agronomy

Article

The Economic and Environmental Aspects of *Miscanthus × giganteus* Phytomanagement Applied to Non-Agricultural Land

Aigerim Mamirova [1,2,*] and Valentina Pidlisnyuk [1]

[1] Department of Environmental Chemistry and Technology, Faculty of Environment, Jan Evangelista Purkyně University, Pasteurova 15, 400 96 Usti nad Labem, Czech Republic; valentyna.pidlisniuk@ujep.cz

[2] Department of Biotechnology, Faculty of Biology and Biotechnology, Al-Farabi Kazakh National University, Al-Farabi 71, Almaty 050040, Kazakhstan

* Correspondence: aigerim.mamirova@mail.com; Tel.: +7-702-348-80-09

Abstract: *Miscanthus × giganteus* (*M × g*) is a promising energy crop in phytotechnology with biomass production. Despite considerable vegetation and harvest under varying climate conditions and across different soils, field-scale studies on utilising *M × g* remain scarce. Analysing the literature and our own findings, this study intends to highlight the potential of *M × g* phytotechnology for revitalising non-agricultural lands (NAL), including brownfields, and illustrate the expediency of applying biochar to enhance biomass yield, energy efficiency, and economic feasibility. To validate the feasibility of *M × g* production on brownfields, two scenarios within the value chain "biomass–biogas–electricity" for green harvest were examined. The assumptions were as follows: (1) a methane yield of 5134 m^3 ha^{-1} y^{-1}, and (2) substrate-specific methane yields of 247 and 283 mL (g oDM)$^{-1}$ for the first and subsequent years, respectively. The findings suggest that Scenario 2 is better suited for cultivating *M × g* on brownfields/NAL, being more sensitive and eliminating inaccuracies and the generalisations of results. From the third year onward, the revenue of *M × g* production on biochar-amended brownfields showed greater potential for future profitability. Future research should confirm the positive trend in the energy efficiency ratio of *M × g* phytotechnology on a larger scale, particularly in real brownfield applications.

Keywords: phytomanagement; biochar; energy revenue; economic cost; brownfields

Citation: Mamirova, A.; Pidlisnyuk, V. The Economic and Environmental Aspects of *Miscanthus × giganteus* Phytomanagement Applied to Non-Agricultural Land. *Agronomy* **2024**, *14*, 791. https://doi.org/10.3390/agronomy14040791

Received: 18 March 2024
Revised: 7 April 2024
Accepted: 9 April 2024
Published: 11 April 2024

1. Introduction

In the wider framework of sustainable energy transitions, avenues exploring resource-efficient and low-carbon emission alternatives are emerging [1]. The application of phytotechnology with biomass production is one of the promising solutions which unites generating resources for energy with the further decontamination of the polluted environment [2]. Additionally, the utilisation of energy crops in abandoned territories has gained promise in fostering bioeconomy implementation [3]. However, apart from the limitations in the practical utilisation of this approach, another obstacle arises in the precise terminological interpretation of land labelled a "marginal land" or a "brownfield". A marginal land is considered a site that has poor soil quality or harsh conditions that render it unsuitable for profitable agricultural or commercial applications, i.e., an area where cost-effective production is not feasible [4–6]. A brownfield is an "area previously being in use which can be derelict, excluded from using, sometimes contaminated" [7–10]. Thus, the key distinction between brownfield and marginal land lies in a historical perspective: a brownfield is a territory that was over-utilised in the past and requires revitalisation, whereas marginal land is an area with unfavourable conditions for agriculture. Therefore, the term "brownfield" is broader and can be utilised to refer to contaminated/overused land.

There are about 4.2 million brownfield sites in Europe, with the highest number being in Germany (362,000 sites), while Poland and Romania have the largest brownfield areas (62,000 and 900,000 ha, respectively) [11–13]. In the USA, 450,000 brownfields have been reported [14], and 10% of them are suspected to be contaminated. Due to strong requests to increase the amount of productive land areas, these large territories have to be restored and returned to the land bank. Phytotechnology is one of the most cost-effective and eco-friendly approaches for this, with limited revitalisation expenses in the range of EUR 17.3 to 70.9 m^{-3} [15,16]. Combining phytotechnology with biomass production is an economically beneficial approach [2] which additionally contributes to the bioenergy sector with about 33–46 MWh ha^{-1} y^{-1} of renewable energy sources. Another essential benefit of phytotechnology is the process of CO_2 abatement, calculated as EUR 55–501 ha^{-1} and carbon offsetting equal to 13 t CO_{2e} ha^{-1} y^{-1} [17,18].

Processing thermochemical biomass to derive energy includes combustion, gasification, hydrothermal convection, pyrolysis, liquefaction, and modifications to these processes [19]. Currently, combustion remains the most widely used technology, despite its low net efficiency (20–40%). However, gasification has become preferable, demonstrating greater efficiency, higher pollution–emission standards [20], and an advantage in generating gas to be converted into heat, electricity, biofuels, or platform chemicals [21]. Various input materials can be utilised in gasification, including the biomass of energy crops or their mixture with wood and agricultural residues [22–25].

The perennial grass *Miscanthus* × *giganteus* ($M \times g$) is an energy crop with good phytotechnology potential [26,27]. Its biomass has an impressive energy capacity close to that of wood [28], causing it to be recognised as a potential alternative energy source [29]. A significant aspect of integrating $M \times g$ into phytotechnology is the plant's resilience and high adaptability to adverse conditions, including the possibility of being cultivated in areas typically improper for the cultivation of conventional crops. This crop can immobilise pollutants and effectively mitigate contaminations in varied soils [30,31].

There has been an attempt to utilise $M \times g$ on agricultural marginal soil with the optimisation of the yield and quality of biomass [32]. Significant progress has been recently made regarding $M \times g$ biomass processing to derived bioproducts [33] and market share [34,35], as this cellulose-rich material has been processed into energy [28,36–38], insulation materials [39], pulp [23], paper [40], biopolymers [41,42], and cellulose nanocrystals [43].

Despite the evident advantages of $M \times g$ phytotechnology, it is still not widely implemented. The most substantial obstacles are the expensive plant material (rhizomes) [44] and establishing a fully stable stand in the third year of multiyear growing [32]. Furthermore, there is a weak knowledge of technology profitability when it is applied to non-agricultural lands. The current study intends to overcome this gap, evaluating the economic value of $M \times g$ phytotechnology and ensuring energy profits when biomass is produced in brownfields.

2. Materials and Methods

2.1. Field Establishment

Three long-term running $M \times g$ plantations were researched: Chomutov, the Czech Republic (CZ)—this field was established in 2021 on a marginal post-mining land; Almaty, the Republic of Kazakhstan (KZ)—this field was established in 2017 on a marginal land; and Dolyna, Ukraine (UA)—this field was established in 2018 on a post-military land. The cultivation conditions are presented in Table 1.

Table 1. The cultivation peculiarities of the $M \times g$ research plantations.

Parameters	CZ	KZ	UA
GPS coordinates	50°27′38″ N 13°23′07″ E	43°13′38.161″ N 76°54′59.443″ E	48°58′01.4″ N 23°59′33.3″ E
Climate: Köppen–Geiger classification [a]	2006: *Cfb* 2016: *Dfb*	2006: *Dfa* 2016: *BSk*	2016: *Dfb* 2016: *Dfb*
Year of establishment	2021	2017	2018
Plantation age	3 (2023)	3 (2019)	3 (2020)
Soil type [b]	Cambisols	Kastanozems	Cambisols
Soil amendments	No	No	No
Plot size, m^2	5	5	25
Plot replication	4	3	3
Rhizomes $plot^{-1}$, pcs	30	30	56
Rhizomes ha^{-1}, pcs	40,000	40,000	22,000
Z_{ci} [c]	8.40	3.24	13.2

Note: [a]—[45,46]; [b]—[47]; [c]—[48]; Z_{ci}—total soil contamination coefficient; *BSk*: arid–steppe–cold; *Cfb*: warm temperate–fully humid–warm summer; *Dfa*: snow–fully humid–hot summer; and *Dfb*: cold–without dry season–warm summer.

The level of soil contamination was calculated based on the total contamination coefficient [48]:

$$Z_{ci} = \Sigma\,(K_{ci} + \cdots + K_{cn}) - (n-1) \quad (1)$$

$$K_c = C_i / C_{\varphi i} \quad (2)$$

where K_c—concentration coefficient of i element; n—number of elements with $K_c > 1$; C_i—actual concentration of i element (mg kg^{-1}); and $C_{\varphi i}$—maximum permissible (or background) concentration of i element (mg kg^{-1}).

The biomass productivity (plant height, aboveground biomass dry weight (DW), and biomass HHV) was evaluated at each of the fields in the 3rd year of vegetation, and climate conditions, temperature, level of soil contamination, and economic viability were taken into account.

2.2. Soil Amendment

An $M \times g$ plantation established in 2021 at the marginal post-mining site located in Chomutov, the Czech Republic (CZ), was optimised with different soil amendments, specifically amendments featuring biochar, digestate, paper mill sludge, and sewage sludge. Biochar (Agmeco s.r.o., Brno, CZ) was produced via pyrolyzing wastewater treatment sewage sludge. The digestate used was an anaerobically stabilised and dehydrated material obtained from a waste biogas plant located in Ahníkov, Chomutov region, CZ. Paper mill sludge was obtained from a paper manufacturer in the Chomutov region, CZ. Sewage sludge is anaerobically stabilised sludge; the sewage sludge used in this study was obtained from the wastewater treatment plant in Udlice, Chomutov region, CZ.

The agrochemical profile of the research soil was as follows: pH (KCl)—5.24 ± 0.17; pH (H_2O)—5.98 ± 0.07; organic matter—2.86 ± 0.22%; hydrolysed nitrogen (N)—3.93×10^3 mg kg^{-1}; available phosphorus (P)—28.8 ± 2.12 mg kg^{-1}; available potassium (K)—125 ± 16.2 mg kg^{-1}; available calcium (Ca)—1 925 ± 201 mEq/100 g; available magnesium (Mg)—200 ± 13.5 mEq/100 g; and available sulphur (S)—66.9 ± 1.93 mg kg^{-1} [49]. According to the standard [50], the soil K content was high, Mg content was satisfactory, Ca content was satisfactory, P content was low, and organic matter content was medium–high [51]. The chemical content of the amendments has been presented earlier, specifically in [51]. The agricultural practice exploited in the plantation is presented in Table 2.

Table 2. Characteristics of $M \times g$ plots (Chomutov, CZ).

Parameter	Unit	Control	Biochar		Digestate	Paper Mill Sludge	Sewage Sludge
Area	m^2	30	30	30	30	30	30
Rhizomes	pcs	120	120	120	120	120	120
Application rate	%.vol	-	5	10	5	5	5
Amount of amendment	g pl^{-1}	-	111	221	219	347	413

Notes: pl—plant/rhizome.

2.3. Energy and Economic Efficiency

The higher heating value (HHV) of $M \times g$ biomass was estimated by adiabatic combustion in an IKA C5003 calorimeter (IKA-Werke GmbH & Co. KG, Staufen, Germany) using a dynamic method [52]. The lower heating value (LHV) was calculated according to Equation (2) [53]:

$$LHV\ (\text{MJ kg}^{-1}) = \frac{HHV\ (\text{MJ kg}^{-1} DM) \times\ (100 - W)}{100} - W\ (\%) \times 0.0244\ (\text{MJ kg}^{-1}\%) \quad (3)$$

where W—biomass moisture content, and 0.0244—the correction factor for water valorisation enthalpy.

The common energy characteristics of biomass from energy crops are energy output, efficiency, and gain [53,54]. These parameters were determined according to the following equations:

$$EO\ \ (\text{GJ ha}^{-1}) = LHV\ \ (\text{GJ t}^{-1}) \times FMY\ \ (\text{t ha}^{-1}), \quad (4)$$

$$EG\ \ (\text{GJ ha}^{-1}) = EO\ \ (\text{GJ ha}^{-1}) - EI\ \ (\text{GJ ha}^{-1}), \quad (5)$$

$$EER\ \ (\text{GJ ha}^{-1}) = \frac{EO\ \ (\text{GJ ha}^{-1})}{EI\ \ (\text{GJ ha}^{-1})}, \quad (6)$$

where EO—energy output, FMY—fresh matter yield, EG—energy gain, EI—energy inputs, and EER—energy efficiency ratio.

The estimation of energy input in the production cycle was conducted using estimates taken from the literature [55–59]. The inputs for tractors and machines were determined using the following formula [60]:

$$EI\ (\text{MJ ha}^{-1}) = Weight\ (\text{kg}) \times \frac{Operation\ time\ (\text{hr ha}^{-1})}{Service\ life\ \ (\text{hr})} \times Energy\ equivalent\ (\text{MJ kg}^{-1}) \quad (7)$$

The economic efficiency of biomass was determined based on the following equation:

$$Revenue\ (\text{EUR ha}^{-1}) = Production\ value\ (\text{EUR ha}^{-1}) - Total\ production\ cost\ \ (\text{EUR ha}^{-1}) \quad (8)$$

Total production cost comprised the labour, machinery, diesel, and materials cost at each farming operation, such as soil tillage, soil amendment, planting, and harvest, for all years of cultivation.

2.4. Statistical Analysis

Data analysis was conducted using RStudio software (version 2023.06.0 Build 421, RStudio PBC, Boston, MA, USA, 2023). Tukey HSD tests were performed for pairwise comparisons of the means, while an ANOVA was used to confirm statistical significance. Subsequently, the treatments were categorised by letter in descending order, and graphs were generated. Significance was declared at $p < 0.05$.

3. Results

A comparative analysis was applied to assess the biomass energy capacity of crops with phytotechnology potential (Table S1). $M \times g$ is among the extensively studied energy crops supported by long-term cultivation (>3 till 20 years [44,61]). Numerous data are available for lab-scale experiments; however, testing the crop at the field scale is limited [62]. $M \times g$ biomass exhibited a substantially high HHV and energy output values of 20.5 MJ kg^{-1} and 858 GJ ha^{-1}, respectively (Table S1), even when the crop was cultivated in trace element (TE)-contaminated soil [29].

3.1. Harvest Value Modelling

3.1.1. Field Conditions

The results of the chemical analysis indicated that the most contaminated soil belongs to the plantation located in Dolyna, Ukraine, followed by that in Chomutov, the Czech Republic, and the cleanest soil belongs to the plantation in Almaty, Kazakhstan (Table 3). The CZ soil contained Cr, Zn, and Pb in concentrations which exceeded the MPC by 1.91, 2.00, and 1.77 times, respectively. In the KZ soil, the concentrations of Cr, As, and Sr exceeded the MPC values by 3.30, 1.35, and 18.1 times, respectively. In the UA soil, the concentrations of Cr exceeded the MPC by 1.45 times; despite the concentrations of other TEs being lower than the MPC values, the UA soil was the most contaminated based on the total contamination coefficient [48].

Table 3. Concentrations of trace elements in the soils (mg kg^{-1}).

TE	MPC CR [1]	CZ	MPC KZ [2]	KZ	MPC UA [3]	UA
V	130	<LOD	43	24.1 ± 0.30	-	<LOD
Cr	90	172 ± 11.5	6	19.8 ± 0.20	100	145 ± 49.0
Mn	-	1086 ± 1.53	1500	409 ± 9.00	1500	825 ± 38.0
Fe	-	46,623 ± 1541	-	15,570 ± 105	-	42,481 ± 148
Co	30	<LOD	20	6.60 ± 0.10	-	<LOD
Ni	50	50.7 ± 4.23	20	22.3 ± 0.50	85	63.0 ± 11.0
Cu	60	50.1 ± 3.57	33	19.9 ± 1.20	100	40.0 ± 7.00
Zn	120	240 ± 8.06	55	52.4 ± 4.30	300	111 ± 6.00
As	20	<LOD	2	2.70 ± 0.10	20	15.0 ± 2.00
Sr	200 [4]	209 ± 1.32	7	127 ± 2.40	1000	148 ± 2.00
Pb	60	106 ± 7.17	32	17.0 ± 1.00	30	22.0 ± 3.00

Note: MPC—maximum permissible concentration; LOD—limit of detection; [1]—[63]; [2]—[64]); [3]—[65]; [4]—[66].

Biomass productivity was estimated based on the plant height and harvest value (recalculated for hectare), and the results are presented in Figure 1. The results showed that the $M \times g$ height and harvest value were the highest for the KZ plantation, being 1.46 and 1.35 times higher than in the CZ plantation and 1.46 and 3.06 times higher than in the UA plantation. It should be mentioned that the plant height in the UA plantation was comparable to that of the CZ plantation; however, the biomass yield in the UA plantation was 2.27 times lower, most likely due to the lower planting density and higher soil contamination (Tables 1 and 3).

Data from the literature [67,68] and our own investigations [39,69] illustrated that climatic conditions play a crucial role in $M \times g$ biomass yield. The average temperature, rainfall, and solar radiation values for the research plantations were compared (Table S1). When analysing the mean monthly temperatures, the highest values were recorded for the KZ plantation during the crucial months of the plant's development (May–September). The highest rainfall was reported for the UA plantation, with annual precipitation (May–July) values of 1124, 1092, and 1214 mm in 2018, 2019, and 2020, respectively. In contrast, the KZ plantation experienced the lowest annual precipitation, with 608, 668, and 675 mm in 2017, 2018, and 2019, respectively. The KZ plantation received notably more solar radiation throughout the year compared to the CZ and UA plantations, meaning that it may be among the factors influencing biomass productivity.

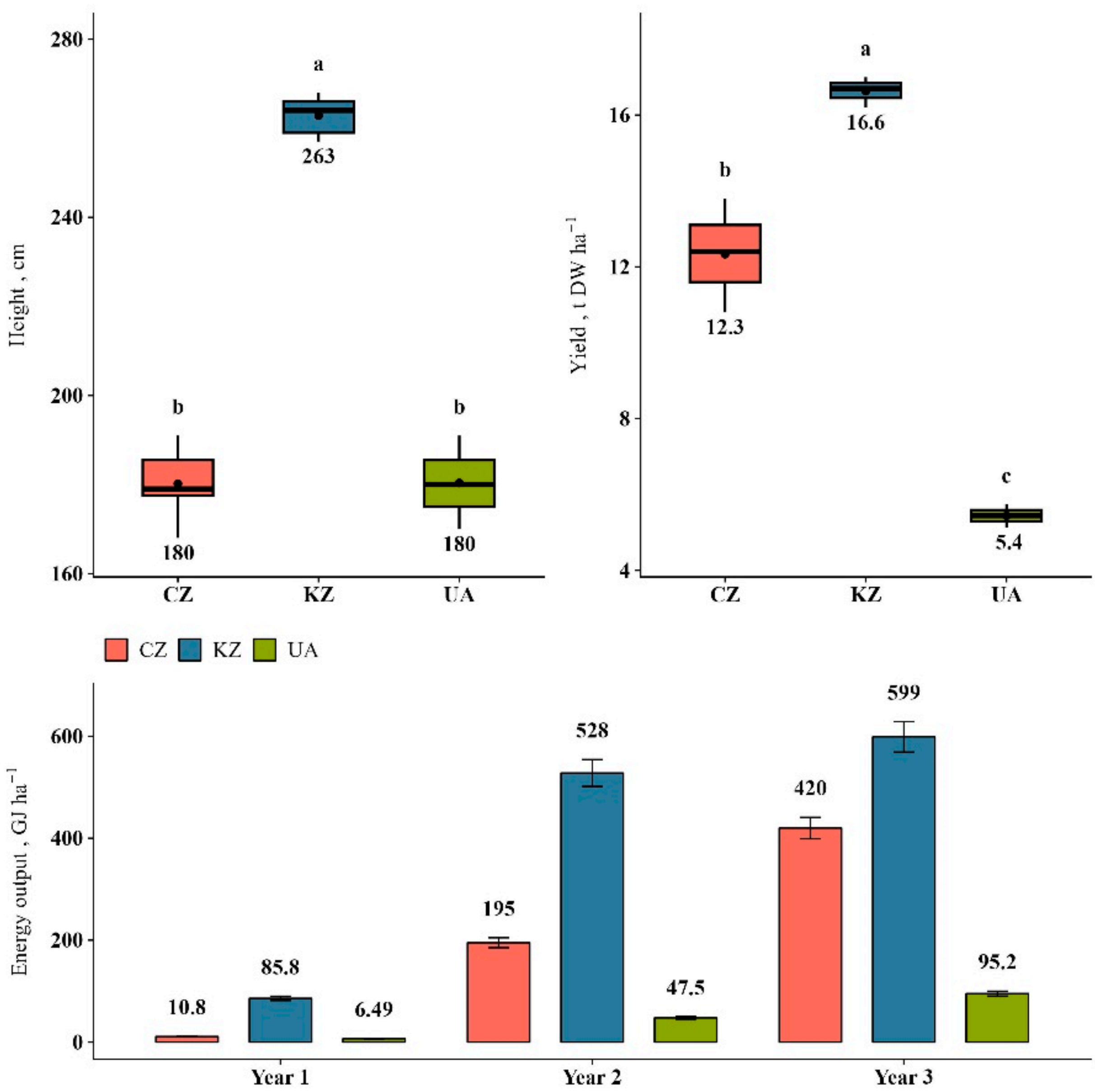

Figure 1. The height, harvest value, and energy output of $M \times g$ biomass produced at the research fields. Different letters within one parameter serve as statistical groups and indicate significant differences.

In addition, the results strongly suggested that biomass yield was additionally determined by the soil contamination level. The lowest yield was recorded for the UA plantation, which was the most contaminated (Table 3).

The high heating values (HHVs) of biomass were measured to assess the energy perspectivity of plant cultivation in fields with different climate conditions. The results showed that the CZ biomass had an HHV of 17.3 ± 0.01 MJ kg^{-1}, and a higher HHV equal to 18.0 ± 0.04 MJ kg^{-1} was recorded for the KZ biomass. Under the assumption that the CZ and UA soils qualified as contaminated, the energy output (EO) values of the produced biomass were compared (Figure 1). In the initial year, the EOs of biomass received from the CZ and UA plantations exhibited a substantial similarity, whereas the EO of the biomass from the KZ plantation was 7.94 and 13.2 times higher than that of the CZ and UA plantations, respectively. Nevertheless, it is worth noting that the CZ EO surpassed that of the UA soil by a factor of 1.66 (Figure 1). In the second year of vegetation, this disparity significantly expanded, reaching a magnitude of ×4.11. Meanwhile, the KZ

EO was 2.71 and 11.1 times higher than the CZ and UA EOs. Interestingly, the disparity between the EOs of the CZ and KZ plantations was almost neglected in the third year of vegetation (×1.43), whereas the difference between the EOs of CZ and UA kept growing, reaching ×4.42.

3.1.2. Optimisation of $M \times g$ Cultivation at the Field Scale

Before the establishment of the $M \times g$ plantation in Chomutov, CZ, the soil was treated by different soil amendments, implying that this operation will increase $M \times g$ biomass yield. When evaluating $M \times g$ biomass productivity in the CZ soil, it was observed that biochar at the application rates of 5 and 10% increased the biomass DM by 1.45 and 1.94 times, respectively. Interestingly, the incorporation of sewage sludge and paper mill sludge decreased the $M \times g$ yield after the third year of vegetation compared with the control, and the incorporation of digestate only slightly increased the harvest value (Table 4). The HHV of $M \times g$ biomass harvest in the third year of vegetation fluctuated in a narrow range (17.1–17.5 MJ kg^{-1}), even though there was a statistically significant difference between certain pairs containing biochar at 10% or digestate (Table 4).

Table 4. Harvest value and energy capacity of harvested biomass (Chomutov, CZ). Different letters within one parameter serves as statistical groups and indicate the significant differences.

Parameter	Unit	Control	Biochar		Digestate	Paper Mill Sludge	Sewage Sludge
Biomass yield after 3rd year of vegetation							
Harvest value	t ha^{-1}	12.4 ± 1.50 c	18.0 ± 1.20 b	24.1 ± 1.06 a	14.3 ± 1.68 bc	10.7 ± 1.31 c	12.9 ± 1.41 c
Energy capacity							
HHV	MJ kg^{-1}	17.3 bc	17.4 ab	17.1 d	17.5 a	17.3 bc	17.2 c

3.2. Miscanthus Production Cycle

The energy gain and profitability of $M \times g$ biomass were confirmed numerically when the crop was cultivated on agricultural land [56,57,70–75]. However, the application of $M \times g$ to non-agricultural land was particularly scarce [76–78]. The current study focused on calculating the profitability of $M \times g$ phytotechnology when the crop was cultivated in non-agricultural land, including brownfields. For calculation, the labour requirements for farming operations such as ploughing, harrowing, planting, weed control, and harvests of 2, 1.29, 23.48, 1, and 3 man h^{-1} ha^{-1} were used [74,76]. The values of energy equivalents requested for calculation of energy inputs were taken from the literature, i.e., the value for labour was equal to 40 MJ h^{-1} [56]; the tractor and machines were operated at 112 MJ kg^{-1} [56]; diesel—48 MJ L^{-1} [56]; the soil amendment was conducted at 506 MJ ha^{-1} [58,59]; the planting material was added at 4 MJ rhizome^{-1}; the herbicide was applied at 295 MJ kg^{-1} of the active compound [55]; and the labour cost was EUR 7.93 h^{-1} [79]. Using these energy equivalents, the energy input and economic cost of $M \times g$ production in the non-agricultural land was calculated as per Chomutov, CZ (Table 5). It was difficult to define a reasonable market price for biochar due to the absence of a developed market. The prices mentioned in the literature ranged from EUR 138 to 1336 t^{-1} [80–83]; therefore, an average price of EUR 499 t^{-1} was used in the calculation.

Table 5. The energy input (EI) and economic cost of implementing *M* × *g* phytotechnology in brownfields.

Farming Operation		Labour			Machinery		Diesel			Materials		Total Input	
		man h^{-1} ha^{-1}	EUR ha^{-1}	MJ ha^{-1}	kg ha^{-1}	MJ ha^{-1}	L ha^{-1}	EUR ha^{-1}	MJ ha^{-1}	EUR ha^{-1}	MJ ha^{-1}	EUR ha^{-1}	MJ ha^{-1}
Soil tillage	Ploughing	2.00	15.9	80.0	0.38	42.6	25.0	37.0	1200	-	-	52.9	1323
	Harrowing	1.29	10.2	51.6	0.13	14.6	3.33	4.93	160	-	-	15.2	226
Soil amendment							Normative			-	-	-	-
Biochar		23.48 [a]	186	939			4.44 t × EUR 499			2216	506 [b]	2402	1445
		23.48 [a]	186	939			8.84 t × EUR 499			4411	506 [b]	4597	1445
Digestate		23.48 [a]	186	939			8.76 t × EUR 5.47 [84]			47.9	506 [b]	234	1445
Paper mill sludge (PMS)		23.48 [a]	186	939			13.9 t × EUR 50.0 [85]			694	506 [b]	880	1445
Sewage sludge (SS)		23.48 [a]	186	939			16.5 t × EUR 129 [86]			2131	506 [b]	2317	1445
Planting		23.48	186	939	0.88	98.6	11.7	17.3	562	12,000	160,000	12,204	161,599
Plant material					40,000 rhizomes × EUR 0.30 [d]								
Weed control		3.00	23.8	120	1.17	132	22.5	33.3	1080	74.7	531	132	1862
Herbicide (RoundUp)					5.00 L × EUR 14.9 [87]								
Harvest		3.00	23.8	120	1.17	131	22.5	33.3	1080	-	-	57.1	1331
Total expenses													
1st year	Control	32.8	260	1311	3.73	418	85.0	126	4081	12,075	160,531	12,460	166,341
	Biochar	56.3	446	2250	3.73	418	85.0	126	4081	14,291	161,037	14,863	167,786
		56.3	446	2250	3.73	418	85.0	126	4081	16,486	161,037	17,058	167,786
	Digestate	56.3	446	2250	3.73	418	85.0	126	4081	12,123	161,037	12,695	167,786
	PMS	56.3	446	2250	3.73	418	85.0	126	4081	12,769	161,037	13,341	167,786
	SS	56.3	446	2250	3.73	418	85.0	126	4081	14,206	161,037	14,778	167,786
2nd year and following years		6.00	47.6	240	2.34	262	45.0	66.6	2160	74.7	531	189	3193
Equivalents	Value	-	7.93	40.0	-	112	-	1.48 [c]	48	4	295	-	-
	Unit	-	EUR h^{-1}	MJ h^{-1}	-	MJ kg^{-1}	-	EUR L^{-1}	MJ L^{-1}	MJ pl^{-1}	MJ kg^{-1}	EUR ha^{-1}	MJ ha^{-1}

Note: [a]—this value was taken from planting because the biochar was applied for each hole and not by mulching; [b]—energy equivalent for soil amendment; [c]—Ceskybenzin.cz [88]; [d]—price was offered by d.o.o. Miscanthus (Croatia, www.miscanthus.hr, accessed on 18 March 2024) for the case when the research plantation was established in Chomutov.

The attractiveness of utilising brownfields for the application of $M \times g$ phytotechnology for the production of biomass lies in the potential for low or no costs regarding land leasing. In our scenario, the land was secured without incurring any lease expenses; consequently, land rent costs were not factored into the calculations. The soil amendment was carried out manually, as opposed to the conventional mulching method, when amendments were spread on the soil surface. Consequently, machinery-related energy and economic inputs were not considered in our calculations. During the initial year of plant growth, manual weed control techniques were implemented, followed by the application of the herbicide RoundUp. For the second and following years, the process included only weed control and harvest operations (Table 5).

As seen from Table 5, for the first year, which included plantation establishment and the share of plant material, the following values were calculated: energy cost—96.3–97.1% and economic costs—82.6–97.9%. Muylle et al. [57] reported an 81% EI share of input material for $M \times g$ production; this lower value can be explained by the fact that they used a lower planting density equal to ~3 pl m^{-2}. The incorporation of soil amendments increased the economic cost, while the energy input was the same. As the energy input and economic cost essentially decreased in the following years of production, values of 1.90–1.92% for energy input and 0.67–1.52% for economic cost were noted. In the first year, the EI for $M \times g$ production was 166–168 GJ ha^{-1}, and in the following years, the EI dropped to 3.19 GJ ha^{-1}.

The values of energy output, gain, and efficiency ratio were calculated in accordance with Jankowski et al. [54] and Sokólski et al. [53]. The results showed that the best energy characteristics were obtained for biomass produced in soil with biochar amendments and increasing the biochar application rate from 5 to 10% led to better energy characteristics (Figure 2). The energy efficiency ratio for biomass produced in soil amended by 5% biochar overcame the control's values by 20.5%, and for 10% biochar, the increase was 30.8%. The incorporation of other soil amendments (digestate, paper mill sludge, and sewage sludge) decreased the energy efficiency ratio by 1.65–14.9%. This fact illustrated that the incorporation of biochar is the best tool for enhancing biomass energy characteristics when $M \times g$ phytotechnology is applied to non-agricultural land, including brownfields.

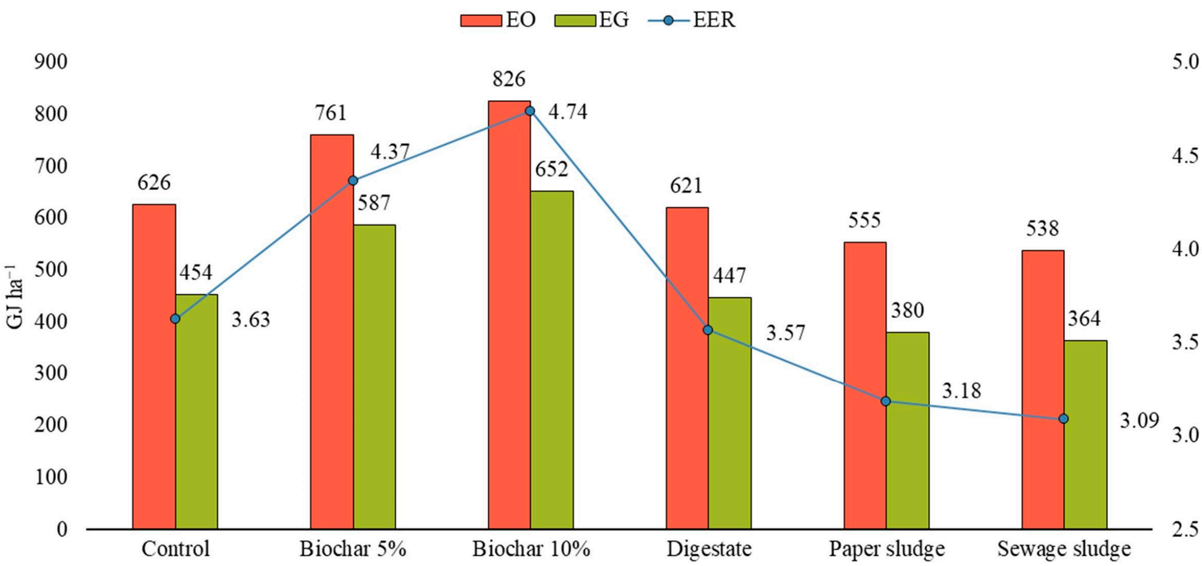

Figure 2. The energy output, gain, and efficiency ratio of $M \times g$ biomass production at the brownfields for three years of vegetation.

Two scenarios were considered in order to validate the feasibility of $M \times g$ production in non-agricultural land, including brownfields. The following value chain was exploited: "biomass—biogas—electricity". Of the two scenarios proposed, the first one was the commonly used approach in which calculation is based on determined methane yield during the transformation of biomass to energy [78]. The second scenario was particularly designed in the current study for cases when $M \times g$ was cultivated in the presence of soil amendments. The calculation was based on substrate-specific methane yield (SMY) [89]. In both scenarios, $M \times g$ biomass collected in the autumn was under consideration (so-called "green harvest"), and the scenarios endured three years of production.

In the first scenario, the following assumptions were made: methane yield in a green harvest $M \times g$ biomass was equal to 5134 m^3; the average value of methane ha^{-1} y^{-1} ranged from 4542 to 6153 m^3 methane ha^{-1} y^{-1} [35,78,89,90]; in accordance with [91], 1 m^3 methane produces 0.036 GJ; 1 GJ_{el} costs EUR 45.12 [78].

In the second scenario, the idea of calculation was based on the verification of the SMY value depending on the soil amendments used and the biomass yield obtained. The following assumptions were applied: the organic dry matter (oDM) of $M \times g$ biomass was considered at 96 wt.% [92]; the SMY was equal to 247 mL (g oDM)$^{-1}$ for the first year [90] and 283 mL (g oDM)$^{-1}$ for the second and third years of production [93]; in accordance with [91], 1 m^3 methane produces 0.036 GJ; 1 GJ_{el} costs EUR 45.12 [78].

The first scenario is general and was proposed for $M \times g$ plantations that are cultivated in the marginal land [78]. However, the vagueness of the term definitions led to inaccuracies in citations, and it also complicated the definition of a proper approach in terms of modelling profitability; this occurred because the plantation used by Wagner et al. [78] and defined as marginal land, was, in reality, a low-quality land high in clay and stone content [89] which, in reality, can be recognised as agricultural land. The second scenario aided in eliminating the inaccuracy and is considered to suit cases of cultivating $M \times g$ on brownfields/non-agricultural lands that are more sensitive.

The revenue generated from transforming the $M \times g$ biomass to energy by the exploitation of both scenarios is presented in Table 6. As anticipated, the revenue gained from $M \times g$ biomass after the first year of cultivation was negative for both scenarios, although a peak was reached in the case of the biochar application (Table 6). The results showed that in the case of the first scenario, the application of soil amendments led to a reduction in the revenue of up to 37.7% in the following years because of the additional expenses for the soil amendments and corresponding labour inputs. However, in the case of the second scenario, the revenue received after the third year of biomass cultivation showed a good result when it was cultivated in biochar-amended land, and the cost ranged from EUR 7.75 to 10.4 thousand, thus surpassing the control variant by 46.8 and 97.7%. In contrast, when the soil was amended by paper mill sludge, the revenue was lower than the control by 14.2%. Comparing the revenue received from the full three years, only the biochar-amended treatments showed better tendencies compared to the control. The obtained results indicate that by utilising $M \times g$ phytotechnology in brownfields, the time to achieve profitability from a value chain of "biomass—biogas—electricity", is longer compared to that with agricultural land.

Table 6. The revenue gained from transforming $M \times g$ biomass into energy, calculated following two scenarios (EUR).

Treatment	Scenario 1				Scenario 2			
	Year 1	Year 2	Year 3	Total	Year 1	Year 2	Year 3	Total
Control	−4121	8150	8150	12,179	−12,378	1603	5283	−5492
Biochar 5%	−6523	8150	8150	9777	−14,700	2318	7754	−4628
Biochar 10%	−8718	8150	8150	7582	−16,863	2838	10,446	−3578
Digestate	−4355	8150	8150	11,945	−12,539	1356	6122	−5062
PMS	−5001	8150	8150	11,299	−13,248	1276	4533	−7439
SS	−6438	8150	8150	9862	−14,710	1122	5504	−8084

The calculation results ensured that despite the elevated production costs of $M \times g$ phytotechnology in the first year of vegetation (incurred mainly because of the cost of plantation establishment and planting materials), the application of biochar led to an increase in the energy output of biomass and enhanced the economic profitability of the process. The second scenario is recommended for use for non-agricultural land/brownfields.

3.3. SWOT Analysis of $M \times g$ Phytotechnology

To determine the importance of $M \times g$ cultivation in non-agricultural land, including brownfields, along with the potential to produce biomass as a renewable energy source, a SWOT analysis was performed based on data from the literature and our own investigation (Table 7).

Table 7. SWOT analysis of the $M \times g$ biomass production, modified from Kalabić et al. [94]; Lewandowski et al. [32]; Liu et al. [95]; Paschalidou et al. [96]; and Erickson and Pidlisnyuk [39].

S (Strengths)	W (Weaknesses)
• $M \times g$ is feasible for a wide range of climatic conditions; • Land availability; • Improvement of the rural economy; • Rapid growth; • Lignocellulose-rich biomass; • A perennial crop; • Low maintenance cost; • Essential reductions in production cost after establishment; • Disease and cold resistance; • Minimal nutritional requirements; • High energy balance; • Sterile hybrid (non-invasive); • Useful on land that is slightly to moderately contaminated by TEs; • Low content of TEs in $M \times g$ aboveground biomass (phytostabilisation); • Soil erosion prevention; • GHG mitigation; • Carbon sequestration.	• Competition with weeds in the first two years of vegetation; • Requires sufficient irrigation in the first year; • Stable production is only reached after 3 years; • High initial establishment cost due to rhizome price (~80%); • Intolerant to flooding and long drought; • Abiotic stress causes changes in cell wall compositions; • Cannot tolerate salinity stress; • Economic viability (it is still a long process to move from biomass collection to processing, which increases bioenergy production cost; • A slow and lengthy process of phytotechnology.
O (Opportunities)	**T (Threats)**
• Sustainable development of brownfields; • Variety in the value-added products produced from $M \times g$ biomass; • Creation of cultivars that are resistant to severe climatic conditions; • $M \times g$ plantation supports fauna biodiversity by providing shelter; • Climate change adaptation by C sequencing during canopy duration, increasing the ecosystem value of landscapes.	• Feed for wild animals; • No resistance to high concentrations of contaminants; • Long-term stands (monoculture) can cause a reduction in local flora biodiversity; • Biomass moisture of <20% can cause self-ignition during storage; • Could induce a rise in fuel prices and contribute to a higher labour cost; • Underdeveloped biomass market; • Underdeveloped bioproduct (pulp, paper, insulation materials, etc.) market; • Low interest in local communities for innovative solutions; • Insufficient interest from landowners for remediation; • Insufficient educational knowledge regarding $M \times g$ production.

4. Conclusions

This analysis of published data and our own results revealed that $M \times g$ phytotechnology can be utilised in non-agricultural land, including brownfields. This approach will aid in resolving environmental challenges and provide essential alternatives for bioenergy production. An evaluation of different factors' (climate conditions and soil contamination levels) impact on $M \times g$ height, biomass yield, energy output, and higher heating value was performed for three Miscanthus plantations located in Chomutov, the Czech Republic; Almaty, Kazakhstan; and Dolyna, Ukraine. It was shown that climate factors and soil contamination have the greatest impact on biomass yield and energy output. For the optimisation of $M \times g$ cultivation at a field scale, the amendment of non-agricultural soil by biochar can be recommended. Compared with other tested amendments (digestate, sewage sludge, and paper mill sludge), biochar improved the energy efficiency ratio to the greatest extent. The assessment of biomass revenue through a value chain of "biomass—biogas—electricity" illustrated its profitability starting from the third year of vegetation. It is necessary to prove the positive trend of energy efficiency ratios and the revenue of Miscanthus biomass production with biochar during a multiyear practice in brownfields at the commercial scale. In addition, the presented analysis is set to be enriched by considering additional parameters such as energy density, transportation radius, and the variability of the alternative energy market.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14040791/s1. Table S1: Climate conditions in the research fields. Source: AQUASTAT [97].

Author Contributions: Conceptualisation, V.P.; methodology, A.M.; software, A.M.; validation, A.M.; formal analysis, A.M.; investigation, A.M.; resources, V.P.; writing—original draft preparation, A.M. and V.P.; writing—review and editing, A.M. and V.P.; visualisation, A.M.; supervision, V.P.; project administration, V.P.; funding acquisition, V.P. All authors have read and agreed to the published version of the manuscript.

Funding: The research was supported by NATO SPS MYP G6094 and Project AP14973042 supported by the Ministry of Science and Higher Education, Republic of Kazakhstan.

Data Availability Statement: Data are available from the corresponding author on reasonable request.

Acknowledgments: The authors would like to thank Robert Ato Newton, Jan Evangelista Purkyně University, the Czech Republic; Sergiy Ust'ak, Crop Research Institute, the Czech Republic; and Pavlo Shapoval, National University Lvivska Polytechnika, Ukraine, for their assistance during data collection.

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

References

1. Prabha, J.; Kumar, M.; Tripathi, R. Chapter 17—Opportunities and Challenges of Utilizing Energy Crops in Phytoremediation of Environmental Pollutants: A Review. In *Bioremediation for Environmental Sustainability*; Kumar, V., Saxena, G., Shah, M.P., Eds.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 383–396, ISBN 978-0-12-820318-7.
2. Evangelou, M.W.H.; Papazoglou, E.G.; Robinson, B.H.; Schulin, R. Phytomanagement: Phytoremediation and the Production of Biomass for Economic Revenue on Contaminated Land. In *Phytoremediation: Management of Environmental Contaminants*; Ansari, A.A., Gill, S.S., Gill, R., Lanza, G.R., Newman, L., Eds.; Springer International Publishing: Cham, Germany, 2015; Volume 1, pp. 115–132, ISBN 978-3-319-10395-2.
3. European Commission; Joint Research Centre; Fritsche, U.; Brunori, G.; Chiaramonti, D.; Galanakis, C.; Matthews, R.; Panoutsou, C.; Avraamides, M.; Borzacchiello, M.; et al. *Future Transitions for the Bioeconomy towards Sustainable Development and a Climate-Neutral Economy—Foresight Scenarios for the EU Bioeconomy in 2050*; Avraamides, M., Borzacchiello, M., Stoermer, E., Eds.; Publications Office of the European Union: Luxembourg, 2020; ISBN 978-92-76-28414-7.
4. FAO. *Bioenergy Environmental Impact Analysis (BIAS): Analytical Framework*; Environment and Natural Resources Management Working Paper; Land and Water Division: Rome, Italy, 2010; p. 177.
5. Kang, S.; Post, W.M.; Nichols, J.A.; Wang, D.; West, T.O.; Bandaru, V.; Izaurralde, R.C. Marginal Lands: Concept, Assessment and Management. *J. Agric. Sci.* **2013**, *5*, 129. [CrossRef]
6. Schroers, J. *Towards the Development of Marginal Land Use Depending on the Framework of Agricultural Market, Policy and Production Techniques*; University of Giessen: Giessen, Germany, 2006.

7. Alker, S.; Joy, V.; Roberts, P.; Smith, N. The Definition of Brownfield. *J. Environ. Plan. Manag.* **2000**, *43*, 49–69. [CrossRef]
8. EPA. The Small Business Liability Relief and Brownfields Revitalization Act: A Critique. 2002; p. 27. Available online: https://www.congress.gov/107/plaws/publ118/PLAW-107publ118.pdf (accessed on 18 March 2024).
9. Newton, R.A.; Pidlisnyuk, V.; Wildová, E.; Nováková, L.; Trögl, J. State of Brownfields in the Northern Bohemia, Saxony, and Lower Silesian Regions and Prospects for Regeneration by Utilization the Phytotechnology with the Second-Generation Crops. *Land* **2023**, *12*, 354. [CrossRef]
10. Tang, Y.-T.; Nathanail, C.P. Sticks and Stones: The Impact of the Definitions of Brownfield in Policies on Socio-Economic Sustainability. *Sustainability* **2012**, *4*, 840–862. [CrossRef]
11. GUS. *Environment 2022*; Statistical Analyses; Statistics Poland, Spatial and Environmental Surveys Department: Warsaw, Poland, 2023; p. 191.
12. Oliver, L.; Ferber, U.; Grimski, D.; Millar, K.; Nathanail, P. The Scale and Nature of European Brownfields. In Proceedings of the CABERNET 2005-International Conference on Managing Urban Land LQM Ltd., Nottingham, UK, 13–15 April 2005; pp. 5–6.
13. Rey, E.; Laprise, M.; Lufkin, S. The Multiple Potentials of Urban Brownfields. In *Neighbourhoods in Transition: Brownfield Regeneration in European Metropolitan Areas*; Rey, E., Laprise, M., Lufkin, S., Eds.; The Urban Book Series; Springer International Publishing: Cham, Germany, 2022; pp. 47–63, ISBN 978-3-030-82208-8.
14. Hammond, E.B.; Coulon, F.; Hallett, S.H.; Thomas, R.; Hardy, D.; Kingdon, A.; Beriro, D.J. A Critical Review of Decision Support Systems for Brownfield Redevelopment. *Sci. Total Environ.* **2021**, *785*, 147132. [CrossRef]
15. da Silva, J.; Rosa, G.B.; Sganzerla, W.G.; Ferrareze, J.P.; Simioni, F.J.; Campos, M.L. Strategies and Prospects in the Recovery of Contaminated Soils by Phytoremediation: An Updated Overview. *Commun. Plant Sci.* **2023**, *13*, 1–12. [CrossRef]
16. Singh, H.; Pant, G. Phytoremediation: Low Input-Based Ecological Approach for Sustainable Environment. *Appl. Water Sci.* **2023**, *13*, 85. [CrossRef]
17. Ali, M.H.; Khan, M.I.; Bashir, S.; Azam, M.; Naveed, M.; Qadri, R.; Bashir, S.; Mehmood, F.; Shoukat, M.A.; Li, Y.; et al. Biochar and *Bacillus* sp. MN54 Assisted Phytoremediation of Diesel and Plant Growth Promotion of Maize in Hydrocarbons Contaminated Soil. *Agronomy* **2021**, *11*, 1795. [CrossRef]
18. Gomes, H.I. Phytoremediation for Bioenergy: Challenges and Opportunities. *Environ. Technol. Rev.* **2012**, *1*, 59–66. [CrossRef]
19. Jankowski, K.J.; Kołodziej, B.; Dubis, B.; Sugier, D.; Antonkiewicz, J.; Szatkowski, A. The Effect of Sewage Sludge on the Energy Balance of Cup Plant Biomass Production. A Six-Year Field Experiment in Poland. *Energy* **2023**, *276*, 127478. [CrossRef]
20. Couto, N.D.; Silva, V.B.; Monteiro, E.; Rouboa, A.; Brito, P. An Experimental and Numerical Study on the Miscanthus Gasification by Using a Pilot Scale Gasifier. *Renew. Energy* **2017**, *109*, 248–261. [CrossRef]
21. Molino, A.; Chianese, S.; Musmarra, D. Biomass Gasification Technology: The State of the Art Overview. *J. Energy Chem.* **2016**, *25*, 10–25. [CrossRef]
22. Bocianowski, J.; Fabisiak, E.; Joachimiak, K.; Wojech, R.; Wojciak, A. *Miscanthus × giganteus* as an Auxiliary Raw Material in NSSC Birch Pulp Production. *Cellul. Chem. Technol.* **2019**, *53*, 271–279. [CrossRef]
23. Cappelletto, P.; Mongardini, F.; Barberi, B.; Sannibale, M.; Brizzi, M.; Pignatelli, V. Papermaking Pulps from the Fibrous Fraction of *Miscanthus × giganteus*. *Ind. Crop. Prod.* **2000**, *11*, 205–210. [CrossRef]
24. Ivanovski, M.; Goričanec, D.; Urbancl, D. The Evaluation of Torrefaction Efficiency for Lignocellulosic Materials Combined with Mixed Solid Wastes. *Energies* **2023**, *16*, 3694. [CrossRef]
25. Marín, F.; Sánchez, J.L.; Arauzo, J.; Fuertes, R.; Gonzalo, A. Semichemical Pulping of *Miscanthus × giganteus*. Effect of Pulping Conditions on Some Pulp and Paper Properties. *Bioresour. Technol.* **2009**, *100*, 3933–3940. [CrossRef] [PubMed]
26. Andrejić, G.; Šinžar-Sekulić, J.; Prica, M.; Dželetović, Ž.; Rakić, T. Phytoremediation Potential and Physiological Response of *Miscanthus × giganteus* Cultivated on Fertilized and Non-Fertilized Flotation Tailings. *Environ. Sci. Pollut. Res.* **2019**, *26*, 34658–34669. [CrossRef] [PubMed]
27. Jeżowski, S.; Głowacka, K.; Kaczmarek, Z. Variation on Biomass Yield and Morphological Traits of Energy Grasses from the Genus Miscanthus during the First Years of Crop Establishment. *Biomass Bioenergy* **2011**, *35*, 814–821. [CrossRef]
28. Zhang, Y.; Zahid, I.; Danial, A.; Minaret, J.; Cao, Y.; Dutta, A. Hydrothermal Carbonization of Miscanthus: Processing, Properties, and Synergistic Co-Combustion with Lignite. *Energy* **2021**, *225*, 120200. [CrossRef]
29. Nebeská, D.; Pidlisnyuk, V.; Stefanovska, T.; Trögl, J.; Shapoval, P.; Popelka, J.; Černý, J.; Medkow, A.; Kvak, V.; Malinská, H. Impact of Plant Growth Regulators and Soil Properties on *Miscanthus × giganteus* Biomass Parameters and Uptake of Metals in Military Soils. *Rev. Environ. Health* **2019**, *34*, 283–291. [CrossRef]
30. Al Souki, K.S.; Burdová, H.; Mamirova, A.; Kuráň, P.; Kříženecká, S.; Oravová, L.; Tolaszová, J.; Nebeská, D.; Popelka, J.; Ust'ak, S.; et al. Evaluation of the *Miscanthus × giganteus* Short Term Impacts on Enhancing the Quality of Agricultural Soils Affected by Single and/or Multiple Contaminants. *Environ. Technol. Innov.* **2021**, *24*, 101890. [CrossRef]
31. Burdová, H.; Kwoczynski, Z.; Nebeská, D.; Souki, K.S.A.; Pilnaj, D.; Grycová, B.; Klemencová, K.; Leštinský, P.; Kuráň, P.; Trögl, J. The Influence of Diesel Contaminated Soil on *Miscanthus × giganteus* Biomass Thermal Utilization and Pyrolysis Products Composition. *J. Clean. Prod.* **2023**, *406*, 136984. [CrossRef]
32. Lewandowski, I.; Clifton-Brown, J.; Trindade, L.M.; van der Linden, G.C.; Schwarz, K.-U.; Müller-Sämann, K.; Anisimov, A.; Chen, C.-L.; Dolstra, O.; Donnison, I.S.; et al. Progress on Optimizing Miscanthus Biomass Production for the European Bioeconomy: Results of the EU FP7 Project OPTIMISC. *Front. Plant Sci.* **2016**, *7*, 1620. [CrossRef] [PubMed]

33. Clifton-Brown, J.; Hastings, A.; Mos, M.; McCalmont, J.P.; Ashman, C.; Awty-Carroll, D.; Cerazy, J.; Chiang, Y.-C.; Cosentino, S.; Cracroft-Eley, W.; et al. Progress in Upscaling Miscanthus Biomass Production for the European Bio-Economy with Seed-Based Hybrids. *GCB Bioenergy* **2017**, *9*, 6–17. [CrossRef]
34. Kiesel, A. *The Potential of Miscanthus as Biogas Feedstock. Doctor Scientiarum Agriculturae*; University of Hohenheim: Stuttgart, Germany, 2020.
35. Kiesel, A.; Wagner, M.; Lewandowski, I. Environmental Performance of Miscanthus, Switchgrass and Maize: Can C4 Perennials Increase the Sustainability of Biogas Production? *Sustainability* **2017**, *9*, 5. [CrossRef]
36. Licht, L.A.; Isebrands, J.G. Linking Phytoremediated Pollutant Removal to Biomass Economic Opportunities. *Biomass Bioenergy* **2005**, *28*, 203–218. [CrossRef]
37. Parajuli, R.; Sperling, K.; Dalgaard, T. Environmental Performance of Miscanthus as a Fuel Alternative for District Heat Production. *Biomass Bioenergy* **2015**, *72*, 104–116. [CrossRef]
38. Stolarski, M.J.; Krzyżaniak, M.; Warmiński, K.; Tworkowski, J.; Szczukowski, S. Perennial Herbaceous Crops as a Feedstock for Energy and Industrial Purposes: Organic and Mineral Fertilizers versus Biomass Yield and Efficient Nitrogen Utilization. *Ind. Crop. Prod.* **2017**, *107*, 244–259. [CrossRef]
39. Erickson, L.E.; Pidlisnyuk, V. (Eds.) *Phytotechnology with Biomass Production: Sustainable Management of Contaminated Sites*, 1st ed.; CRC Press Taylor & Francis Group: Boca Raton, FL, USA, 2021; ISBN 978-0-367-52280-3.
40. Danielewicz, D.; Surma-Ślusarska, B. *Miscanthus × giganteus* Stalks as a Potential Non-Wood Raw Material for the Pulp and Paper Industry. Influence of Pulping and Beating Conditions on the Fibre and Paper Properties. *Ind. Crop. Prod.* **2019**, *141*, 111744. [CrossRef]
41. Brinchi, L.; Cotana, F.; Fortunati, E.; Kenny, J.M. Production of Nanocrystalline Cellulose from Lignocellulosic Biomass: Technology and Applications. *Carbohydr. Polym.* **2013**, *94*, 154–169. [CrossRef]
42. Quesada-Salas, M.C.; Vuillemin, M.E.; Dillies, J.; Dauwe, R.; Firdaous, L.; Bigan, M.; Lambertyn, V.; Cailleu, D.; Jamali, A.; Froidevaux, R.; et al. 1-Ethyl-3-Methyl Imidazolium Acetate, Hemicellulolytic Enzymes and Laccase-Mediator System: Toward an Integrated Co-Valorization of Polysaccharides and Lignin from Miscanthus. *Ind. Crop. Prod.* **2023**, *197*, 116627. [CrossRef]
43. Babicka, M.; Woźniak, M.; Bartkowiak, M.; Peplińska, B.; Waliszewska, H.; Zborowska, M.; Borysiak, S.; Ratajczak, I. Miscanthus and Sorghum as Sustainable Biomass Sources for Nanocellulose Production. *Ind. Crop. Prod.* **2022**, *186*, 115177. [CrossRef]
44. Roik, M.; Sinchenko, V.; Purkin, V.; Kvak, V.; Humentik, M. (Eds.) *Miscanthus in Ukraine*; FOP Yamchinskiy Press: Kyiv, Ukraine, 2019; ISBN 978-617-7804-11-5.
45. Beck, H.E.; Zimmermann, N.E.; McVicar, T.R.; Vergopolan, N.; Berg, A.; Wood, E.F. Present and Future Köppen-Geiger Climate Classification Maps at 1-Km Resolution. *Sci. Data* **2018**, *5*, 180214. [CrossRef] [PubMed]
46. Kottek, M.; Grieser, J.; Beck, C.; Rudolf, B.; Rubel, F. World Map of the Köppen-Geiger Climate Classification Updated. *Meteorol. Z.* **2006**, *15*, 259–263. [CrossRef] [PubMed]
47. FAO. *World Reference Base for Soil Resources 2014: International Soil Classification Systems for Naming Soils and Creating Legends for Soil Maps (Update 2015)*; World Soil Resources: Rome, Italy, 2014.
48. Vodyanitskii, Y.N. Equations for Assessing the Total Contamination of Soils with Heavy Metals and Metalloids. *Eurasian Soil Sci.* **2010**, *43*, 1184–1188. [CrossRef]
49. Pidlisnyuk, V.; Mamirova, A.; Newton, R.A.; Stefanovska, T.; Zhukov, O.; Tsygankova, V.; Shapoval, P. The Role of Plant Growth Regulators in *Miscanthus × giganteus* Growth on Trace Elements-Contaminated Soils. *Agronomy* **2022**, *12*, 2999. [CrossRef]
50. *275/1998 Sb*; Release of the Ministry of Agriculture Related the Agrochemical Testing of the Soils and Evaluation the Land Properties of the Forest Land (with Amendments 335/2017 Sb). Ministry of Agriculture: Prague, Czech Republic, 2017.
51. Stefanovska, T.; Skwiercz, A.; Pidlisnyuk, V.; Zhukov, O.; Kozacki, D.; Mamirova, A.; Newton, R.A.; Ust'ak, S. The Short-Term Effects of Amendments on Nematode Communities and Diversity Patterns under the Cultivation of *Miscanthus × giganteus* on Marginal Land. *Agronomy* **2022**, *12*, 2063. [CrossRef]
52. *ASTM E711-87*; Standard Test Method for Gross Calorific Value of Refuse-Derived Fuel by the Bomb Calorimeter (Re-Approved 2004). American Society for Testing and Materials: West Conshohocken, PN, USA, 2012; p. 9.
53. Sokólski, M.; Jankowski, K.J.; Załuski, D.; Szatkowski, A. Productivity, Energy and Economic Balance in the Production of Different Cultivars of Winter Oilseed Rape. A Case Study in North-Eastern Poland. *Agronomy* **2020**, *10*, 508. [CrossRef]
54. Jankowski, K.J.; Sokólski, M.; Szatkowski, A.; Kozak, M. Crambe—Energy Efficiency of Biomass Production and Mineral Fertilization. A Case Study in Poland. *Ind. Crop. Prod.* **2022**, *182*, 114918. [CrossRef]
55. Clements, D.R.; Weise, S.F.; Brown, R.; Stonehouse, D.P.; Hume, D.J.; Swanton, C.J. Energy Analysis of Tillage and Herbicide Inputs in Alternative Weed Management Systems. *Agric. Ecosyst. Environ.* **1995**, *52*, 119–128. [CrossRef]
56. Dubis, B.; Jankowski, K.J.; Załuski, D.; Bórawski, P.; Szempliński, W. Biomass Production and Energy Balance of Miscanthus over a Period of 11 Years: A Case Study in a Large-Scale Farm in Poland. *GCB Bioenergy* **2019**, *11*, 1187–1201. [CrossRef]
57. Muylle, H.; Van Hulle, S.; De Vliegher, A.; Baert, J.; Van Bockstaele, E.; Roldán-Ruiz, I. Yield and Energy Balance of Annual and Perennial Lignocellulosic Crops for Bio-Refinery Use: A 4-Year Field Experiment in Belgium. *Eur. J. Agron.* **2015**, *63*, 62–70. [CrossRef]
58. Roberts, K.G.; Gloy, B.A.; Joseph, S.; Scott, N.R.; Lehmann, J. Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential. *Environ. Sci. Technol.* **2010**, *44*, 827–833. [CrossRef] [PubMed]

59. West, T.O.; Marland, G. A Synthesis of Carbon Sequestration, Carbon Emissions, and Net Carbon Flux in Agriculture: Comparing Tillage Practices in the United States. *Agric. Ecosyst. Environ.* **2002**, *91*, 217–232. [CrossRef]
60. Nemecek, T.; Kägi, T.; Blaser, S. *Life Cycle Inventories of Agricultural Production Systems. Final Report Ecoinvent v2.0. Chapter 6. Agricultural Machinery. 6.2.7 Functional Unit and Application of the Modules*; EcoInvent Centre: Zürich, Switzerland, 2007; p. 360.
61. Angelini, L.G.; Ceccarini, L.; Nassi o Di Nasso, N.; Bonari, E. Comparison of *Arundo donax* L. and *Miscanthus* × *giganteus* in a Long-Term Field Experiment in Central Italy: Analysis of Productive Characteristics and Energy Balance. *Biomass Bioenergy* **2009**, *33*, 635–643. [CrossRef]
62. Jeżowski, S.; Mos, M.; Buckby, S.; Cerazy-Waliszewska, J.; Owczarzak, W.; Mocek, A.; Kaczmarek, Z.; McCalmont, J.P. Establishment, Growth, and Yield Potential of the Perennial Grass *Miscanthus* × *giganteus* on Degraded Coal Mine Soils. *Front. Plant Sci.* **2017**, *8*, 726. [CrossRef] [PubMed]
63. MECR. *Ministry of the Environment of the Czech Republic. Decree Laying down Detailed Rules for the Protection of Quality of Agricultural Land and Amending. Decree Specifying Some Details of Agricultural Land Resources Protection*; Ministry of the Environment of the Czech Republic (MECR): Praha, Czech Republic, 2016.
64. HS ES. Hygienic Standards for the Safety of the Environment (Soil). In *Order of the Minister of Health of the Republic of Kazakhstan dated April 21, 2021 No. RK DSM-32. Registered with the Ministry of Justice of the Republic of Kazakhstan on April 22, 2021 No. 22595*; HS ES: Astana, Republic of Kazakhstan, 2021.
65. *GOST 17.4.1.02-83 USSR*; Protection of the Environment. Soils. Classification of the Chemical Substances for the Control of Pollutants. StandardInform: Moscow, Russia, 1983.
66. Sudhakaran, M.; Ramamoorthy, D.; Savitha, V.; Balamurugan, S. Assessment of Trace Elements and Its Influence on Physico-Chemical and Biological Properties in Coastal Agroecosystem Soil, Puducherry Region. *Geol. Ecol. Landsc.* **2018**, *2*, 169–176. [CrossRef]
67. Bilandžija, N.; Zgorelec, Ž.; Pezo, L.; Grubor, M.; Velaga, A.G.; Krička, T. Solid Biofuels Properites of *Miscanthus* × *giganteus* Cultivated on Contaminated Soil after Phytoremediation Process. *J. Energy Inst.* **2022**, *101*, 131–139. [CrossRef]
68. Bilandžija, N.; Voća, N.; Leto, J.; Jurišić, V.; Grubor, M.; Matin, A.; Geršić, A.; Krička, T. Yield and Biomass Composition of *Miscanthus* × *giganteus* in the Mountain Area of Croatia. *Trans. FAMENA* **2018**, *42*, 51–60. [CrossRef]
69. Pidlisnyuk, V.; Zgorelec, Ž. Impact of Nutrients and Trace Elements in Soil on Plant Growth: Case of the Second-Generation Energy Crops. *Agronomy* **2022**, *12*, 2768. [CrossRef]
70. Ericsson, K.; Rosenqvist, H.; Nilsson, L.J. Energy Crop Production Costs in the EU. *Biomass Bioenergy* **2009**, *33*, 1577–1586. [CrossRef]
71. Hastings, A.; Mos, M.; Yesufu, J.A.; McCalmont, J.; Schwarz, K.; Shafei, R.; Ashman, C.; Nunn, C.; Schuele, H.; Cosentino, S.; et al. Economic and Environmental Assessment of Seed and Rhizome Propagated Miscanthus in the UK. *Front. Plant Sci.* **2017**, *8*, 1058. [CrossRef] [PubMed]
72. Mantziaris, S.; Iliopoulos, C.; Theodorakopoulou, I.; Petropoulou, E. Perennial Energy Crops vs. Durum Wheat in Low Input Lands: Economic Analysis of a Greek Case Study. *Renew. Sustain. Energy Rev.* **2017**, *80*, 789–800. [CrossRef]
73. Rodias, E.; Berruto, R.; Bochtis, D.; Busato, P.; Sopegno, A. A Computational Tool for Comparative Energy Cost Analysis of Multiple-Crop Production Systems. *Energies* **2017**, *10*, 831. [CrossRef]
74. Winkler, B.; Mangold, A.; von Cossel, M.; Clifton-Brown, J.; Pogrzeba, M.; Lewandowski, I.; Iqbal, Y.; Kiesel, A. Implementing Miscanthus into Farming Systems: A Review of Agronomic Practices, Capital and Labour Demand. *Renew. Sustain. Energy Rev.* **2020**, *132*, 110053. [CrossRef]
75. Witzel, C.-P.; Finger, R. Economic Evaluation of Miscanthus Production—A Review. *Renew. Sustain. Energy Rev.* **2016**, *53*, 681–696. [CrossRef]
76. Panoutsou, C.; Alexopoulou, E. Costs and Profitability of Crops for Bioeconomy in the EU. *Energies* **2020**, *13*, 1222. [CrossRef]
77. Soldatos, P. Economic Aspects of Bioenergy Production from Perennial Grasses in Marginal Lands of South Europe. *BioEnergy Res.* **2015**, *8*, 1562–1573. [CrossRef]
78. Wagner, M.; Mangold, A.; Lask, J.; Petig, E.; Kiesel, A.; Lewandowski, I. Economic and Environmental Performance of Miscanthus Cultivated on Marginal Land for Biogas Production. *GCB Bioenergy* **2019**, *11*, 34–49. [CrossRef]
79. CZSO. *The Development of the Czech Labour Market—1. Quarter of 2023*; Czech Statistical Office: Prague, Czech Republic, 2023; p. 6.
80. Harsono, S.S.; Grundman, P.; Lau, L.H.; Hansen, A.; Salleh, M.A.M.; Meyer-Aurich, A.; Idris, A.; Ghazi, T.I.M. Energy Balances, Greenhouse Gas Emissions and Economics of Biochar Production from Palm Oil Empty Fruit Bunches. *Resour. Conserv. Recycl.* **2013**, *77*, 108–115. [CrossRef]
81. Maroušek, J.; Strunecký, O.; Stehel, V. Biochar Farming: Defining Economically Perspective Applications. *Clean Technol. Environ. Policy* **2019**, *21*, 1389–1395. [CrossRef]
82. Nematian, M.; Keske, C.; Ng'ombe, J.N. A Techno-Economic Analysis of Biochar Production and the Bioeconomy for Orchard Biomass. *Waste Manag.* **2021**, *135*, 467–477. [CrossRef] [PubMed]
83. Shackley, S.; Sohi, S.; Ibarrola, R.; Hammond, J.; Mašek, O.; Brownsort, P.; Cross, A.; Prendergast-Miller, M.; Haszeldine, S. Biochar, Tool for Climate Change Mitigation and Soil Management. In *Geoengineering Responses to Climate Change: Selected Entries from the Encyclopedia of Sustainability Science and Technology*; Lenton, T., Vaughan, N., Eds.; Springer: New York, NY, USA, 2013; pp. 73–140, ISBN 978-1-4614-5770-1.

84. Aso, S.N. Digestate: The Coproduct of Biofuel Production in a Circular Economy, and New Results for Cassava Peeling Residue Digestate. In *Renewable Energy—Technologies and Applications*; IntechOpen: Rijeka, Croatia, 2020; ISBN 978-1-83881-001-6.
85. Huber, P.; Ossard, S.; Fabry, B.; Bermond, C.; Craperi, D.; Fourest, E. Conditions for Cost-Efficient Reuse of Biological Sludge for Paper and Board Manufacturing. *J. Clean. Prod.* **2014**, *66*, 65–74. [CrossRef]
86. Domini, M.; Abbà, A.; Bertanza, G. Analysis of the Variation of Costs for Sewage Sludge Transport, Recovery and Disposal in Northern Italy: A Recent Survey (2015–2021). *Water Sci. Technol.* **2022**, *85*, 1167–1175. [CrossRef] [PubMed]
87. Inpest.cz Roundup Klasik PRO. Available online: https://www.inpest.cz/postriky-na-plevele-v-bramborach/roundup-klasik-pro-20l (accessed on 30 June 2023).
88. Ceskybenzin.cz Ceny Benzínu a Nafty Jako na Dlani. Available online: https://www.ceskybenzin.cz/index.php?akce=okoli&pumpa=68&typ_palivo=3 (accessed on 19 August 2023).
89. Mangold, A.; Lewandowski, I.; Möhring, J.; Clifton-Brown, J.; Krzyżak, J.; Mos, M.; Pogrzeba, M.; Kiesel, A. Harvest Date and Leaf:Stem Ratio Determine Methane Hectare Yield of Miscanthus Biomass. *GCB Bioenergy* **2019**, *11*, 21–33. [CrossRef]
90. Kiesel, A.; Lewandowski, I. Miscanthus as Biogas Substrate—Cutting Tolerance and Potential for Anaerobic Digestion. *GCB Bioenergy* **2017**, *9*, 153–167. [CrossRef]
91. Suhartini, S.; Lestari, Y.P.; Nurika, I. Estimation of Methane and Electricity Potential from Canteen Food Waste. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *230*, 012075. [CrossRef]
92. Kononchuk, O.; Pidlisnyuk, V.; Mamirova, A.; Khomenchuk, V.; Herts, A.; Grycová, B.; Klemencová, K.; Leštinský, P.; Shapoval, P. Evaluation of the Impact of Varied Biochars Produced from *M.* × *giganteus* Waste and Application Rate on the Soil Properties and Physiological Parameters of *Spinacia oleracea* L. *Environ. Technol. Innov.* **2022**, *28*, 102898. [CrossRef]
93. Mangold, A.; Lewandowski, I.; Hartung, J.; Kiesel, A. Miscanthus for Biogas Production: Influence of Harvest Date and Ensiling on Digestibility and Methane Hectare Yield. *GCB Bioenergy* **2019**, *11*, 50–62. [CrossRef]
94. Kalabić, D.; Drazić, G.; Drazić, N.; Ikanović, J. Production of Agri-Energy Crop *Miscanthus* × *giganteus* on Land Degraded by Power Industry: SWOT Analysis. *Pol. J. Environ. Stud.* **2019**, *28*, 3243–3251. [CrossRef]
95. Liu, T.T.; McConkey, B.G.; Ma, Z.Y.; Liu, Z.G.; Li, X.; Cheng, L.L. Strengths, Weaknesses, Opportunities and Threats Analysis of Bioenergy Production on Marginal Land. *Energy Procedia* **2011**, *5*, 2378–2386. [CrossRef]
96. Paschalidou, A.; Tsatiris, M.; Kitikidou, K. Perennial vs Annual Energy Crops-SWOT Analysis (Case Study: Greece). *Int. Ref. J. Eng. Sci.* **2018**, *7*, 01–24.
97. FAO. *AQUASTAT Climate Information Tool*; FAO: Rome, Italy, 2023.