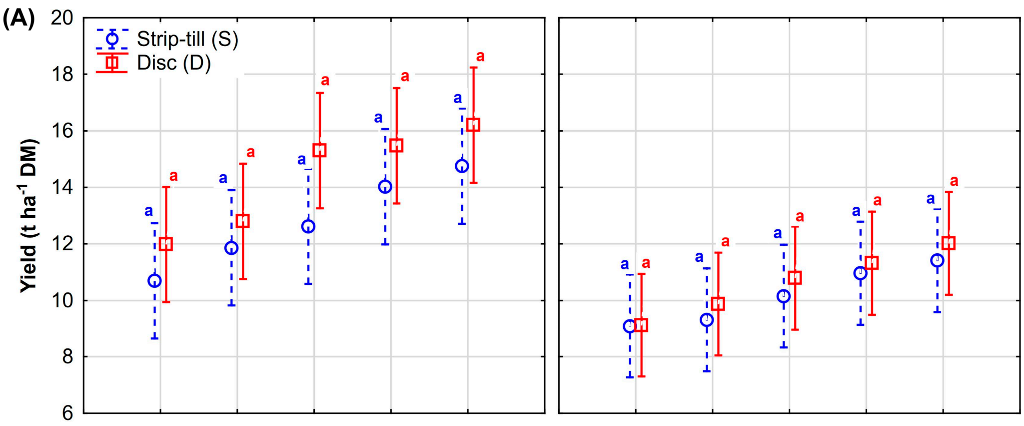

Figure 6. *Cont.*

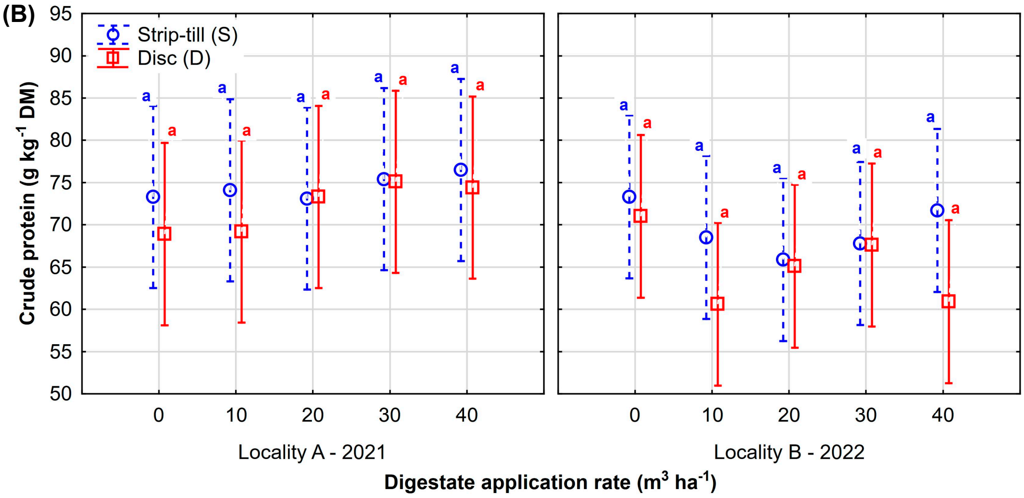

Figure 6. Yields of silage maize in dry matter (**A**) and crude protein (CP) in dry matter (**B**) for individual variants (digestate doses and type of application) in the experimental localities; vertical bars denote 0.95 confidence intervals; lower case letters denote significant differences within each experimental locality separately.

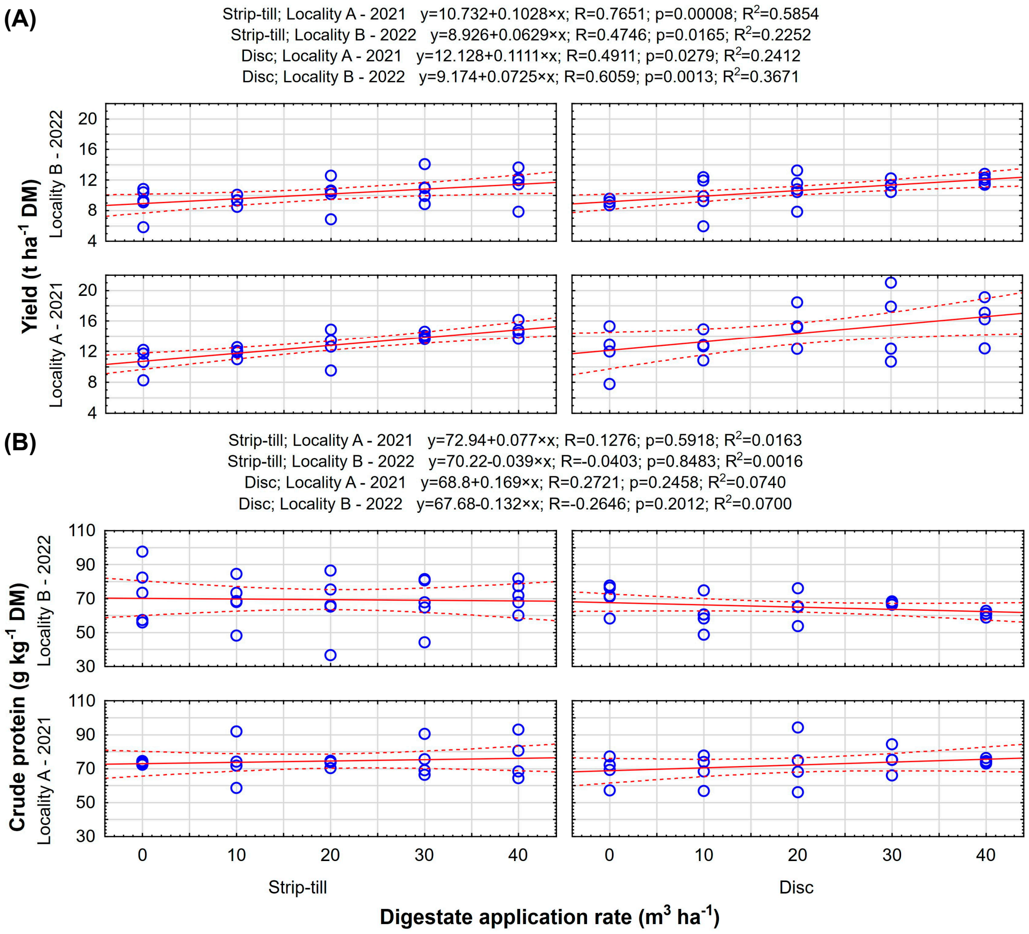

Figure 7. Linear regression analysis of yields of silage maize in dry matter (**A**) and crude protein (CP) in dry matter (**B**) on digestate application rates for different methods of digestate application in the experimental localities; dotted regression bands denote confidence at 0.95 level.

4. Discussion

While static or dynamic chambers are commonly used for long-term field gas measurements, a wind tunnel method was exploited in this experiment. One potential disadvantage of this approach was the requirement for an electrical power supply [39]. Ammonia fluxes are the most temperature-dependent of the gases [40]. Thus, when compared with other studies where digestate was applied to soil, the measured NH_3 concentrations were lower than [41] and also lower than [31], who measured fluxes in a laboratory experiment. This difference may be caused partly by the different temperature at which the experiment was conducted. Specifically, in Locality A in 2021 during the digestate application and flux measurements, the weather was partly cloudy, and the air temperature reached 10.72 °C ± 0.77 °C (mean ± st. dev.), with a relative humidity of 79.83% ± 12.01%. In 2022 in Locality B, the weather during the application and measurements was sunny, and the air temperature reached 22.38 °C ± 2.53 °C, with a relative humidity of 55.02% ± 15.16%. The second year of the experiment, the temperature was significantly higher and the humidity significantly lower compared to the year of 2021 at a probability level of 0.05. Furthermore, the slightly different chemical composition of the digestate may have affected the results [42]. In addition, the results may be partly influenced by the measurement method.

When comparing the average carbon dioxide fluxes at the digestate rate of 30 $m^3\ ha^{-1}$, Czubaszek and Wysocka-Czubaszek [43] measured approximately two and a half times higher methane flux and more than six times higher carbon dioxide flux values than in our experiment. This substantial difference is due to the fact that they used a broadcast application without incorporation into the soil. On the contrary, Rosace et al. [44] measured, in their experiment, approximately more than six times lower carbon dioxide fluxes in a comparable measurement period straight after the digestate application. This difference in values may have been caused by a different measurement method (laboratory analysis) and by the different physical properties of soils, especially their texture, which influences the rate of escape of emissions into the atmosphere [45,46].

There was also no apparent trend for fluxes to increase with the dose in 2021 as opposed to the year of 2022. The lower temperature may have been one of the causes, since overall lower releases from the soil to the air occurred [47]. When compared with Czubaszek and Wysocka-Czubaszek [43] and their 30 $m^3\ ha^{-1}$ rate, approximately 5.5 times higher average carbon dioxide fluxes were measured in our study at the same digestate application rate. Their digestate application method on the soil surface was the key reason for the considerable flux increase. This was also confirmed by Pezzolla et al. [48], who applied a rate of 10 $m^3\ ha^{-1}$ on the soil surface and measured approximately 40% higher fluxes compared to our experiment's respective values.

Since optimal field management and application techniques may lead to reduced emissions, both investigated methods of digestate application are more appropriate in terms of gas emissions than the surface application when digestate is incorporated into the soil only after several days, as was reported by Birkmose [49].

Although remote sensing is a valuable tool for vegetation assessment, no significant overall differences in vegetation indices were observed based on the application methods. Nevertheless, statistically significant differences were observed in vegetation indices based on application methods in 2021, but these were not confirmed in 2022. These results are partially in line with the findings of another study, suggesting that maize is capable of nitrogen uptake regardless of the application method [50]. While Shaver et al. [51] reported a high correlation between the leaf nitrogen content of maize and the NDVI index, our results confirm significant differences in plant conditions with increasing digestate application rates—between rates of 0 and 10, 10 and 20, 10 and 40, 30 and 40. Water and nitrogen deficiencies can increase plant growth stress and reduce yield [52]. The NDWI was used as an indicator of water stress, since it reflects the water content of the plant [53]. However, in our study, the effect of the digestate dosage on the NDWI, was not observed except for the dose of 40. The spatial resolution of 10 $m \cdot px^{-1}$ is useful for the fundamental establishment of vegetation status for precision farming methods, especially for large plots [54]. The ambiguous results of this study could be explained by the insufficient satellite resolution regarding the size of the experimental plots, where UAVs or other more accurate methods, i.e., hand-held optical sensors, would have been more appropriate [55,56].

The yield results indicate that higher values are achieved with an increasing digestate rate, which was confirmed by the results of the study by Przygocka-Cyna and Grzebisz [50]. Results from other authors have shown that digestate provides satisfactory agronomic performances that are comparable to mineral fertilizers in maize cultivation [57,58]. Concerning the rational use of the landscape in maize production, apart from conventional tillage (including autumn ploughing), minimal- or no-tillage systems have been used in research and agricultural practice in recent years. Thus, using minimum- or no-till is mainly for the sake of soil conservation and fuel savings, while these systems may not lead to any statistically significant differences in yields [59]. Although the overall difference in yield was statistically significant between the different application methods, individual years did not indicate this difference. If this difference was not demonstrated in the long-term experiments, the authors of this study would suggest using strip-till methods in agricultural practice. The strip-till technology in maize cultivation was also recommended by Battisti et al.; additionally, the authors also recommend the application of digestate as a starter fertilizer [60]. Moreover, this method is environmentally friendlier in terms of carbon storage than a tillage of the entire surface [61]. However, strip-till needs to be complemented by other sustainable practices such as rational crop rotation [62]. The digestate dose and application method did not have any statistically significant effect on the crude protein. Nevertheless, Silva et al. found that it was advisable to apply nitrogen fertilization at later stages of maize growth to increase crude protein [63]. Nevertheless, this difference could be due to different maize growth periods.

In addition, the authors recommend that further research should be carried out, ideally on the same plot over several years to provide more accurate results.

5. Conclusions

This field experiment was carried out to investigate the differences in selected GHG and ammonia emissions based on the rate and method of digestate application. For all gases studied, i.e., ammonia, carbon dioxide, and methane, there were statistically significant differences in terms of locality, year, the digestate application method, and, to some extent, the rate with which digestate was applied. In Locality B in 2022, with significantly higher temperatures, fluxes proved to be higher as well. The disc application method demonstrated significantly higher fluxes compared to the strip-till method. The highest digestate rates of 30 and 40 m^3 ha^{-1} produced significantly higher average NH_3 and CH_4 fluxes than the control and lower digestate rates of 10 and 20 m^3 ha^{-1}. For CO_2, the flux of the control variant without digestate application differed significantly from all the variants with digestate applied to them. Generally, the maize yield grew when the digestate rate increased. However, the crop status, evaluated by remote sensing methods, did not consistently demonstrate a positive crop reaction to rising rates, especially at 40 m^3 ha^{-1}.

Based on the results of this study, the authors suggest the application of digestate based on strip-till technology at rates of around 20 m^3 ha^{-1} for agricultural practice. At this rate, ammonia and methane fluxes did not increase significantly, whereas the average maize yield did not differ from those reached at higher digestate rates.

Author Contributions: Conceptualization, J.K. and P.Š.; methodology, P.Š.; data analysis, P.Š. and V.N.; field measurements, J.K., P.Š., V.N., P.B. and A.D.; writing—original draft preparation, J.K., M.D., P.Š. and V.N.; supervision, J.K. All authors have read and agreed to the published version of the manuscript.

Funding: Supported by the project TAČR TH04030132 of the Technology Agency of the Czech Republic, by the project of long-time development of the Research Institute of Agricultural Engineering, p.r.i. no. RO0623, and by the Czech University of Life Sciences, Faculty of Engineering, in the frame of the internal project IGA 2022: 31180/1312/3106.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors would like to express their gratitude to the Technology Agency and the Czech University of Life Sciences, Faculty of Engineering, for providing financial grant support. The main author would also like to thank all colleagues that took part in the research for their support and cooperation.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Arora, N.K. Impact of Climate Change on Agriculture Production and Its Sustainable Solutions. *Environ. Sustain.* **2019**, *2*, 95–96. [CrossRef]
2. Jacob, D.; Kotova, L.; Teichmann, C.; Sobolowski, S.P.; Vautard, R.; Donnelly, C.; Koutroulis, A.G.; Grillakis, M.G.; Tsanis, I.K.; Damm, A.; et al. Climate Impacts in Europe Under +1.5 °C Global Warming. *Earth's Future* **2018**, *6*, 264–285. [CrossRef]
3. European Commission Directive. European Commission Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 Amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as Regards the Promotion of Energy from Renewable Sources, and Repealing Council. *Off. J. Eur. Union* **2023**, *2413*, 1–77.
4. Martinát, S.; Dvořák, P.; Frantál, B.; Klusáček, P.; Kunc, J.; Kulla, M.; Mintálová, T.; Navrátil, J.; Horst, D. Van Der Spatial Consequences of Biogas Production and Agricultural Changes in the Czech Republic after EU Accession: Mutual Symbiosis, Coexistence or Parasitism? *AUPO Geogr.* **2013**, *44*, 75–92.
5. European Commission. *A Sustainable Bioeconomy for Europe: Strengthening the Connection between Economy, Society and the Environment*; European Commission: Brussels, Belgium, 2018; ISBN 9789279941450.
6. Chen, Y.; Cheng, J.J.; Creamer, K.S. Inhibition of Anaerobic Digestion Process: A Review. *Bioresour. Technol.* **2008**, *99*, 4044–4064. [CrossRef] [PubMed]
7. Makdi, M.; Tomcsik, A.; Orosz, V. Digestate: A New Nutrient Source—Review. In *Biogas*; Kumar, S., Ed.; InTech: Rijeka, Croatia, 2012; p. 14.
8. Herrmann, A. Biogas Production from Maize: Current State, Challenges and Prospects. 2. Agronomic and Environmental Aspects. *BioEnergy Res.* **2013**, *6*, 372–387. [CrossRef]
9. Al Seadi, T.; Drosg, B.; Fuchs, W.; Rutz, D.; Janssen, R. Biogas digestate quality and utilization. In *The Biogas Handbook*; Wellinger, A., Murphy, J., Baxter, D.B.T.-T.B.H., Eds.; Elsevier: Amsterdam, The Netherlands, 2013; pp. 267–301, ISBN 978-0-85709-498-8.
10. Chojnacka, K.; Moustakas, K. Anaerobic Digestate Management for Carbon Neutrality and Fertilizer Use: A Review of Current Practices and Future Opportunities. *Biomass Bioenergy* **2024**, *180*, 106991. [CrossRef]
11. Lukehurst, C.T.; Frost, P.; Al Seadi, T. *Utilisation of Digestate from Biogas Plants as Biofertiliser*; International Energy Agency (IEA): Paris, France, 2010.
12. Maucieri, C.; Nicoletto, C.; Caruso, C.; Sambo, P.; Borin, M. Effects of Digestate Solid Fraction Fertilisation on Yield and Soil Carbon Dioxide Emission in a Horticulture Succession. *Ital. J. Agron.* **2017**, *12*, 116–123. [CrossRef]
13. Clemens, J.; Trimborn, M.; Weiland, P.; Amon, B. Mitigation of Greenhouse Gas Emissions by Anaerobic Digestion of Cattle Slurry. *Agric. Ecosyst. Environ.* **2006**, *112*, 171–177. [CrossRef]
14. Doyeni, M.O.; Stulpinaite, U.; Baksinskaite, A.; Suproniene, S.; Tilvikiene, V. The Effectiveness of Digestate Use for Fertilization in an Agricultural Cropping System. *Plants* **2021**, *10*, 13. [CrossRef]
15. Monlau, F.; Francavilla, M.; Sambusiti, C.; Antoniou, N.; Solhy, A.; Libutti, A.; Zabaniotou, A.; Barakat, A.; Monteleone, M. Toward a Functional Integration of Anaerobic Digestion and Pyrolysis for a Sustainable Resource Management. Comparison between Solid-Digestate and Its Derived Pyrochar as Soil Amendment. *Appl. Energy* **2016**, *169*, 652–662. [CrossRef]
16. Smith, K.A.; Jackson, D.R.; Misselbrook, T.H.; Pain, B.F.; Johnson, R.A. PA—Precision Agriculture. *J. Agric. Eng. Res.* **2000**, *77*, 277–287. [CrossRef]
17. Misselbrook, T.H.; Smith, K.A.; Johnson, R.A.; Pain, B.F. SE—Structures and Environment. *Biosyst. Eng.* **2002**, *81*, 313–321. [CrossRef]
18. Webb, J.; Pain, B.; Bittman, S.; Morgan, J. The Impacts of Manure Application Methods on Emissions of Ammonia, Nitrous Oxide and on Crop Response—A Review. *Agric. Ecosyst. Environ.* **2010**, *137*, 39–46. [CrossRef]
19. Koszel, M.; Parafiniuk, S.; Szparaga, A.; Bochniak, A.; Kocira, S.; Atanasov, A.Z.; Kovalyshyn, S. Impact of Digestate Application as a Fertilizer on the Yield and Quality of Winter Rape Seed. *Agronomy* **2020**, *10*, 878. [CrossRef]
20. Kolackova, I.; Smolkova, B.; Latal, O.; Skalickova, S.; Skladanka, J.; Horky, P.; Knot, P.; Hammerschmiedt, T.; Kintl, A.; Holatko, J.; et al. Does Digestate Dose Affect Fodder Security and Nutritive Value? *Agriculture* **2022**, *12*, 133. [CrossRef]

21. Houlton, B.Z.; Almaraz, M.; Aneja, V.; Austin, A.T.; Bai, E.; Cassman, K.G.; Compton, J.E.; Davidson, E.A.; Erisman, J.W.; Galloway, J.N.; et al. A World of Cobenefits: Solving the Global Nitrogen Challenge. *Earth's Future* **2019**, *7*, 865–872. [CrossRef]
22. Mohammed, S.; Gill, A.R.; Alsafadi, K.; Hijazi, O.; Yadav, K.K.; Hasan, M.A.; Khan, A.H.; Islam, S.; Cabral-Pinto, M.M.S.; Harsanyi, E. An Overview of Greenhouse Gases Emissions in Hungary. *J. Clean. Prod.* **2021**, *314*, 127865. [CrossRef]
23. Lamolinara, B.; Pérez-Martínez, A.; Guardado-Yordi, E.; Guillén Fiallos, C.; Diéguez-Santana, K.; Ruiz-Mercado, G.J. Anaerobic Digestate Management, Environmental Impacts, and Techno-Economic Challenges. *Waste Manag.* **2022**, *140*, 14–30. [CrossRef]
24. Šimek, M. *Greenhouse Gases from Soil and Agriculture: Properties, Production, Consumption, Emissions and Mitigation Options*; Academia: San Francisco, CA, USA, 2019.
25. Oertel, C.; Matschullat, J.; Zurba, K.; Zimmermann, F.; Erasmi, S. Greenhouse Gas Emissions from Soils—A Review. *Geochemistry* **2016**, *76*, 327–352. [CrossRef]
26. Forrestal, P.J.; Harty, M.; Carolan, R.; Lanigan, G.J.; Watson, C.J.; Laughlin, R.J.; McNeill, G.; Chambers, B.J.; Richards, K.G. Ammonia Emissions from Urea, Stabilized Urea and Calcium Ammonium Nitrate: Insights into Loss Abatement in Temperate Grassland. *Soil Use Manag.* **2016**, *32*, 92–100. [CrossRef]
27. Dietrich, M.; Fongen, M.; Foereid, B. Greenhouse Gas Emissions from Digestate in Soil. *Int. J. Recycl. Org. Waste Agric.* **2020**, *9*, 1–19. [CrossRef]
28. Askri, A.; Laville, P.; Trémier, A.; Houot, S. Influence of Origin and Post-Treatment on Greenhouse Gas Emissions After Anaerobic Digestate Application to Soil. *Waste Biomass Valorization* **2016**, *7*, 293–306. [CrossRef]
29. Schwager, E.A.; VanderZaag, A.C.; Wagner-Riddle, C.; Crolla, A.; Kinsley, C.; Gregorich, E. Field Nitrogen Losses Induced by Application Timing of Digestate from Dairy Manure Biogas Production. *J. Environ. Qual.* **2016**, *45*, 1829–1837. [CrossRef] [PubMed]
30. United States Department of Agriculture Natural Resources Conservation Service. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*; United States Department of Agriculture Natural Resources Conservation Service: Washington, DC, USA, 1999.
31. Parker, D.B.; Gilley, J.; Woodbury, B.; Kim, K.-H.; Galvin, G.; Bartelt-Hunt, S.L.; Li, X.; Snow, D.D. Odorous VOC Emission Following Land Application of Swine Manure Slurry. *Atmos. Environ.* **2013**, *66*, 91–100. [CrossRef]
32. Darra, N.; Espejo-Garcia, B.; Kasimati, A.; Kriezi, O.; Psomiadis, E.; Fountas, S. Can Satellites Predict Yield? Ensemble Machine Learning and Statistical Analysis of Sentinel-2 Imagery for Processing Tomato Yield Prediction. *Sensors* **2023**, *23*, 2586. [CrossRef]
33. Huang, S.; Tang, L.; Hupy, J.P.; Wang, Y.; Shao, G. A Commentary Review on the Use of Normalized Difference Vegetation Index (NDVI) in the Era of Popular Remote Sensing. *J. For. Res.* **2021**, *32*, 1–6. [CrossRef]
34. McVeagh, P.; Yule, I.; Grafton, M. Pasture Yield Mapping from Your Groundspread Truck. In Proceedings of the 25th Annual FLRC Workshop Advanced Nutrient Management: Gains from the Past—Goals for the Future, Palmerston North, New Zealand, 7–9 February 2012; pp. 1–5.
35. Li, J.; Wang, R.; Zhang, M.; Wang, X.; Yan, Y.; Sun, X.; Xu, D. A Method for Estimating Alfalfa (Medicago Sativa L.) Forage Yield Based on Remote Sensing Data. *Agronomy* **2023**, *13*, 2597. [CrossRef]
36. Tunca, E.; Köksal, E.S.; Çetin, S.; Ekiz, N.M.; Balde, H. Yield and Leaf Area Index Estimations for Sunflower Plants Using Unmanned Aerial Vehicle Images. *Environ. Monit. Assess.* **2018**, *190*, 682. [CrossRef]
37. Rouse, R.W.H.; Haas, J.A.W.; Deering, D.W. Monitoring Vegetation Systems in the Great Plains with ERTS. In Proceedings of the Third Earth Resources Technology Satellite-1 Symposium; NASA SP-351, Washington, DC, USA, 10–14 December 1974; Volume I, pp. 309–317.
38. JRC European Commission. NDWI (Normalized Difference Water Index). *Prod. Fact Sheet* **2011**, *5*, 6–7.
39. Sommer, S.G.; Misselbrook, T.H. A Review of Ammonia Emission Measured Using Wind Tunnels Compared with Micrometeorological Techniques. *Soil Use Manag.* **2016**, *32*, 101–108. [CrossRef]
40. Misselbrook, T.H.; Van Der Weerden, T.J.; Pain, B.F.; Jarvis, S.C.; Chambers, B.J.; Smith, K.A.; Phillips, V.R.; Demmers, T.G.M. Ammonia Emission Factors for UK Agriculture. *Atmos. Environ.* **2000**, *34*, 871–880. [CrossRef]
41. Wolf, U.; Fuß, R.; Höppner, F.; Flessa, H. Contribution of N_2O and NH_3 to Total Greenhouse Gas Emission from Fertilization: Results from a Sandy Soil Fertilized with Nitrate and Biogas Digestate with and without Nitrification Inhibitor. *Nutr. Cycl. Agroecosystems* **2014**, *100*, 121–134. [CrossRef]
42. Rivera, F.; Muñoz, R.; Prádanos, P.; Hernández, A.; Palacio, L. A Systematic Study of Ammonia Recovery from Anaerobic Digestate Using Membrane-Based Separation. *Membranes* **2021**, *12*, 19. [CrossRef] [PubMed]
43. Czubaszek, R.; Wysocka-Czubaszek, A. Emissions of Carbon Dioxide and Methane from Fields Fertilized with Digestate from an Agricultural Biogas Plant. *Int. Agrophysics* **2018**, *32*, 29–37. [CrossRef]
44. Rosace, M.C.; Veronesi, F.; Briggs, S.; Cardenas, L.M.; Jeffery, S. Legacy Effects Override Soil Properties for CO 2 and N 2 O but Not CH 4 Emissions Following Digestate Application to Soil. *GCB Bioenergy* **2020**, *12*, 445–457. [CrossRef]
45. Yang, X.; Fan, J.; Jones, S.B. Effect of Soil Texture on Estimates of Soil-Column Carbon Dioxide Flux Comparing Chamber and Gradient Methods. *Vadose Zone J.* **2018**, *17*, 1–9. [CrossRef]
46. Movahedi, A.; Dzinyela, R.; Aghaei-Dargiri, S.; Alhassan, A.R.; Yang, L.; Xu, C. Advanced Study of Drought-Responsive Protein Pathways in Plants. *Agronomy* **2023**, *13*, 849. [CrossRef]
47. Rong, L.; Nielsen, P.V.; Zhang, G. Effects of Airflow and Liquid Temperature on Ammonia Mass Transfer above an Emission Surface: Experimental Study on Emission Rate. *Bioresour. Technol.* **2009**, *100*, 4654–4661. [CrossRef]

48. Pezzolla, D.; Bol, R.; Gigliotti, G.; Sawamoto, T.; López, A.L.; Cardenas, L.; Chadwick, D. Greenhouse Gas (GHG) Emissions from Soils Amended with Digestate Derived from Anaerobic Treatment of Food Waste. *Rapid Commun. Mass Spectrom.* **2012**, *26*, 2422–2430. [CrossRef]
49. Birkmose, T.S. *Nitrogen Recovery from Organic Manures: Improved Slurry Application Techniques and Treatment—the Danish Scenario*; International Fertiliser Society: Cambridge, UK, 2009.
50. Przygocka-Cyna, K.; Grzebisz, W. The Multifactorial Effect of Digestate on the Availability of Soil Elements and Grain Yield and Its Mineral Profile—The Case of Maize. *Agronomy* **2020**, *10*, 275. [CrossRef]
51. Shaver, T.M.; Khosla, R.; Westfall, D.G. Evaluation of Two Crop Canopy Sensors for Nitrogen Variability Determination in Irrigated Maize. *Precis. Agric.* **2011**, *12*, 892–904. [CrossRef]
52. Gheysari, M.; Mirlatifi, S.M.; Bannayan, M.; Homaee, M.; Hoogenboom, G. Interaction of Water and Nitrogen on Maize Grown for Silage. *Agric. Water Manag.* **2009**, *96*, 809–821. [CrossRef]
53. Zhou, H.; Zhou, G.; Song, X.; He, Q. Dynamic Characteristics of Canopy and Vegetation Water Content during an Entire Maize Growing Season in Relation to Spectral-Based Indices. *Remote Sens.* **2022**, *14*, 584. [CrossRef]
54. D'Urso, G. Current Status and Perspectives for the Estimation of Crop Water Requirements from Earth Observation. *Ital. J. Agron.* **2010**, *5*, 107–120. [CrossRef]
55. Inoue, Y. Satellite- and Drone-Based Remote Sensing of Crops and Soils for Smart Farming—A Review. *Soil Sci. Plant Nutr.* **2020**, *66*, 798–810. [CrossRef]
56. Karaca, C.; Thompson, R.B.; Peña-Fleitas, M.T.; Gallardo, M.; Padilla, F.M. Evaluation of Absolute Measurements and Normalized Indices of Proximal Optical Sensors as Estimators of Yield in Muskmelon and Sweet Pepper. *Remote Sens.* **2023**, *15*, 2174. [CrossRef]
57. Piccoli, I.; Grillo, F.; Longo, M.; Furlanetto, I.; Ragazzi, F.; Obber, S.; Bonato, T.; Meneghetti, F.; Ferlito, J.; Saccardo, L.; et al. A Farm-Scale Sustainability Assessment of the Anaerobic Digestate Application Methods. *Eur. J. Agron.* **2023**, *146*, 126811. [CrossRef]
58. Sigurnjak, I.; Vaneeckhaute, C.; Michels, E.; Ryckaert, B.; Ghekiere, G.; Tack, F.M.G.; Meers, E. Fertilizer Performance of Liquid Fraction of Digestate as Synthetic Nitrogen Substitute in Silage Maize Cultivation for Three Consecutive Years. *Sci. Total Environ.* **2017**, *599*, 1885–1894. [CrossRef]
59. Chețan, F.; Rusu, T.; Chețan, C.; Simon, A.; Vălean, A.-M.; Ceclan, A.O.; Bărdaș, M.; Tărău, A. Application of Unconventional Tillage Systems to Maize Cultivation and Measures for Rational Use of Agricultural Lands. *Land* **2023**, *12*, 2046. [CrossRef]
60. Battisti, M.; Zavattaro, L.; Capo, L.; Blandino, M. Maize Response to Localized Mineral or Organic NP Starter Fertilization under Different Soil Tillage Methods. *Eur. J. Agron.* **2022**, *138*, 126534. [CrossRef]
61. Palm, C.; Blanco-Canqui, H.; DeClerck, F.; Gatere, L.; Grace, P. Conservation Agriculture and Ecosystem Services: An Overview. *Agric. Ecosyst. Environ.* **2014**, *187*, 87–105. [CrossRef]
62. Colombi, T.; Keller, T. Developing Strategies to Recover Crop Productivity after Soil Compaction—A Plant Eco-Physiological Perspective. *Soil Tillage Res.* **2019**, *191*, 156–161. [CrossRef]
63. Silva, P.R.F.d.; Strieder, M.L.; Coser, R.P.d.S.; Rambo, L.; Sangoi, L.; Argenta, G.; Forsthofer, E.L.; Silva, A.A.d. Grain Yield and Kernel Crude Protein Content Increases of Maize Hybrids with Late Nitrogen Side-Dressing. *Sci. Agric.* **2005**, *62*, 487–492. [CrossRef]