Article

Life Cycle Assessment of Giant Miscanthus: Production on Marginal Soil with Various Fertilisation Treatments

Michał Krzyżaniak [1,*] **, Mariusz J. Stolarski** [1] **and Kazimierz Warmiński** [2]

1   Department of Plant Breeding and Seed Production, Centre for Bioeconomy and Renewable Energies, University of Warmia and Mazury in Olsztyn, 10-719 Olsztyn, Poland; mariusz.stolarski@uwm.edu.pl

2   Department of Chemistry, Research Group of Environmental Toxicology, University of Warmia and Mazury in Olsztyn, 10-719 Olsztyn, Poland; kazimierz.warminski@uwm.edu.pl

*   Correspondence: michal.krzyzaniak@uwm.edu.pl; Tel.: +48-89-5246146

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Abstract: In Poland, unutilised land occupies approximately two million hectares, and it could be partly dedicated to the production of perennial crops. This study aimed to determine the environmental impact of the production of giant miscanthus (*Miscanthus* x *giganteus* J.M. Greef & M. Deuter). The experiment was set up on a low-fertility site. The crop was cultivated on sandy soil, fertilised with digestate, and mineral fertilisers (in the dose of 85 and 170 kg ha^{-1} N), and was compared with giant miscanthus cultivated with no fertilisation (control). The cradle-to-farm gate system boundary was applied. Fertilisers were more detrimental to the environment than the control in all analysed categories. The weakest environmental links in the production of miscanthus in the non-fertilised treatment were fuel consumption and the application of pre-emergent herbicide. In fertilised treatments, fertilisers exerted the greatest environmental impact in all the stages of crop production. The production and use of fertilisers contributed to fossil depletion, human toxicity, and freshwater and terrestrial ecotoxicity. Digestate fertilisers did not lower the impact of biomass production. The current results indicate that the analysed fertiliser rates are not justified in the production of giant miscanthus on nutrient-deficient soils.

Keywords: *Miscanthus* x *giganteus*; bioenergy; environmental impact; agricultural production; circular bioeconomy; digestate

1. Introduction

Giant miscanthus (*Miscanthus* x *giganteus* J.M.Greef & M.Deuter) is grown in Europe and the world as a source of biomass for bio-based industries. The species has a variety of applications, including in heat and power generation and the production of ethanol and construction materials [1–4]. Giant miscanthus yields are estimated at 10–20 Mg ha^{-1} dry matter (d.m.) per year, but they can range from 2.5 to 60 Mg ha^{-1} year^{-1} d.m., subject to climate and local environmental conditions [5–8].

Giant miscanthus can be cultivated on low-quality soils that are not suitable for growing food or fodder crops [9]. In Europe, marginal land covers around 64 million ha, of which nearly 54 million ha can be used for biomass production to promote sustainable development and protect the environment [10]. In Poland, unutilised agricultural (including arable land, meadow, pasture, orchard, arable land with trees or shrubs) land occupies an estimated area of two million ha and accounts for 14.2% of the total agricultural land [11]. Nearly half of the marginal land is not suitable for the cultivation of food and fodder crops, but it could be sown with crops for biobased products and biofuels. In Poland, low-quality soils are often deficient in organic matter and nutrients, and considerable inputs are required to restore their productive capacity. Agricultural inputs could be reduced using digestates

from agricultural biogas plants, which are problematic residues. The European Biogas Association reports that there are more than 18 thousand biogas plants in Europe [12]. The storage, disposal, and management of digestate pose a challenge for the biogas industry. Biogas digestates can be applied directly as fertilisers, but they can also be processed into fertilisers with a high content of carbon, nitrogen, and phosphorus [13–15]. Recycling as a fertiliser is considered to be the most sustainable utilisation of digestate, as it can provide benefits for society in general and the environment in particular, as well as to help the preservation of limited natural resources such as fossil resources of mineral phosphorus [16].

Research into the application of organic by-products for fertilising perennial plants on low-quality soils has been conducted at the University of Warmia and Mazury in Olsztyn for 10 years [17–20]. These efforts involved life cycle assessments of the environmental impact of lignocellulosic plants fertilised with processed digestates. Such assessments (LCA) have been performed for Virginia mallow (*Sida hermaphrodita* Rusby L.), a relatively under-utilised crop whose popularity continues to increase on account of its potential applications in the biofuel and energy sector [21–23]. This article presents a life cycle assessment of giant miscanthus, a plant species which is more widely cultivated than Virginia mallow. In Europe, the area under giant miscanthus is estimated at 40,000 ha, and Great Britain and Germany are the leading producers [24]. Therefore, the aim of this study was to determine the environmental impact associated with giant miscanthus cultivation on sandy soil, fertilised with biogas digestate and mineral fertilisers and compared with a non-fertilised treatment.

2. Materials and Methods

2.1. Goal, Scope and Functional Units

This attributional LCA aimed to determine the environmental impact of the production of giant miscanthus in treatments fertilised with digestate, in treatments supplied with mineral fertilisers and in non-fertilised treatment. The Attributional LCA modelling describes the environmentally relevant physical flows to and from a life cycle and its subsystems [25]. The cradle-to-farm gate system boundary was applied, and the functional units were 1 Mg of dry biomass and 1 GJ of energy from fresh biomass.

The system boundaries (Figure 1) covered the co-production of digestate in a biogas plant, conversion of digestate into fertilisers, mineral fertilisers, and equipment production.
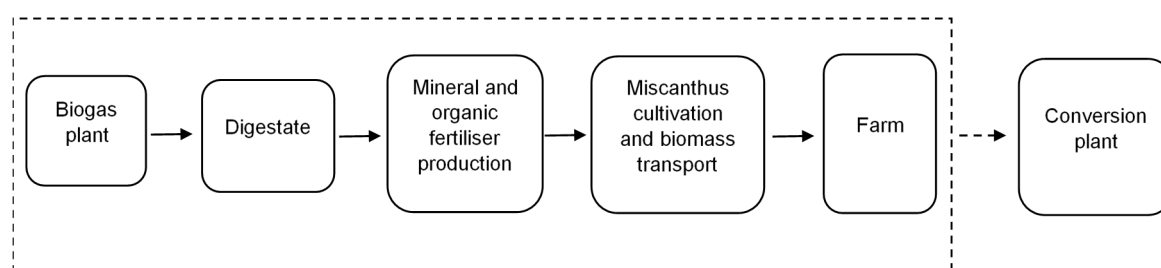

Figure 1. System boundaries for the cultivation, harvest, and transport of miscanthus.

2.2. Modelling and Data Sources

A life cycle inventory (LCI) was based on the results of field trials conducted in 2013-2015 at the UWM farm in Leginy. The trials were set up on a low-fertility site on sandy soil and contained 2.65% of organic matter. The contents of N-total, P_2O_5, K_2O in the soil were 0.08%, 129, and 104 mg kg^{-1}, respectively, and the soil pH was 5.3. More details on the site are described in Stolarski et al. [19]. The field operations performed for the plantation establishment and operation are presented in Table 1.

The study involved five treatments: wet digestate (WD), dry digestate (DD), torrefied digestate (TD), mineral fertilisation (MF), and non-fertilised treatment (base scenario/control—C). Digestate

fertilisers were applied at 85 and 170 kg ha^{-1} N, as described by [26]. Mineral N fertiliser was applied as ammonium nitrate at the same nitrogen rates; phosphorus and potassium fertilisers were applied at 30 kg ha^{-1} P$_2$O$_5$ and 60 kg ha^{-1} K$_2$O, as triple superphosphate and potassium salt. It was assumed that the miscanthus plantation lifetime was 15 years. It was assumed that the miscanthus biomass yield in the plantation lifetime would be equal to the average yield of this crop for the first three years of field experiments [19] multiplied by 15 years of operating the plantation. Energy yields were calculated from the product of fresh miscanthus biomass and its lower heating value (Table 2). The digestate used for fertiliser production was composed of 50% pig manure and 50% cattle manure. The conversion of digestate to fertilisers was described in Krzyżaniak et al. [26].

Table 1. Field operations.

Operation	Diesel Oil (kg ha^{-1})	Materials	Comments
Establishment and Closure of Plantation-Operations Performed Once per Plantation Lifetime			
Spraying	2.04	Glyphosate—Roundup 360 SL. 5 dm^3 ha^{-1}	
Disking	8.98		
Ploughing	29.30		5–ridge plough, ploughing depth—30 cm
Harrowing (x2)	11.20		2 operations
Planting	14.06	rhizomes 10,000 ha^{-1}	4-row planting machine, suitable for seedlings, rhizomes, or locally produced tubers
Mechanical weed control (3x)	21.09		3 operations
Plantation closure	44.65		Ploughing liquidating Miscanthus plantation after 15 years of its use (5–ridge plough. ploughing depth—30 cm)
Operations Performed Annually			
Application of wet digestate	12.86–25.94		Fertiliser inputs differed subject to fertilisation rate
Application of dry and torrefied digestate	7.03–14.06		Fertiliser inputs differed subject to fertilisation rate
Application of mineral NPK fertiliser	7.02		The lower and higher fertilisation rates were applied at the same time
Soil mixing with fertilisers	12.65		
Harvest	11.25–73.84		Subject to yield; average harvester capacity: 10 Mg h^{-1}
Biomass transport	37.2–57.7 (tkm)*		Subject to yield

* units in tonne-kilometre (tkm)

Table 2. Organic carbon (OC) contribution of digestates, dry biomass yield, and net energy yield during 15 years of miscanthus cultivation.

Fertilisation	N Rate (kg ha^{-1} N)	OC in Digestate (kg ha^{-1} C)	Biomass Yield (Mg ha^{-1} d.m.)	Net Energy Yield (GJ ha^{-1})
Wet digestate (WD)	85	750	33.3c	528
	170	1499	36.2 bc	576
Dried digestate (DD)	85	2515	40.8 abc	657
	170	5030	53.0 abc	855
Torrefied digestate (TD)	85	2786	47.0 abc	753
	170	5572	62.1 ab	1005
Mineral fertilisers (MF)	85	0	55.1 abc	867
	170	0	64.1 a	1014
Control (C)	0	0	54.9 abc	878

a, b, c letters mean that yields are statistically different (Tukey's test at $p < 0.05$)

Greenhouse gases (GHG) emissions were determined with the use of the methods described by [26]. In brief, GHG emissions associated with soil carbon sequestration and N_2O emissions were calculated with the below Equation (1):

$$E_{GHG} = -\frac{44}{12} \times SCS + GWP_{N_2O} \times \left(E_{direct\ N_2O} + E_{indirect\ N_2O} \right) \tag{1}$$

where: E_{GHG}—greenhouse gas emissions [kg ha^{-1} CO_2 eq.], SCS—soil carbon sequestration [kg ha^{-1} C], GWP_{N_2O}—global warming potential of N_2O, $E_{direct\ N2O} + E_{indirect\ N2O}$—direct and indirect emissions of N_2O [kg ha^{-1} N_2O], 44/12—CO_2/C molar ratio.

The GHG emission balance was determined on the assumption that CH_4 emissions equal zero because giant miscanthus was grown on non-waterlogged mineral soil. The nitrification and denitrification of nitrogen compounds in soil was the main source of N_2O emissions (direct emissions). The production of N_2O from the atmospheric deposition of NH_3 and NO_x volatilised from soils, N leaching, and runoff (indirect emissions), was also taken into account [27]. Soil carbon sequestration was adopted at 9.7% of the net C input [28]. The net C input was calculated from the difference between the amount of organic matter (OM) available to giant miscanthus (digestate and crop residues) and spring barley (cultivated in a conventional tillage system) with straw incorporated into the soil (as reference) [29,30]. The number of crop residues introduced to soil was calculated in the C-TOOL model [31]. The procedure of selecting parameters for the C-TOOL model was described by Krzyżaniak et al. [26]. The amount of OM introduced to soil with digestate was calculated based on the applied digestate rate and the carbon content of digestate determined with the CHS 500 elemental analyser (ELTRA GmbH, Germany).

The emissions of ammonia (NH_3), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOC), and particulate matter PM10, nitrate, and phosphate leaching were calculated according to the methods described in the authors' previous work [26].

2.3. Life Cycle Impact Assessment (LCIA)

A life cycle impact assessment of giant miscanthus was carried out using the ReCiPe Midpoint (H) method. This method is the successor of two popular methods, Ecoindicator 99 and CML-IA. The objective of the method is to transform the Life Cycle Inventory data into a limited number of indicator scores. ReCiPe can be used with two levels of indicators: midpoint (as in the authors' studies) and endpoint categories. Eight of eighteen impact categories were selected based on other studies on perennial crops [26,32,33]: climate change, human toxicity, particulate matter formation, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, and fossil depletion. Impact categories were normalised (Europe ReCiPe H/H) and recalculated per European citizen. The population of the EU28 was set at 464 million people.

3. Results and Discussion

3.1. Miscanthus Production without Fertilisation (Base Scenario)

The production of giant miscanthus in the base scenario was associated with net emissions of 33.83 kg CO_2 equivalents (eq.) per tonne of dry biomass (Table 3) (including the capture of 2.19 kg CO_2 eq.). Biomass harvest transport and plantation closure contributed most to the climate change category (Figure 2). The impact on human toxicity was 3.80 kg Mg^{-1} d.m.1,4-DB eq., and the main contributors were glyphosate use, biomass transport, and harvest (Table 3, Figure 2). Particulate matter formation reached 0.60 kg Mg^{-1} d.m. PM10 eq. Field emissions (mostly particulate matter from the soil) were mainly responsible for PM10 release. Fuel combustion associated with the operation of harvesting machines was the second-largest source of PM10 emissions. In the terrestrial acidification, emissions were determined at 0.31 kg Mg^{-1} d.m. SO_2 eq. and fuel combustion accounted for 64.7% of emissions in this category. Other contributors were plantation closure and biomass transport. Total

emissions in the freshwater eutrophication category reached 0.0034 kg P eq. per tonne of dry biomass (Table 3). The pre-emergent herbicide had the main impact, followed by biomass transport and biomass harvest. In the terrestrial ecotoxicity, the highest emissions (0.006 kg Mg^{-1} d.m. 1,4-DB eq. in total) were found for the production and use of pre-emergent herbicide, followed by fuel use for harvest. In the freshwater ecotoxicity category, total 1,4-DB emissions were determined at 0.169 kg Mg^{-1} d.m., where pre-emergent herbicide and biomass transport were the main contributors. Fossil depletion was determined at 12.42 kg Mg^{-1} d.m. oil equivalents, and it was associated mainly with harvest (Table 3, Figure 2). Fuel consumption contributed the most to fossil depletion during harvest and other field operations.

The results indicate that the use of pre-emergent herbicide and fuel consumption were the main contributors to all but one impact categories in the base scenario (C). Field operations contributed most to particulate matter formation.

3.2. Production of Giant Miscanthus with Fertilisation

GHG emissions associated with miscanthus production in the base scenario were determined at 33.8 kg Mg^{-1} d.m. The energy inputs per 1 GJ of produced biomass reached 2.1 kg CO_2 eq. (Figure 3). A notable increase in biomass yield was observed in treatments TD 170 and MF 170 (13% and 17%, respectively) relative to control (Table 2). In treatment MF 85, fertilisation increased miscanthus yield by only 0.4%. In the remaining treatments, biomass yields were 3–39% lower than for control. As a result, agricultural inputs did not induce a significant increase in yields but led to high GHG emissions per unit of biomass and energy (Figure 3). The environmental impact in the climate change category increased in every fertilisation treatment. The lowest increase (30%) in GHG emissions relative to control was noted in treatment TD 170. Greenhouse gas emissions were very high for both fertiliser rates in treatments WD and MF. The contribution of these treatments to climate change was 13- to 20-fold higher relative to the base scenario. Greenhouse gas emissions were lower for miscanthus produced without fertilisers than for Virginia mallow produced without fertilisers (95.9 kg Mg^{-1} d.m. CO_2 eq.) [26]. The above can be attributed to higher soil carbon sequestration in the miscanthus plantation, whereas in the production of Virginia mallow, the highest GHG emissions were associated with the depletion of soil organic matter. In the study of treatments, WD and MF were also associated with high emissions of greenhouse gases, but these emissions were lower in treatments TD and DD than in control, which can be attributed to higher yields and higher soil carbon sequestration [26]. In a study by Brandão et al. [34], GHG emission of giant miscanthus production was 707 kg ha^{-1} CO_2 eq. The analysis was performed for high yield values, which led to high carbon sequestration and emissions of 27.6 kg Mg^{-1} d.m. CO_2 eq. In an Irish study [35], the emissions from the production of miscanthus pellets in treatments with mineral and organic fertilisers were determined at 20.23 and 15.50 kg GJ^{-1} CO_2 eq., respectively, when biomass was transported over a distance of 50 km. GHG emissions reached 5.98 and 1.25 kg GJ^{-1} CO_2 eq., respectively, when biomass was not pelleted. Therefore, fertilisation with biosolids contributed far less to climate change. Other studies showed that perennial plants have higher soil carbon sequestration potential than annual plants, and their production in a biobased economy could minimise the adverse consequences of climate change [36].

Particulate matter formation was higher in all fertilisation treatments than for the control (Figure 4). Mineral fertilisation increased emissions 2–2.5-fold, whereas digestates increased its 3.7–6.2-fold. Field emissions contributed most to PM10 formation in all fertilisation treatments (61–84%). Particulate matter formation in miscanthus production with digestate and mineral fertilisers was 10–200% higher than in the production of Virginia mallow in the corresponding treatments [26].

Table 3. Environmental impact of miscanthus production without fertilisation (base scenario) per 1 Mg of biomass dry matter.

Impact Category	Unit	Total	Chemical Weed Control	Disking	Winter Ploughing	Harrowing	Planting	Mechanical Weeding	Harvest	Transport	Plantation Closure	Field Emissions
Climate Change	kg CO2 eq.	33.8	1.09	0.61	1.99	0.76	0.96	1.43	21.8	4.31	3.04	−2.19
Particulate Matter Formation	kg PM10 eq.	0.60	0.002	0.003	0.009	0.004	0.004	0.007	0.10	0.01	0.01	0.44
Terrestrial Acidification	kg SO$_2$ eq.	0.31	0.005	0.006	0.018	0.007	0.009	0.013	0.201	0.02	0.03	0
Freshwater Eutrophication	kg P eq.	0.003	0.002	0.00001	0.00005	0.00002	0.00002	0.00003	0.0005	0.001	0.0001	0
Human Toxicity		3.80	1.36	0.02	0.06	0.03	0.028	0.06	0.83	1.31	0.12	0
Terrestrial Ecotoxicity	kg 1,4-DB eq.	0.006	0.002	0.00005	0.0003	0.00006	0.0002	0.0001	0.002	0.0007	0.0003	0
Freshwater Ecotoxicity		0.17	0.12	0.0005	0.002	0.0006	0.0008	0.001	0.02	0.03	0.002	0
Fossil Depletion	kg oil eq.	12.42	0.41	0.21	0.69	0.26	0.33	0.50	7.55	1.43	1.05	0
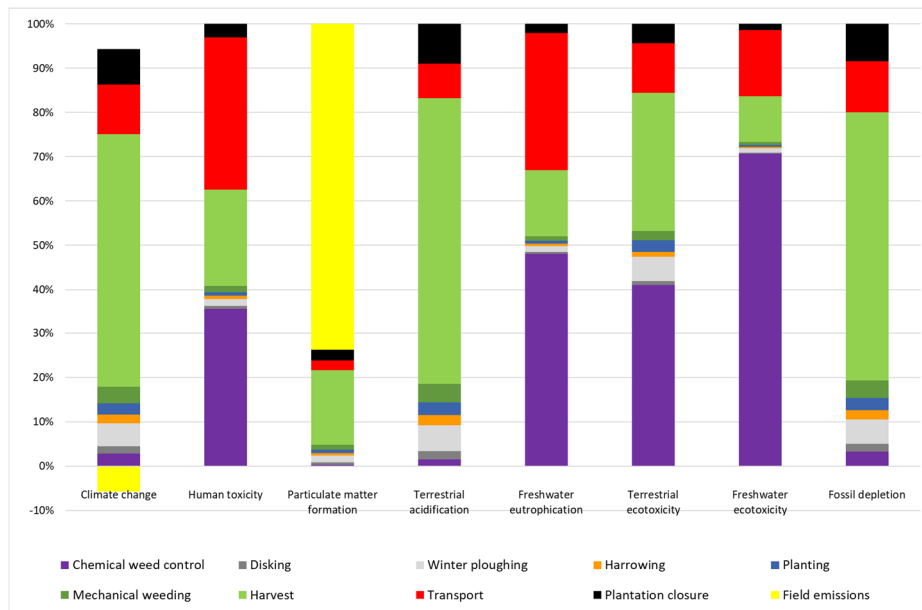
Figure 2. Contribution of miscanthus production processes in selected impact categories in the base scenario (control).
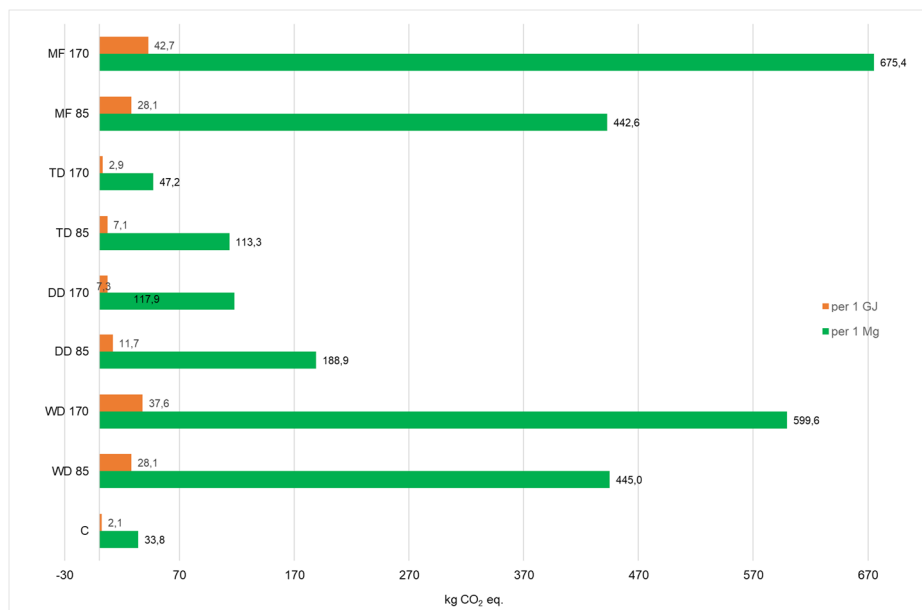

Figure 3. Greenhouse gases emission for miscanthus production in different fertilisation treatments.

Particulate matter emitted by agricultural facilities, soil, and farming operations is classified as pollution. The type, properties, and moisture content of soil as well as wind speed, significantly influence PM10 emissions associated with tillage and wind erosion. Dry, mechanically tilled soils with sparse vegetation cover have the highest dust-generating potential [37–39]. An increase in dust emissions was observed during tillage on biochar amended soils [40]. For this reason, no-till systems and perennial crops are more environmentally-friendly than annual crops produced in conventional systems [37]. Particulate matter emitted by agricultural soils contains far fewer toxic compounds (heavy metals, persistent organic pollutants) than that produced by fuel combustion, traffic, and industrial operations [41,42]. Agricultural operations also lead to the production of particulate matter from the combustion of diesel oil. These particulates penetrate the respiratory tract of humans and animals and are deposited in the pulmonary region of the lungs and exert adverse health effects [43].
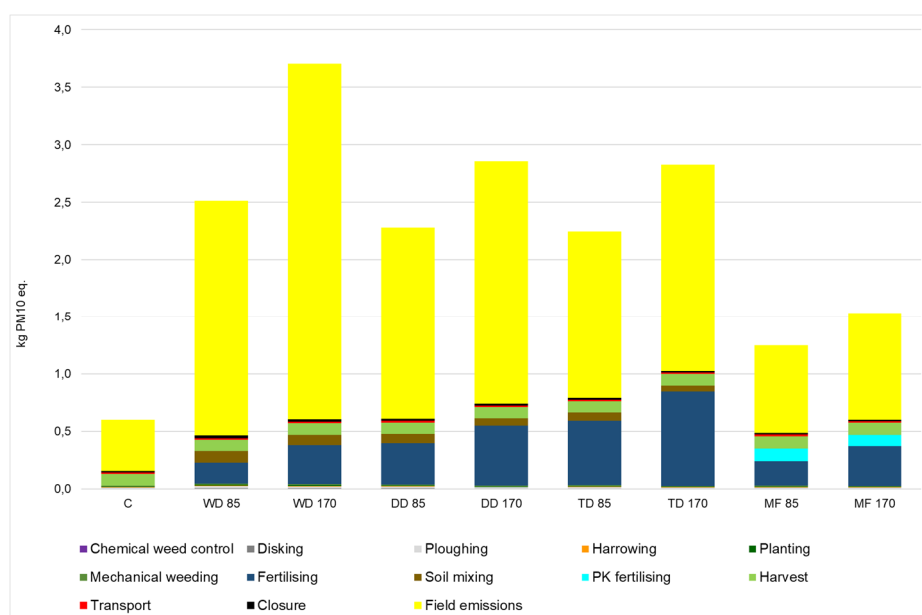
Figure 4. Particulate matter formation per 1 Mg dry matter (d.m.) of miscanthus in different fertilisation treatments.

Environmental impact of terrestrial acidification was lower in mineral fertilisation treatment than in all digestate treatments (Figure 5). Both digestate rates (85 and 170 kg N ha^{-1}) showed approximately 30-fold higher and 40- to 54-fold higher impact, respectively, relative to control. These emissions can be attributed to nitrogen leaching from the applied fertilisers (52–91% contribution). In other studies, acidification potential was determined at 0.59 kg Mg^{-1} d.m. SO$_2$ eq. for SRC willows [44], 0.91 kg Mg^{-1} d.m. SO$_2$ eq. for maize [45], and 1.10–1.32 kg Mg^{-1} d.m. SO$_2$ eq. for wheat with mineral fertilisation [33]. In the present study, the acidifying effect of digestate was considerably higher than in other experiments, which can be attributed mainly to higher crop yields (up to 10-times higher) in the other cited studies. In the current experiment, higher fertilisation rates did not increase yields compared with the control (except MF170 and TD 170 variants), and excess nitrogen was released as NH$_3$ and NO$_x$, compounds that contribute to acidification.
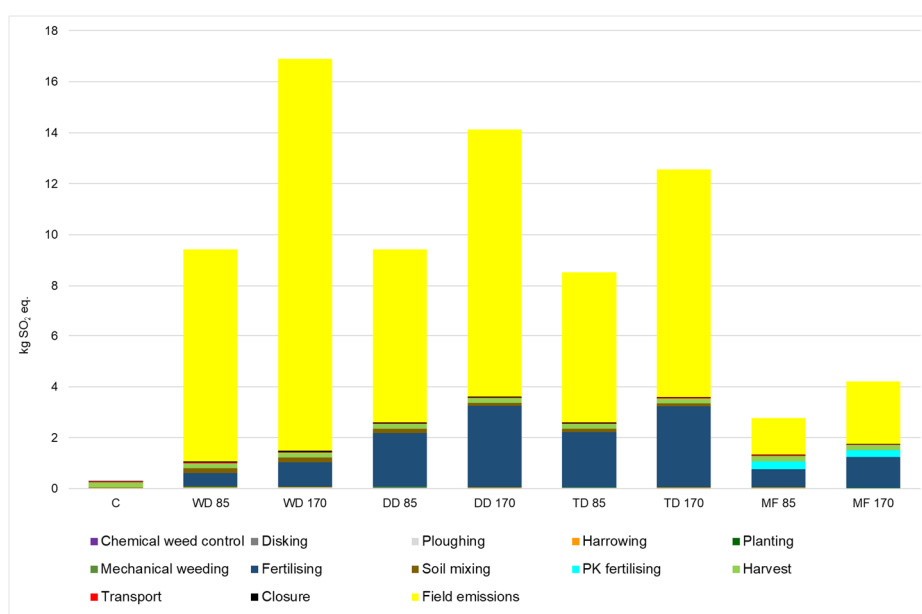

Figure 5. Terrestrial acidification per 1 Mg d.m. of miscanthus in different fertilisation treatments.

A significant portion of N and P applied to the soil with fertiliser and manure reaches freshwater systems and is transported by rivers to coastal areas, thus contributing to the eutrophication of groundwater, rivers, lakes, coastal, and marine ecosystems [46]. Fertilisation treatments contributed to this effect as well. The impact of WD 85 and WD 170 was 40–72 times higher than in the control, and N, and P leaching had the highest impact (86–94%) in this category (Figure 6). In contrast, in MF 170 and MF 85, the main contributor to freshwater eutrophication was triple superphosphate production (66–72%). Fertilised treatments emitted 9% (TD 170) to 203% (WD 170) more P equivalents.
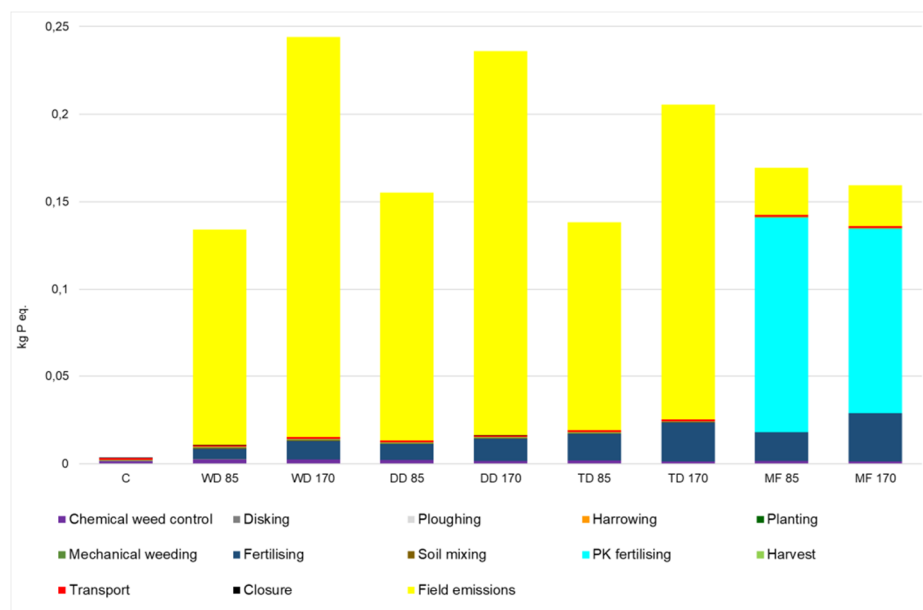
Figure 6. Freshwater eutrophication per 1 Mg d.m. of miscanthus in different fertilisation treatments.

In the authors' previous study of Virginia mallow, fertilisers (particularly various forms of digestate) also contributed to freshwater eutrophication [26]. Murphy et al. [35] found that the replacement of synthetic fertiliser with biosolids increased acidification potential by 290–400% and eutrophication potential by 258–300%. In a study by Stolarski et al. [19], higher fertilisation rates did not promote the growth of giant miscanthus, and higher yields were noted in the third year of the experiment in a plot without organic fertilisation. The authors also reported that fertilisation was practically unnecessary in the first year of the experiment. According to other researchers, nutrients released by decomposing leaves are re-circulated into the soil, and nitrogen is relocated to the rhizomes in winter, which is why giant miscanthus requires very little or no fertilisation. In this study, fertilisation did not compensate for low biomass yields on nutrient-deficient soils, which led to low nutrient availability, nutrient leaching, and considerable freshwater eutrophication.

Every fertilisation treatment had a higher environmental impact on human toxicity than the control. Both fertilisation rates in treatments WD and DD were the least detrimental to the environment relative to control (Figure 7). The associated emissions were approximately 4–6 times higher than in the control. The greatest contributors were the production of equipment in treatment WD and digestate drying in treatment DD. The impact of treatment MF was 12–16 times higher than C, and the production of nitrogen and phosphorus mineral fertilisers were the greatest contributors. Treatment TD was most detrimental to the environment, with a negative impact 24 and 35 times higher than in C. The emissions in TD 85 and TD 170 were determined at 90.7 and 132.6 kg Mg^{-1} d.m. 1,4-DB eq., respectively.

In the terrestrial ecotoxicity category, the emissions in TD 85 and TD 170 were 86 and 129 times higher, respectively, than in the control (Figure 8). In those variants, wood was used as fuel for digestate torrefaction. It was also assumed that wood ash (contaminated with heavy metals) was used to fertilise agricultural land, which significantly contributed to terrestrial ecotoxicity. The emissions in WD and

DD were 2–3 times higher than in C, and the greatest contributors were the production and use of diesel oil for fertilisation, followed by the application of glyphosate in weed control. The impact of mineral fertilisers on terrestrial ecotoxicity was four and five times higher (MF 85 and MF 170, respectively) relative to the control. In these treatments, N fertilisation (mainly ammonium nitrate production) was responsible for 51–66% of the impact.
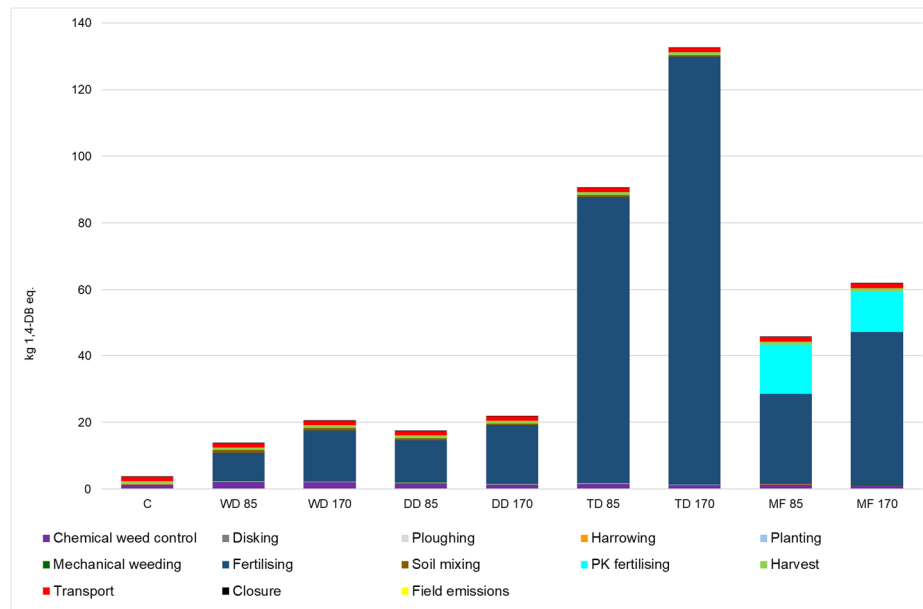

Figure 7. Human toxicity per 1 Mg d.m. of miscanthus in different fertilisation treatments.
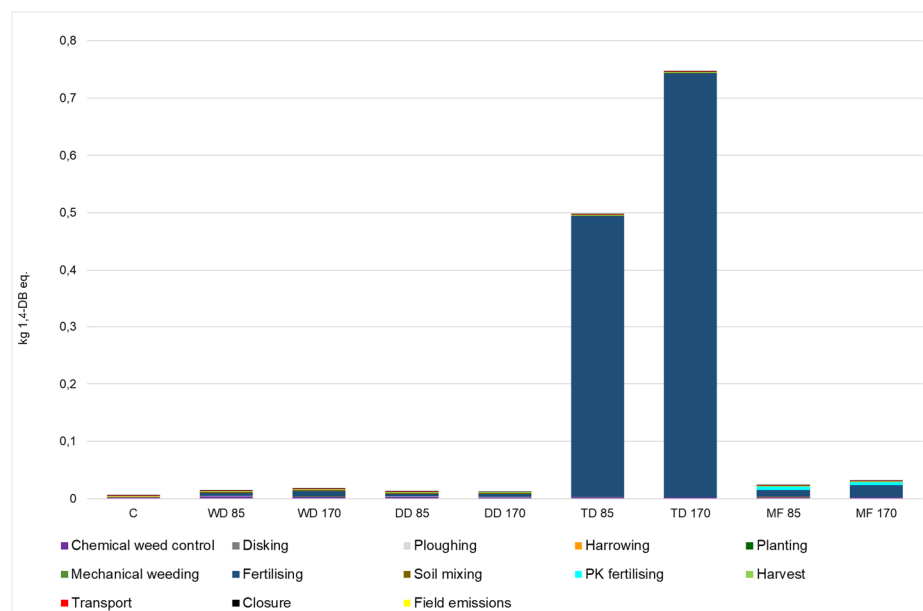
Figure 8. Terrestrial ecotoxicity per 1 Mg d.m. of miscanthus in different fertilisation treatments.

The freshwater ecotoxicity impact associated with the production of giant miscanthus in treatments with digestate utilisation was 2.5–4.7 higher than in the control (Figure 9). The adverse effects of digestate increased in a linear manner with an increase in fertilisation rate as well as digestate drying and torrefaction. Treatments MF 85 and MF 170 were five and six times more detrimental to the environment, respectively, relative to the control. Ammonium nitrate and triple superphosphate

production (in N fertilising and PK fertilising processes (Figure 9) were the main contributors in this impact category (80–85%) followed by chemical weed control.
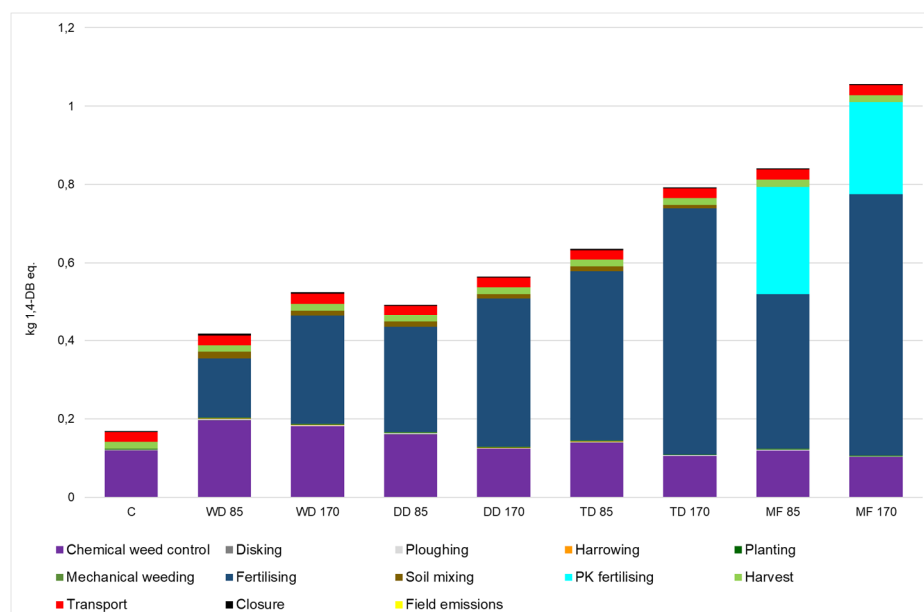

Figure 9. Freshwater ecotoxicity per 1 Mg d.m. of miscanthus in different fertilisation treatments.

Similar results were noted for Virginia mallow in all toxicity categories, but the environmental impact of giant miscanthus production per 1 Mg of dry biomass was higher than for Virginia mallow. This was particularly visible in treatments WD 170, DD 85, and DD 170, whose environmental impact in all three toxicity categories was 60–90% higher [26]. The human and terrestrial toxicity of poplar supplied with mineral fertilisers was lower or similar to that noted in the authors' study in the base scenario and treatments WD and DD [47]. However, the effects of treatments TD and MF on human and terrestrial toxicity were significantly higher than in the referenced experiment.

All fertilisation treatments contributed more to fossil depletion than the control (Figure 10). In the group of digestate treatments, WD 170 exerted the most adverse impact. Treatment WD was characterised by the lowest yield, which also contributed to its adverse environmental effect per tonne of dry biomass. The influence of TD and DD on fossil depletion was approximately three times higher than the base scenario. In all stages of miscanthus production, fertilisation contributed most to fossil depletion and ranged from 41% (WD) to 84% (TD). Diesel use during harvest was also an important contributor. In a life cycle assessment of two oilseed crops (camelina and flax), fertiliser production also exerted the greatest effect on fossil depletion [48]. In the authors' previous study, diesel consumption was the greatest energy input in the production of giant miscanthus [19]. Similar results were noted in this study and the authors' previous study on Virginia mallow. In addition, high fossil depletion occurred in the production of mineral fertilizers. However, in the production of digestate fertilizer (drying), heat from biogas production was used, thanks to which fewer fossil resources were used per one tonne of miscanthus dry matter [26].

The normalisation results of the LCIA per tonne of giant miscanthus dry biomass per European citizen are presented in Figure 11. The impact category with the highest normalised score was freshwater eutrophication. Treatment WD 170, followed by treatments DD 170 and TD 170, was characterised by the most adverse environmental impact. Digestates also significantly contributed to terrestrial acidification. Variants MF 85 and MF 170 contributed less to terrestrial acidification than to freshwater eutrophication. In the particulate matter formation category, digestate treatments also exerted a more adverse impact than mineral fertilisers. The average normalised score was lower in the human toxicity category than

in the particulate matter formation category, but treatments TD 86 and TD 170 were characterised by similar high scores.
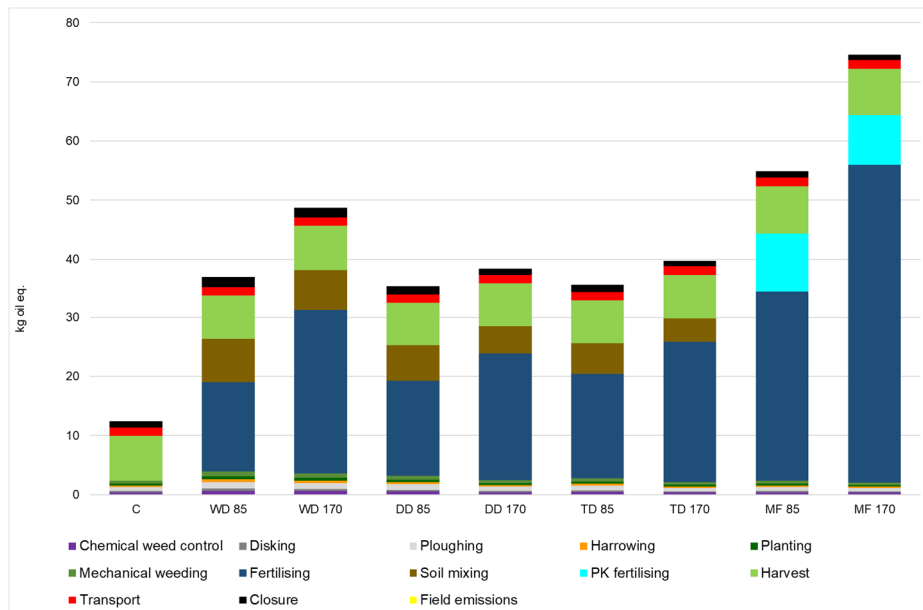

Figure 10. Fossil depletion per 1 Mg d.m. of miscanthus in different fertilisation treatments.
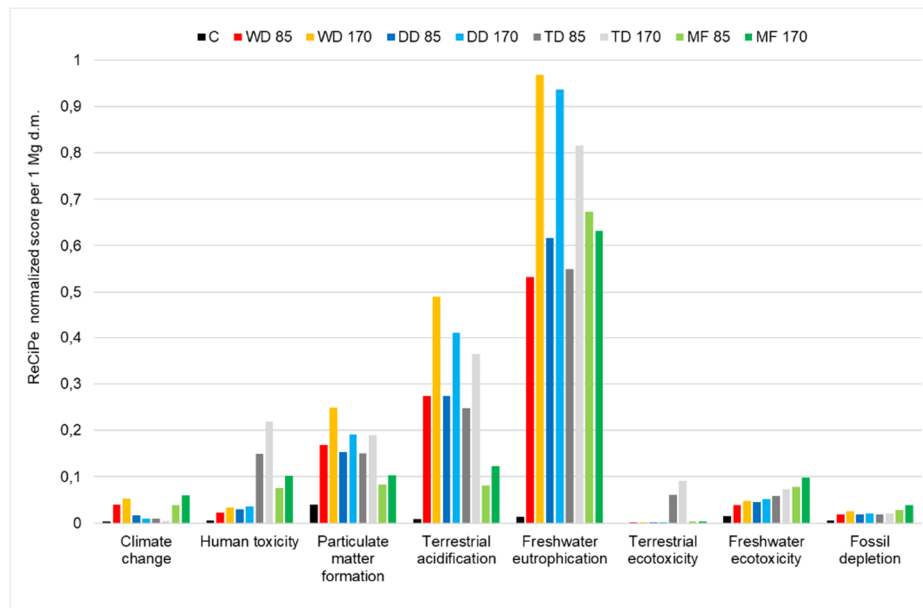

Figure 11. Normalisation scores for giant miscanthus production with the ReCiPe method (hierarchical version with European normalisation).

Low scores in fossil depletion and climate change categories are very important considerations in a circular economy and the renewable energy sector because they point to low consumption of diesel oil and fossil fuels as well as low GHG emissions. A similar sequence of normalised scores was noted in the authors' study of Virginia mallow. The production of Virginia mallow had the greatest influence on freshwater eutrophication than other impact categories. However, due to higher yields, the normalised score (environmental impact) for Virginia mallow was up to 52% lower in comparison with giant miscanthus [26]. In an LCA of poplars supplied with mineral fertilisers and lignin (a residual product

in the process of paper production) as a soil amendment, the normalised score was also highest in the freshwater eutrophication category [47].

4. Conclusions

The study found that the environmental impact of miscanthus fertilisation in all impact categories was higher in comparison with the base scenario (no fertilisation). In the base scenario, the highest energy inputs were associated with the consumption of diesel and the application of pre-emergent herbicide for weed control. The environmental impact of non-fertilised treatment could be reduced by deploying less energy-intensive machines and improving the logistic chain.

In fertilised treatments, the production and application of fertilisers were the weakest links in the biomass production process. Fertiliser production and fuel consumption were the weakest links in fossil depletion, human toxicity, freshwater, and terrestrial ecotoxicity categories. In particulate matter formation, freshwater eutrophication, and terrestrial acidification categories, field emissions contributed most to total emissions. These findings were confirmed by normalised scores, which demonstrated that fertilisation had the greatest impact on freshwater eutrophication and terrestrial acidification. The climate change score was relatively low in all fertilisation treatments.

It can be concluded that the application of fertilisers in the production of giant miscanthus on sandy soil did not increase yields and did not reduce environmental impact per tonne of biomass. The results of this study indicate that fertilisation is not justified in giant miscanthus plantations established on poor soils. Lower fertilisation levels could be applied, but further research is needed to determine the most effective rates. The presented results apply only to giant miscanthus grown under the described conditions in a temperate climate, and more favourable outcomes could be expected on higher-quality soils and in a warmer climate, which is generally preferred by giant miscanthus. Therefore, further field trials are required to confirm and expand on the presented findings.

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