

Article

Pellet Production from Miscanthus: Energy and Environmental Assessment

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Abstract: The production of wood pellets has grown considerably in the last decades. Besides woody biomass, other feedstocks can be used for pellet production. Among these, miscanthus presents some advantages because, even if specifically cultivated, it requires low inputs such as fertilisers and pesticides and shows high biomass yield (up to 28 tons of dry matter ha^{−1} in Europe). Even if in the last years some studies evaluated the environmental impact of woody pellet production, there is no information about the environmental performances of miscanthus pellet production. In this study, the environmental impact of miscanthus pellet was evaluated using the Life Cycle Assessment approach with a cradle-to plant gate perspective. Primary data were collected in a small-medium size pelletizing plant located in Northern Italy where miscanthus is cultivated to be directly processed. The results highlight how the miscanthus pellet shows lower environmental impact compared to woody pellet, mainly due to the lower energy consumption during pelletizing. The possibility to pelletize the miscanthus biomass without any drying offsets the environmental impact related to the miscanthus cultivation for all the evaluated impact categories (except for Marine eutrophication). In detail, for global warming potential, 1 ton of miscanthus pellet shows an impact of 121.6 kg CO₂ eq. (about 8% lower respect to woody pellet) while for the other evaluated impact categories the impact reduction ranges from 4 to 59%. Harvesting, which unlike the other field operations is carried out every year, is by far the main contributor to the impacts of the cultivation phase while electricity is the main contributor to the pelletizing phase.

Keywords: life cycle assessment; miscanthus; pellets; lignocellulosic biofuels



Citation: Fusi, A.; Bacenetti, J.; Proto, A.R.; Tedesco, D.E.A.; Pessina, D.; Facchinetti, D. Pellet Production from Miscanthus: Energy and Environmental Assessment. *Energies* **2021**, *14*, 73. <https://dx.doi.org/10.3390/en14010073>

Received: 1 December 2020

Accepted: 22 December 2020

Published: 25 December 2020

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1. Introduction

The interest about renewable energy is increasing. The current consumption of energy from fossil sources involves environmental concerns due to its contribution to the GHG emissions [1,2]. In the last decades, thanks to favorable subsidy frameworks, the share of renewable energy has increased [3–5]. However, more attention was paid on electricity production [6]. For example, in Europe 29 countries foresee a feed-in-tariff for the electric energy produced from renewable sources [7–9]. Regarding the heat, the subsidy framework to promote the production of renewable heat are less widespread even if the production of heat from renewable sources (e.g., biomass) is a well-known solution.

Woody biomass is historically used as energy source to produce heat mainly at household level. Among the woody biomass the pellet presents several advantages. It has higher density compared to wood chips and logs. Furthermore, pellet can be easily handled also in urban and semi urban areas, thanks to the size of the single pellet piece it can be moved with augers and, consequently, it can be efficiently dosed during the feeding of boilers.

Besides this, the pellet shows stable physic-chemical characteristics (size, moisture and ash content, heating value, etc.) due to a quite standardized production process and to the recently introduced standards [10–12]. Thanks to these features, pellet boilers reach high energy efficiency even when the combustion takes place in small-size boilers [13,14]. On the other hand, pelletizing, for the pressing, requires biomass with a moisture content lower than 11–12% and, consequently, requires energy for biomass drying [15]. From an economic point of view, the cost of pellet is higher than that of wood logs and chips.

The global demand for pellet is growing up and, consequently, even its production. Global wood pellet production has increased significantly at around 14% per year since 2011 [16,17] and in 2018 was estimated at 52.7 million tonnes with a global value of 8.88 billion of USD [18]. The large consumers are European countries, Japan and South Korea while USA is the major wood pellet producer and exporter to the European Union [19].

Concerning the biomass suitable for pellet production, as stated before, the most widely used is the woody one coming from forestry [17–21] and secondarily from agricultural activities (e.g., pruning residues) [13–22]. Nevertheless, also perennial herbaceous energy crops such as miscanthus (*Miscanthus x giganteus*), red canary grass (*Phalaris arundinacea* L.) and common reed (*Arundo donax* L.) can be suitable [23,24]. These crops produce biomass with a lower quality (i.e., higher ash content) respect to woody species but show higher biomass productivity [23]. In particular, miscanthus, originating from East Asia, has been considered a promising perennial gramineous C₄ plant for the bioenergy industry [25]. For this crop, chemical composition and conversion efficiency of lignocellulosic biomass are key factors allowing high biomass production. Reported dry matter yields of *M x giganteus* biomass range from 8 to 44.1 t ha^{−1} [26–29]. Regarding South Europe, Bilandžija et al. [30], recorded in Croatia a yield ranging from 21.90 to 28.51 t/ha while, in Italy, Angelini et al. measured a yield of 28.7 t/ha [24].

The choice of the biomass source can deeply affect the environmental impact of the produced pellet. Over the years, the life cycle assessment approach has been applied more and more for environmental impact evaluation and it is a well-recognised and widely accepted evaluation method [31,32]. LCA approach allows the quantification of the potential environmental impacts related to the life cycle of a product, a process, or a service; it is defined by two ISO standards (14,040 and 14,044) (ISO, 2006). Even if originally developed for industrial processes, LCA is year after year applied also to agricultural and agro-energy processes [21,22,33,34].

Even if, in the last years, some LCA studies about the environmental performances of pellet in Spain [35], Italy [36,37], Finland [38], Thailand [17] and China [39,40] were carried out, up to now there are no studies quantifying the environmental impact of miscanthus pellet. In fact, despite some attention was paid on the last years to the environmental impact of pellet [41–44], up to now, the environmental impact of pellet produced from miscanthus was not investigated.

This study aims to assess the environmental performances of pellet production using miscanthus biomass and to compare the results with the ones related to woody pellet. To this purpose the LCA approach was applied to data collected about a small-medium size pellet production plant located in Northern Italy. To avoid the impact shifting among environmental effects and to get a broad picture of the environmental performance of miscanthus pellet, 15 midpoints impact categories were considered.

2. Materials and Methods

2.1. Description of Production System

The pellet production chain can be divided into two steps: the cultivation of miscanthus and its pelletizing. The cultivation cycle of miscanthus lasts about 15 years: the activity is mainly concentrated in the planting year and in a series of periodic tasks. Ploughing is firstly carried out, followed by harrowing. The rhizomes are buried with a semi-automatic transplanter, with a density of 15,000 plants/ha, at a depth of 7–10 cm and with distances of 0.75 m on the row and 0.9 m between the rows. Fertilization and pesticides applications are

not usually performed; the crop benefits from the capture of atmospheric nitrogen (about $50 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ [45]).

The miscanthus cultivation area considered in this paper benefits from an average annual rainfall of 805 mm/year. Furthermore, to reduce the risk of failures due to drought, one irrigation is carried out in the first cultivation year during the summer. In addition, as regards the water supply, in the case investigated the crop benefits from a significant contribution from the surface aquifer, being located near the floodplain of the Serio river.

Harvesting is performed yearly, in early spring, when the dry matter content of the biomass is around 90% and after the leaves fall, which add nitrogen to the soil thanks to their decomposition. A self-propelled forage harvester is used, cutting and shredding the miscanthus stalks, then conveying them into trailers coupled to tractors for transporting the biomass to the pelletizing plant (average distance 1.5 km). At the end of the crop cycle, and before the intervention of the stalk chopper, an herbicide treatment is carried out to cancel the resprouting capacity of the miscanthus rhizomes.

In the farm, the biomass is temporarily stored under a canopy, then loaded onto two platforms for transfer via a conveyor belt to a disc separator, which removes larger foreign material. The sieved biomass is then stored in a hopper and later conveyed by means of an auger first to a magnet for the separation of ferrous materials and then to a mill for grinding. The dust produced during grinding is intercepted thanks to a cyclone dust collector and subsequently in a bag filter. A further conveyor transports the milled biomass to the pelletizing press, on which a second bag filter separates the dust produced. After a passage on a bucket elevator with counter-current air for cooling, the pellet is further sifted and finally packaged in big bags. Since the miscanthus has a humidity of 10% upon harvesting, no supplementary drying is required before pelletizing. The produced pellet is directly sold to the citizens and/or local dealers.

2.2. Goal and Scope Definition

The goal of this study is assessing the environmental performances of miscanthus pellet produced in a small size pelletizing plant located in Northern Italy ($45^{\circ}38'0'' \text{ N}$, $9^{\circ}46'0'' \text{ E}$). Taking into account that the pellet consumption is increasing in Italy and that the Italian production doesn't satisfy the demand, the local production of pellet from alternative biomass sources is interesting and can be useful for a further development of local production chains.

The outcomes of this LCA can be used to select suitable raw materials for pellet production, to compare pellet produced from different biomass sources and to identify solutions for an effective reduction of the environmental impacts of pellet production.

Even though the geographical scope of this study is Northern Italy, the findings and insights of this study will supply a new reference to future improvement of pellet production from miscanthus or other types of lignocellulosic herbaceous crops (e.g., *Arundo donax* L.) in areas with similar climate and productive conditions. Moreover, the outcomes of this study can be used to develop the processes and logistics of pellet production for other regions as well.

2.2.1. Functional Unit

According to the ISO 14040 "The functional unit is a key element of LCA which has to be clearly defined. The functional unit is a measure of the function of the studied system and it provides a reference to which the inputs and outputs can be related".

In this study, 1 t of miscanthus pellet packed was selected as functional unit; however, to ease the comparison with pellets produced from different biomass sources, also the calorific value (1 GJ) was taken into account as additional functional unit. The consideration of a mass-based functional unit has also been considered in previous LCA studies available in the literature [22,31,43] together with energy-based functional unit allowing the comparison with alternative production systems independently of the feedstock used [40–42].

2.2.2. System Boundary

In this study the LCA approach was applied with a “from cradle to gate” perspective; consequently, all the processes from the raw material extraction to the pellet packaging at the pelletizing plant were included in the system boundary. A “cradle to gate” approach has been widely used in LCA studies focused on renewable energy production from woody biomass [21,22,35].

More in detail, the following steps of the pellet production chain were included: manufacturing of the different production factors consumed (rhizome, fuel, pesticides, maize starch, packaging material), manufacturing maintenance and disposal of capital goods (tractors and operative machines used during miscanthus cultivation, devices and infrastructures of the pelletizing plant) while the steps of distribution, use and end-of-life of pellet were excluded. Regarding the cultivation of miscanthus, the emissions included in the system boundary refer to the combustion of fuel in the tractors and machine engines, the application of pesticides and the nitrogen and phosphorous cycles. No change in soil organic carbon content was considered in accordance with previous studies on perennial energy crops cultivated on arable land [46,47].

Figure 1 shows the considered system boundaries.

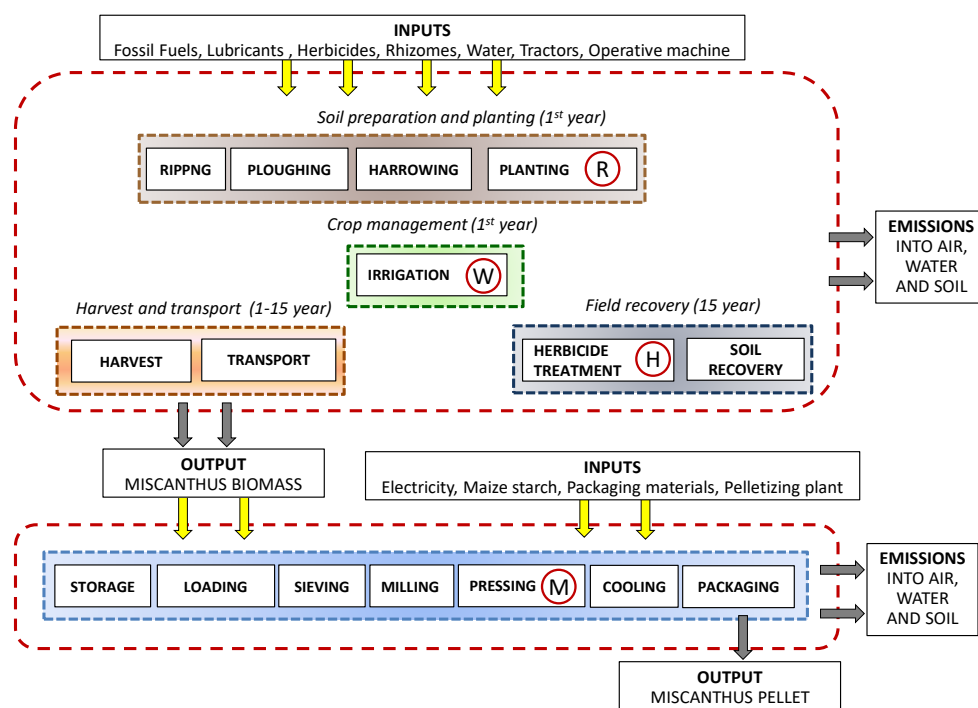


Figure 1. System boundary for the cradle to gate life cycle assessment of miscanthus pellet production (R = rhizomes, W = water, H = herbicide, M = maize starch).

2.3. Inventory Analysis

Primary data about miscanthus cultivation and pellet production were collected by surveys and interviews with the agronomist of the farm as well as with the manager of the pelletizing plant. About the cultivation of miscanthus the primary data collected refer to: the cultivation practice (timing and repetitions of field operations), the mechanization (characteristics of tractors and operative machines, working time), production factors consumption (fuel, lubricating oil, rhizomes, herbicides, water) and yield. Table 1 reports the main inventory data regarding the cultivation of miscanthus.

Table 1. Main inventory data about miscanthus cultivation.

Operation	Year	NN ^[1]	Tractor	Operative Machine		FC ^[2] kg ha ⁻¹	Note
			Mass Power	Type, Main Characteristics (Mass)	Time h ha ⁻¹		
Primary soil tillage with ripper	1	1	7800 kg 140 kW	Ripper, 3 anchors, 40 cm depth (1900 kg)	0.83	35.6	
Primary soil tillage ploughing	1	1	7800 kg 140 kW	Ploughing, 4 furrows, 35 cm depth, (1050 kg)		25.7	
Secondary soil tillage harrowing	1	2	5600 kg 100 kW	Rotary harrow, 5 m width (2250 kg)		22	
Transplanting	1	1	5600 kg 100 kW	Transplanter (1250 kg)	2	25	15,000 rhizomes ha ⁻¹
Irrigation	1	1		Pump 240 kW	2	70	400 m ³ ha ⁻¹
Harvesting	From 1 to 15	1	-	Forager 460 kW (13,150 kg)	0.35	33.3	^[3]
Transport	From 1 to 15	1	7800 kg 140 kW	Trailer, 30 m ³ (2200 kg)	0.7	10	1.5 km
	From 1 to 15	1	5600 kg 100 kW	Trailer, 30 m ³ (2200 kg)	0.7	10	
Chemical weeding	15	1	4000 kg 65 kW	Sprayer, 24 m width (600 kg)	1.0	3.3	10 L·ha ⁻¹ ^[4]
Stumps chopping	15	1	5600 kg 100 kW	Stalk-chopper, 3 m width (1250 kg)	0.6	15	

^[1] NN = number of interventions per year; ^[2] FC = fuel consumption; ^[3] Biomass yield 10 t ha⁻¹ the 1st year, 15 t ha⁻¹ the 2nd year then 20 t ha⁻¹ (10% of moisture content); ^[4] Glyphosate (360 g·L⁻¹ of active ingredient).

Concerning the biomass processing (pelletizing), direct data about the produced pellet were collected, the consumption of energy and other materials (packaging film, maize starch, etc.). Laboratory tests were performed to determine the main characteristics of the produced pellet. More in detail, in accordance to the standardized technical rules, miscanthus pellet samples were collected and analyzed in order to assess the moisture content, the ash content, the pellet durability indices (PDI) and the heating value (EN 18134-1:2015; EN ISO 18122:2015; EN ISO 18125; UNI EN 15210-1) [48–50]. In addition, the percentages of carbon, hydrogen, and nitrogen were determined in accordance with the norm ISO 16948:2015 [51] using a Costech ECS 4010 CHNS-O elemental analyzer. Table 2 reports the main information about the pellet production while Table 3 shows the results regarding the laboratory tests. The miscanthus pellet is characterized by moisture content lower than 10% and by a Heating Value (HHV and LHV) that is lower respect to the woody pellet (18 GJ/ton) [40] but higher than the one produced by orchard pruning residues (16.74 GJ/ton) [52].

Table 2. Life cycle inventory data for miscanthus pellet production.

Process/Activity	Unit	Amount
Input		
Chopped miscanthus	kg·kg of pellet ⁻¹	1.11
Maize starch	g·kg of pellet ⁻¹	5
Electricity	kWh·kg of pellet ⁻¹	0.204
Packaging film	MWh·year ⁻¹	224
Output	G·kg of pellet ⁻¹	2.28
Wood pellet	Ton·year ⁻¹	1103

Table 3. Results of the laboratory test about pellet characterization.

Moisture Content	Ash	Higher Heating Value	Lower Heating Value	C	H	N	O	Pellet Durability Index
8.29%	2.94%	18.64 MJ·kg ⁻¹	17.80 MJ·kg ⁻¹	45.40%	4.10%	1.34%	46.25%	94.6%

Secondary data for the miscanthus cultivation refer to:

- the emission related to the fuel combustion in the tractor engines modelled according to Nemecek and Kägi [53] and Lovarelli and Bacenetti [54,55];
- the emissions related to the nitrogen and phosphorous compounds in the soil estimated following the IPCC guidelines [56] and Prasuhn [57];
- the emissions of active ingredient of pesticides considered completely released into the soil according to Rivera Schmidt et al. [58].

Background data for the production of diesel fuel, rhizomes, pesticide, electricity, tractors and agricultural machines, maize starch, packaging materials and the pellet producing plant were obtained from the Ecoinvent database[®] v.3.6 [59]. The list of the processes retrieved from the Ecoinvent database is detailed in Table 4.

Table 4. List of processes retrieved by the databases.

Process Retrieved from Database	Note
Tractor, 4-wheel, agricultural {GLO} market for APOS, U	Used to build soil tillage, planting, soil restoring and transport ^[1]
Diesel {CH} market for APOS, U	Used to build the different field operations ^[1]
Agricultural machinery, tillage {GLO} market for APOS, U	Used to build the process soil tillage, planting, and stump chopping ^[1]
Agricultural machinery, unspecified {GLO} market for APOS, U	Used to build herbicide application ^[1]
Harvester {GLO} market for APOS, U	Used to build the harvesting operation ^[1]
Agricultural trailer {GLO} market for APOS, U	Used to build the process the transport operation ^[1]
Lubricating oil {RER} production APOS, U	Used in the different field operations as well as at the pelletizing plant ^[1]
Shed {GLO} market for APOS, U	Used to build the different field operations
Glyphosate {GLO} market for APOS, U	Consumed during soil recovery
Miscanthus rhizome, for planting {DE} production APOS, U	Modified considering the Italian context and cultivation practice
Electricity, medium voltage {IT} market for APOS, U	Consumed at the pelletizing plant
Maize starch {GLO} market for APOS, U	Consumed at the pelletizing plant
Dust collector, electrostatic precipitator, for industrial use {GLO} market for APOS, U	Used to build the pelletizing process
Dust collector, multicyclone {GLO} market for APOS, U	Used to build the pelletizing process
Wood pellet factory {RER} production APOS, U	Used to build the pelletizing process
Packaging film, low density polyethylene {GLO} market for APOS, U	Consumed at the pelletizing plant

^[1] Amount calculated in agreement with Lovarelli and Bacenetti [52].

Regarding the rhizomes production, respect to the process included in the database a higher multiplication factor was considered (55 respect to 50) due to the longer growing seasons and the higher average temperature. Consequently, a production of 550,000 rhizomes per hectare (instead of 500,000 as in the Ecoinvent[®] process) was considered (average mass of a rhizome is 70 g).

2.4. Life Cycle Impact Assessment

The inventory dataset was characterized by means of the ReCiPe 2016 Midpoint (H) method, version 1.04/World [60]. In total, 15 midpoint impact categories have been evaluated. More in detail, the evaluated impact categories are:

- Global Warming (GW), expressed as kg CO₂ eq.;
- Stratospheric Ozone depletion (ODP), expressed as mg CFC-11 eq.;
- Ozone formation, Human health (HOFp), expressed as g NO_x eq.;
- Fine particulate matter formation (PMFP), expressed as g PM_{2.5} eq.;
- Ozone formation, Terrestrial ecosystems (EOfp), expressed as g NO_x eq.;
- Terrestrial acidification (TAP), expressed as kg SO₂ eq.;
- Freshwater eutrophication (FEP), expressed as g P eq.;
- Marine eutrophication (MEP), expressed as g N eq.;
- Terrestrial ecotoxicity (TETP), expressed as kg 1,4 DCB eq.;
- Freshwater ecotoxicity (FETP), expressed as kg 1,4 DCB eq.;
- Marine ecotoxicity (METP), expressed as kg 1,4 DCB eq.;
- Human carcinogenic toxicity (HTPc), expressed as kg 1,4 DCB eq.;
- Human non carcinogenic toxicity (HTPnc), expressed as kg 1,4 DCB eq.;
- Mineral resource scarcity (SOP), expressed as g Cu-eq.;
- Fossil resource scarcity (FFP), expressed as kg oil-eq.

In agreement with Costantini et al. [61], ionizing radiation was excluded on account of the low prevalence of nuclear power in Italy, while water consumption and land use were excluded due to lack of detailed data about rhizomes and maize starch production. The inventory data were processed using SimaPro[®] LCA software v 9.1. (PRé Sustainability, Amersfoort, The Netherlands).

3. Results and Discussion

The environmental results for miscanthus cultivation are reported in Figure 2 (relative contribution) and in Table 5 (absolute impact values referring to the production of 1 ton of chopped miscanthus). For the different evaluated impact categories Table 5 reports also the main substances and the processes responsible for the total impact.

With a share of the impact ranging from 41 to 72%, the harvesting operation is the main contributor to the impact across all the evaluated impact categories, except Stratospheric Ozone depletion and Marine Eutrophication, where the emission of N and P compounds shows the highest impact. More in detail, dinitrogen monoxide is the substance mostly contributing to stratospheric ozone depletion while nitrate is the one most affecting marine eutrophication. As reported in detail in Table 5, the impact of harvesting is related, for some impact categories, to diesel production (i.e., Fossil resource scarcity) and consumption (i.e., global warming, ozone formation, human health, fine particulate matter formation, ozone formation, terrestrial ecosystems and terrestrial acidification) while for some others, to manufacturing, maintenance and disposal of the forager (harvester) involving mine operations (i.e., terrestrial ecotoxicity and mineral resource scarcity) or the production and management of waste (freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity and human non-carcinogenic toxicity).

The other operations carried out in the first year of the crop cycle (soil tillage, planting and irrigation) affect the impact by a minimum of 0.03% (marine eutrophication) to a maximum of 21.37% (mineral resource scarcity). transport is responsible for a non-negligible share of the environmental load in the toxicity-related impact categories (from 12% for terrestrial ecotoxicity to 30% for human carcinogenic toxicity). The contribution of the different field operations to human carcinogenic toxicity is mainly due to the emissions related to diesel combustion. The manufacturing of the other production factors (rhizomes and glyphosate) plays a minor role in defining the environmental performance of the miscanthus biomass. Rhizomes production shows a contribution < 5% for all the evaluated impact categories except for freshwater eutrophication (16% due to the emission of N and P compounds due to the fertilizers application) while glyphosate has even a smaller role

being responsible of less than 2% of the impact except for freshwater eutrophication (10%, due to the release of phosphorous during its degradation into the soil).

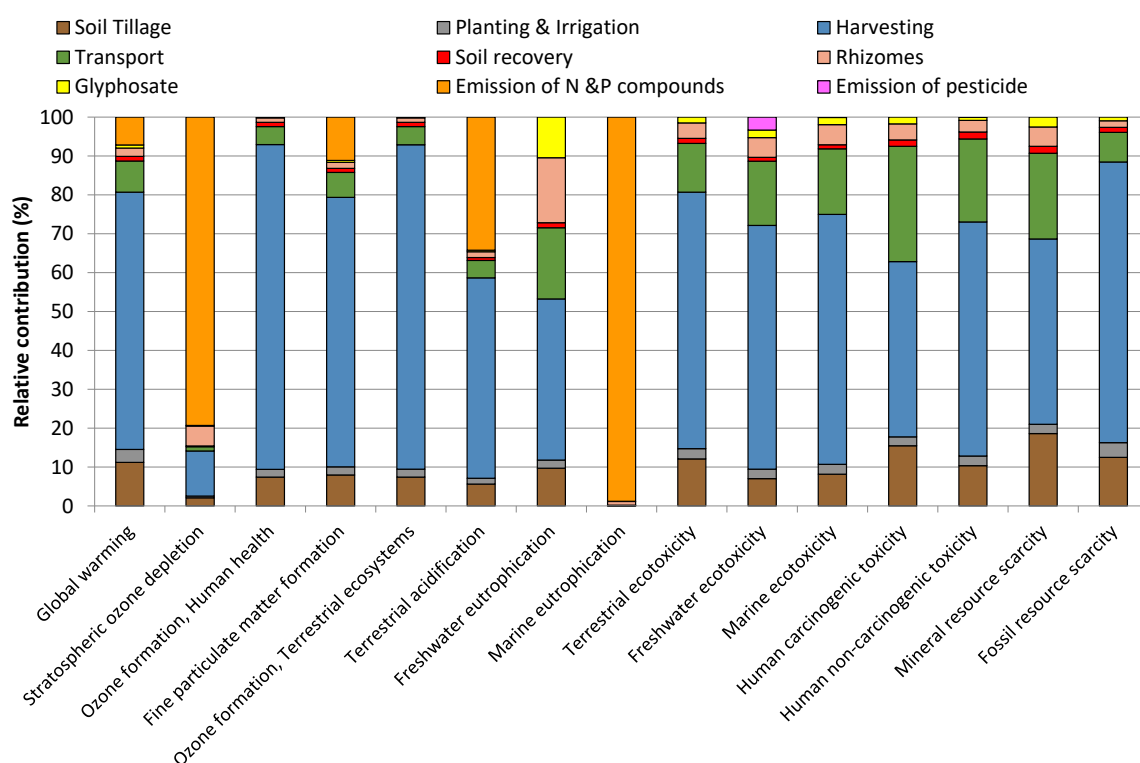


Figure 2. Contribution analysis for miscanthus cultivation.

Regarding the pelletizing step of the pellet production process, the contribution analysis (Figure 3) shows how the energy consumption (electricity) is the main responsible of the environmental performances of miscanthus pellet with a share of the impact higher than 40%, except for marine eutrophication, where the main contributor is the miscanthus biomass (due to the emission of N & P compounds during cultivation), and Mineral resource scarcity, where main contributors are the miscanthus biomass (due to the use of tractors and forager and the manufacturing and maintenance of the pelletizing plant). More in detail, manufacturing and maintenance of the pelletizing plant shows a impact lower than 5% for all the evaluated impact categories except than for the toxicity relates ones and for mineral resource scarcity. The impact related to the waste produced during pelletizing (e.g., dust), included in the label “pelletizing plant” has a negligible role (<0.1%) for all the evaluated impact categories.

With respect to other LCA studies focused on pellet production [41–44,52], for the miscanthus pellet there is no heat consumption for biomass drying since the chopped miscanthus has a moisture content (about 10%) that allows the direct pelletizing. Maize starch and packaging materials show a small contribution for all the evaluated impact categories.

Table 6 reports the absolute impact for the packed miscanthus pellet considering the 2 selected functional unit: 1 ton and 1 GJ of LHW.

To test the robustness of the achieved results a sensitivity analysis was carried out regarding the biomass yield during miscanthus cultivation as well as about the consumption of electricity and packaging material during pelletizing. For these parameters, a variation of $\pm 20\%$ was considered. The results, reported in Table 7, show how the variation of biomass yield, has an effect higher than 5% for 5 of the 15 evaluated impact categories and, as expected, affects marine eutrophication (the environmental effect where the role of cultivation is higher). Also, the variation of the electricity consumption shows a non-negligible impact

for the evaluation impact categories (>10% for 8 for the 15 evaluated impact categories). Finally, differently than for biomass yield and electricity consumption, the variation in the consumption of packaging material has small effect on the environmental performances of miscanthus pellet (lower than 2% for 14 of the 15 impact categories).

Table 5. Environmental impact of 1 ton of miscanthus biomass.

Impact Category	Unit	Total	Main Substance	Main Process
Global warming	kg CO ₂ eq.	13.788	CO ₂ , fossil	Combine harvesting {GLO} processing Miscanthus APOS, U [1]
Stratospheric ozone depletion	mg CFC11 eq.	45.770	NO	Emission N &P compounds
Ozone formation, Human health	kg NO _x eq.	0.153	NO _x	Combine harvesting {GLO} processing Miscanthus APOS, U [1]
Fine particulate matter formation	g PM2.5 eq.	41.400	NO _x & Particulates	Combine harvesting {GLO} processing Miscanthus APOS, U [1]
Ozone formation, Terrestrial ecosystems	kg NO _x eq.	0.155	NO _x	Combine harvesting {GLO} processing Miscanthus APOS, U [1]
Terrestrial acidification	kg SO ₂ eq.	0.110	NO _x & NH ₃	Combine harvesting {GLO} processing Miscanthus APOS, U [1]
Freshwater eutrophication	g P eq.	1.517	PO ₄ ^{3−}	Harvester {GLO} market for APOS [2]
Marine eutrophication	g N eq.	47.995	NO ₃ [−]	Emission N &P compounds
Terrestrial ecotoxicity	kg 1,4DCB	33.270	Copper	Harvester {GLO} market for APOS [3]
Freshwater ecotoxicity	kg 1,4DCB	0.390	Copper	Harvester {GLO} market for APOS [4]
Marine ecotoxicity	kg 1,4DCB	0.496	Copper & zinc	Harvester {GLO} market for APOS [4]
Human carcinogenic toxicity	kg 1,4DCB	0.293	Chromium VI	Harvester {GLO} market for APOS [5]
Human non-carcinogenic toxicity	kg 1,4DCB	16.766	Zinc	Combine harvesting {ITA} processing Miscanthus APOS, U
Mineral resource scarcity	g Cu eq.	78.716	Gold & Iron	Harvester {GLO} market for APOS [6]
Fossil resource scarcity	kg oil eq.	3.819	Oil crude	Diesel {GLO} market for APOS

[1] Process not included in the database and built by modifying the process Combine harvesting {CH} | processing | APOS, U considering the fuel consumption and the mass of the machine reported in Table 1. Emission due to fuel combustion were modified proportionally to the variation of fuel consumed; [2] Mainly due to the treatment of spoil from hard coal mining; [3] Mainly due to the production of metals; [4] mainly due to treatment of sulfidic tailings, from copper mine operation; [5] Mainly due to the management of waste (landfill and incineration) produced for harvester manufacturing; [6] Mainly due to the metal mine operations.

Figure 4 reports the relative comparison between the miscanthus pellet analysed in this study and the woody pellet process included in the Ecoinvent[®] database (v3.6): Wood pellet, measured as dry mass {RER} | wood pellet production | APOS, U. The comparison highlights how the pellet from miscanthus shows better environmental performance (lower impact) for all the evaluated impact categories except for Marine eutrophication. The impact reduction for miscanthus pellet ranges from 4% for Fossil resource scarcity to 59% for Fine particulate matter formation and is related to the lower energy consumption (as stated before, heat is need for biomass drying during the woody pellet production). Even if woody pellet is produced using biomass coming from forestry and whose production does not involve soil tillage, planting, and crop management its impact is higher because the produced biomass needs to be dried. Only for marine eutrophication, the impact category mostly affected by phosphate emissions during miscanthus cultivation, the pellet from miscanthus has a higher impact (three times higher) then the woody one.

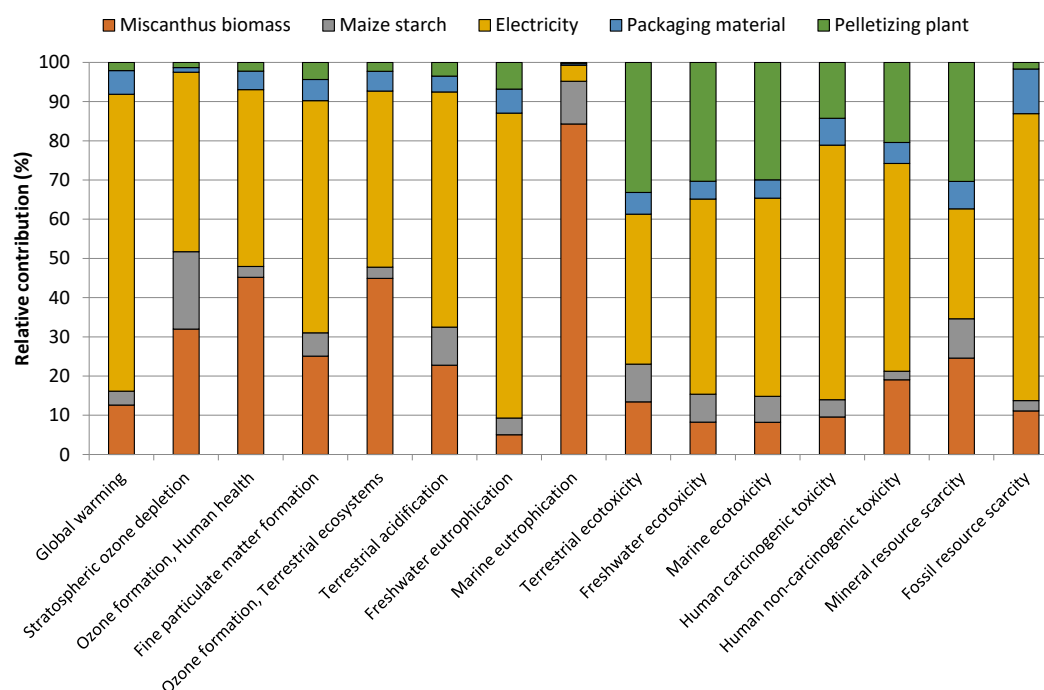


Figure 3. Contribution analysis for miscanthus pellet production.

Table 6. Environmental impact of 1 ton of miscanthus pellet and for 1 GJ of Lower Heating Value (LHV).

Impact Category		FU = 1 ton	FU = 1 GJ
Global warming	kg CO ₂ eq.	121.640	6.796
Stratospheric ozone depletion	mg CFC11 eq.	159.037	8.885
Ozone formation, Human health	kg NO _x eq.	375.776	20.993
Fine particulate matter formation	g PM2.5 eq.	183.354	10.243
Ozone formation, Terrestrial ecosystems	kg NO _x eq.	383.144	21.405
Terrestrial acidification	kg SO ₂ eq.	0.535	0.030
Freshwater eutrophication	g P eq.	33.624	1.878
Marine eutrophication	g N eq.	63.263	3.534
Terrestrial ecotoxicity	kg 1,4DCB	275.529	15.393
Freshwater ecotoxicity	kg 1,4DCB	5.258	0.294
Marine ecotoxicity	kg 1,4DCB	6.737	0.376
Human carcinogenic toxicity	kg 1,4DCB	3.400	0.190
Human non-carcinogenic toxicity	kg 1,4DCB	96.343	5.382
Mineral resource scarcity	g Cu eq.	355.915	19.884
Fossil resource scarcity	kg oil eq.	38.146	2.131

Table 7. Sensitivity analysis results: Impact variation respect to the analysis with biomass yield and electricity and packaging material reported in Section 2.3—Inventory analysis.

Impact Category	Biomass Yield		Electricity		Packaging Material	
	+20%	−20%	+20%	−20%	+20%	−20%
Global warming	2.52%	−2.52%	−15.15%	15.15%	−1.21%	1.21%
Stratospheric ozone depletion	6.39%	−6.39%	−9.15%	9.15%	−0.24%	0.24%
Ozone formation, Human health	9.04%	−9.04%	−9.02%	9.02%	−0.95%	0.95%
Fine particulate matter formation	5.01%	−5.01%	−11.84%	11.84%	−1.08%	1.08%
Ozone formation, Terrestrial ecosystems	8.98%	−8.98%	−8.99%	8.99%	−1.00%	1.00%

Table 7. Cont.

Impact Category	Biomass Yield		Electricity		Packaging Material	
	+20%	−20%	+20%	−20%	+20%	−20%
Terrestrial acidification	4.55%	−4.55%	−12.00%	12.00%	−0.81%	0.81%
Freshwater eutrophication	1.00%	−1.00%	−15.55%	15.55%	−1.22%	1.22%
Marine eutrophication	16.86%	−6.86%	−0.81%	0.81%	−0.08%	0.08%
Terrestrial ecotoxicity	2.68%	−2.68%	−7.66%	7.66%	−1.11%	1.11%
Freshwater ecotoxicity	1.65%	−1.65%	−9.96%	9.96%	−0.90%	0.90%
Marine ecotoxicity	1.63%	−1.63%	−10.11%	10.11%	−0.93%	0.93%
Human carcinogenic toxicity	1.91%	−1.91%	−13.00%	13.00%	−1.36%	1.36%
Human non-carcinogenic toxicity	3.87%	−3.87%	−11.21%	11.21%	−1.09%	1.09%
Mineral resource scarcity	4.91%	−4.91%	−5.60%	5.60%	−1.40%	1.40%
Fossil resource scarcity	2.22%	−2.22%	−14.65%	14.65%	−2.28%	2.28%

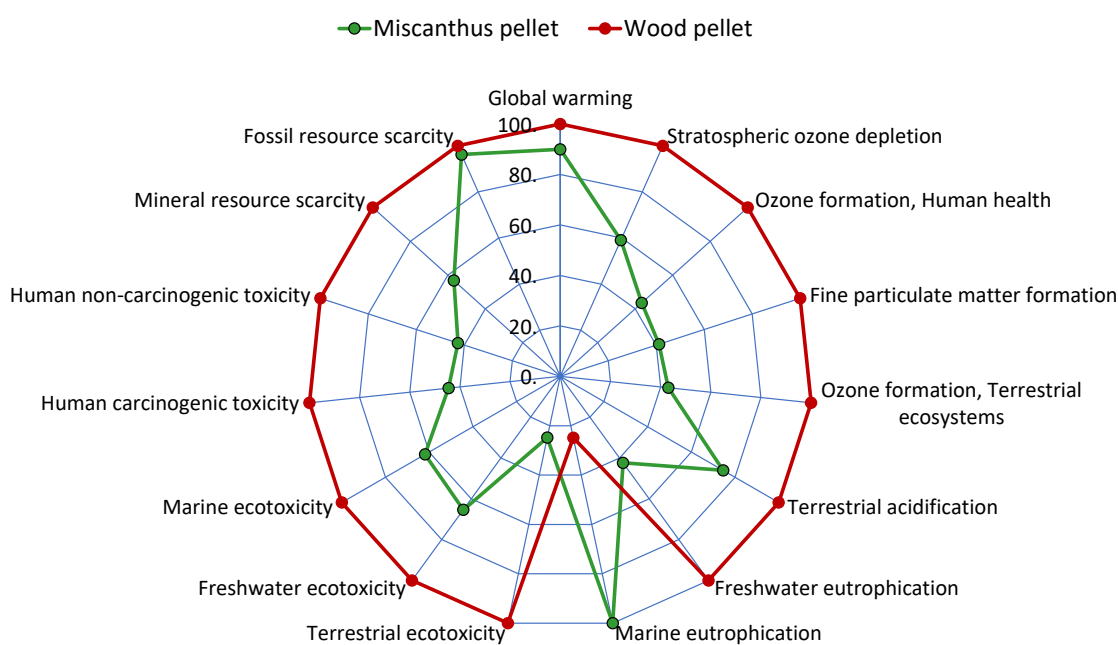


Figure 4. Relative comparison between miscanthus pellet and woody pellet.

4. Conclusions

The production of wood pellet has grown considerably in the last decades thanks to an increasing demand of this fuel and the interest for renewable energy. However, besides woody biomass, other feedstocks can be used for pellet production. Among these, miscanthus presents some advantages because, even if specifically cultivated, it requires low inputs and shows high biomass yield.

In this study, the environmental impact of miscanthus pellet was evaluated using the LCA approach with a “cradle-to plant gate” perspective. The results highlight how the miscanthus pellet shows lower environmental impact compared to woody pellet mainly due to the lower energy consumption during pelletizing. The possibility to pelletize the miscanthus biomass without any drying offsets the environmental impact related to the miscanthus cultivation for all the evaluated impact categories (except for Marine eutrophication, affected by the emission of P compounds occurring during its run-off and glyphosate degradation). Regarding the cultivation, the harvesting that, differently from the other field operations, is carried out every year, is by far the main contributor to the impact.

The achieved results were mainly derived from a site-specific conditions and local features such as topographic, soil, climatic and agricultural activities. Consequently, additional LCA studies are needed to delve the environmental impact of miscanthus pellet in other contexts. In particular, the aspects that should be carefully considered and investigated furtherly refers the possibility that the cultivation requires additional irrigations or fertilization (due to the cultivation in soils with low nutrient availability) or that drying of the biomass would be needed.

Author Contributions: Conceptualization, D.F. and J.B.; methodology, A.F., A.R.P. and J.B.; writing—original draft preparation, A.F., J.B. and D.P.; writing—review and editing, D.F., J.B., D.E.A.T. and D.P.; and supervision, D.F., J.B. and D.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors would like to thank farmer and staff at the pellet factory for kindly providing information.

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

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