Chapter 8
A Review on Potential Candidate Lignocellulosic Feedstocks for Bio-energy Supply Chain

Amalia Zucaro, Angelo Fierro and Annachiara Forte

Abstract In the context of an increased bio-based economy characterized by both reduced dependence upon imported fossil fuels and reduced greenhouse gases emissions, bio-fuels and the other bio-based supply chains have reached a worldwide expansion. Taking into account the high environmental impact of the agricultural production and the potential conflicts among food, energy and environment, this review provides an overview of the opportunities and constraints specifically related to the environmental performance of different candidate lignocellulosic feedstock in the Italian context. Peer-reviewed Life Cycle Assessment (LCA) studies were analysed and compared on a mass basis. Several biomass-based supply chains from wood and herbaceous residues or dedicated crops on marginal and fertile lands (under different fertilization management) were considered. A cradle-to-farm gate attributional LCA approach was applied to assess the environmental profile and the linked major hotspots as useful information to evaluate the most promising feedstock for bio-energy or integrated biorefinery systems. The results have demonstrated that short rotation forestry and medium rotation forestry cultivation systems, characterized by restrained mineral fertilization, can have a better environmental performance than herbaceous crops under both standard and reduced fertilization management, offering substantial benefits for almost all investigated impact categories.

Keywords Environmental performance · Annual and perennial crops
SRF and MRF · Dedicated feedstock · Residual biomass · Energy crops

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A. Zucaro · A. Fierro · A. Forte (✉)
Dipartimento di Biologia, Università di Napoli Federico II, Naples, Italy
e-mail: anforte@unina.it

A. Zucaro
e-mail: amalia.zucaro@unina.it

A. Fierro
e-mail: fierro@unina.it

A. Fierro
Laboratorio di Urbanistica e di Pianificazione del Territorio (LUPT), Università di Napoli
Federico II, Naples, Italy

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8.1 Introduction

The rapid growth in population and industrialization gave rise to increase the energy demand and the dependence on fossil-based products. There is a clear scientific evidence that the global change arises from human influence and it is strictly related to the fossil fuel consumption (IPCC 2014). Therefore, the interest in developing environmentally friendly supply chains from renewable feedstocks has considerably increased (Forte et al. 2016). Over the last decades, the transition to a decarbonised energy system brought to increase the bio-energy production, with an expected growth of bio-fuels, such as bioethanol (EtOH) and biodiesel (Gomiero 2017). In this context, the exploitation of lignocellulosic energy crops for bio-energy or other bio-based productions are increasingly considered as a strategy to not affect food security and reduce environmental impacts (Solinas et al. 2015). The European Union (EU) encourages the employment of second generation feedstock, such as energy crops or waste raw materials (Directive 2009/28/EC). In the Italian context the energy crops have strongly grown over the last years as well, mainly driven by dedicated subsidization policy (Bartoli et al. 2016), with a rising bio-fuel oriented policy for greenhouse gases (GHG) and fossil energy saving in the transport sector (D. Lgs. 03/03/2011 n.28; COM15 final, 2014).

The lignocellulosic materials are considered as the promising feedstock for bio-based industrial processes due to their chemical features and composition (Anwar et al. 2014). Such materials are considered natural and renewable resource essential to the functioning of modern industrial societies even if much of the lignocellulosic biomass is still disposed of by burning (Anwar et al. 2014). This biomass can potentially be converted into different high value products including bio-fuels, chemicals, and cheap energy sources (Anwar et al. 2014; Zucaro et al. 2016a).

However, the environmental performance of bio-fuels, bio-materials and bio-chemicals from lignocellulosic biomass, over the entire production chain, needs to be carefully investigated. The Life Cycle Assessment (LCA) has been widely recognized as one of the most suitable analytical approaches to deeply analyse the environmental performance of processes or products (Bessou et al. 2013).

At the present time, the enhanced use of biomass is strictly connected to the widespread opinion that bio-based products are less pollutant than their fossil-counterparts and do not contribute to net CO_2 emissions. The pertinent scientific literature shows controversial results and highlights the crop phase as the major environmental hotspot of several bio-based supply chains (Forte et al. 2017; Zucaro et al. 2017), due to the farming managements (Milà i Canals et al. 2006; Bessou et al. 2013) and the site-specific conditions for the local emissions (Bessou et al. 2013). For this reason, the environmental performance of dedicated crops or residues biomass should be subject to a constant evaluation and monitoring in site-specific conditions for effective territorial environmental friendly bio-based strategies. In this regard, in the Italian context, preliminary studies were carried out comparing the environmental performance of different oleaginous biomasses (Cocco et al. 2014; Forleo et al. 2017), whilst there is a lack of comprehensive evaluation of the environmental profile of alternative lignocellulosic feedstock for bio-energy/biorefinery purposes. The present work is a literature review of peer-reviewed articles on the LCA of lignocellulosic biomass (dedicated and residual ones) referred to the Italian context. Specifically, different lignocellulosic biomass productions were analysed and compared by means of a cradle-to-farm gate attributional LCA approach to assess the environmental profile and the related major hotspots for the largest number of impact categories. All the resulting information will serve as a useful base to identify the main environmental pros and cons of lignocellulosic bio-based routes in the Italian context.

8.2 Methodological Issues

8.2.1 Papers Selection and Clustering

This review was designed to summarize and critically address the LCA studies for lignocellulosic biomass production for bio-based supply chains in the Italian context. Scientific literature, published in the last 10 years, was investigated through the following e-resources: Scopus, Google Scholar and Sciencedirect. Afterwards, this work focused only on the full attributional LCA studies applied to biomass-based supply chains published in peer-reviewed journals or in peer-reviewed conference proceedings, with a specific focus on the crop phase. The selected studies are reported in Table 8.1, associating an identification number, consistently used thought all figures, to each work and summarizing the most relevant information about key parameters such as: (i) the biomass feedstock, (ii) the type of land used, (iii) the functional unit (FU), (iv) the system boundaries, (v) allocation procedures, (vi) the applied impact assessment methods (IAM) and (vii) the linked analysed impacts. For the present review, the selected system boundaries were from cradle-to-farm gate and the FU was set to 1 kg of total lignocellulosic dry biomass production (thought the specific crop life cycles), since the biomass yield is a key parameter influencing the environmental performance of the farm systems and the whole bio-based supply chains (Bosco et al. 2016). In order to standardize and properly compare the different studies, when necessary the FU was converted to the selected one and the results were extrapolated to match the cradle-to-farm gate system boundary. Additionally, since the choice of the life cycle IAM was not always consistent among the selected studies (Table 8.1), to extensively discuss the results for the largest available number of LCA impact categories, the authors re-elaborated, by means of SimaPro 8.2.0 software (Pré 2018), the results from their own studies (Forte et al. 2015, 2016, 2017; Zucaro et al. 2015, 2016a, b, 2018) moving from the ReCiPe to the ILCD or CML methods. The cumulative energy demand (CED) was also evaluated applying the single-issue method to the data available by the authors. All data were clustered in the following three groups: (i) woody lignocellulosic biomass through short and medium rotation forestry (SRF-MRF), (ii) perennial herbaceous crops, (iii) annual herbaceous crops.

The only available data for agricultural straw residues (herbaceous, straw) was kept separate. In this regard, the results by the ILCD IAM allowed the comparison of environmental impacts among all the three groups (SRF-MRF, herbaceous perennial and herbaceous annual); whilst the results by the CML IAM provided a further specific focus on potential differences between herbaceous perennial and annual feedstock (see Table 8.1 and Sect. 8.2.2 for additional details).

8.2.2 Statistical Analysis

Statistical analyses were performed using the Sigma Plot package (Sigma Plot 2012). The ANOVA 'One Way Analysis of Variance' test ($p < 0.05$) was used to check significant differences among: (i) the environmental impacts of the SRF-MRF, herbaceous perennial and herbaceous annual feedstock by the ILCD IAM; (ii) the key agronomic input (N, P and K fertilizers and diesel) required per 1 kg of dry SRF-MRF, herbaceous perennial and annual biomass produced. The t-test ($p < 0.05$) was used to further investigate the impacts of the perennial herbaceous crops *versus* the annual herbaceous feedstocks through the CML IAM. For each feedstock, the relationships among the environmental impacts and the key agronomic parameters (N, P and K fertilizers and diesel input per 1 kg of dry biomass) were investigated through the Pearson Product-Moment Test and linear regression analysis.

8.3 Results and Discussion

Figure 8.1a shows a significantly lower impact in terms of Climate Change (CC) for the woody biomass compared to both the herbaceous perennial and annual feedstocks, likely linked to the combined effect of the restrained fertilizer inputs (Table 8.2) and the higher biomass yield related to the whole crop life time of willow and poplar crops compared to the herbaceous cultivations. Indeed, SRF-MRF crops are characterized by a higher nitrogen-use efficiency and a reduced use N-fertilizer input (often applied only as organic N in the pre-plant phase) (Banacetti et al. 2012, 2016; Djomo et al. 2015). Otherwise, notwithstanding the CC impact resulted linearly related to the K, P fertilizers and diesel input (Table 8.3), no clear separation was observed among the groups in relation to these parameters, due to comparable fertilization schemes and fuel consumption patterns (linked to the high mechanization for the biomass collection) for woody and herbaceous crops.

The inclusion of the soil carbon dynamic in the GHG inventory might amplify the outcome of comparative analyses between perennial (herbaceous) and annual crops (Bessou et al. 2013), since the former are usually recognized to entail a potential long-term soil carbon storage (SCS) thanks to: (i) a longer C turnover of the more extensive rooting systems (Monti and Zatta 2009); (ii) limited soil management (planting and related tillage, to be shared for the whole lifetime) (Monti et al. 2009); (iii) a reduced

Table 8.1 Selected LCA studies about lignocellulosic crops

	Feedstock	Paper	Land	System boundary	FU	Allocation	LCIA-M	Impact category[a]
1	Wood SRF-Poplar	Banacetti et al. (2012)	Fertile	Cradle-to-farm gate	1 ha of poplar plantation	n.a.	IPCC-GWP, CED	Global warming potential and cumulative energy demand
2	Wood MRF-Poplar							
3	Wood SRC-Poplar	Banacetti et al. (2016)	Fertile	Cradle-to-farm gate	1 t (tonnes) of dry-chipped biomass	LHV of biomass	ILCD method	CC, OD, HTc, HT, PM, POF, A, FE, TE, ME, FEx, MFRD
4	Wood SRC-Willow							
5	Wood SRC-Poplar (best clone)							
6	Wood SRC-Willow (best clone)							
7	Herbaceous Perennial- Switchgrass;	Monti et al. (2009)	Fertile	Cradle-to-farm gate	Hectare and energy based	n.a	CML 2	GWP, OLD, Ac, Eu, T-t, MW-t, FW-t, H-t, A-d.
8	Herbaceous Perennial- Giant reed							

(continued)

Table 8.1 (continued)

	Feedstock	Paper	Land	System boundary	FU	Allocation	LCIA-M	Impact category[a]
9	Herbaceous Perennial-*Miscanthus*							
10	Herbaceous Perennial-Cardoon							
11	Herbaceous Perennial-Switchgrass	Fazio and Monti (2011)	Fertile	Cradle-to-grave (electricity/heat/transport fuels	Land—(hectare) and energy—(Joule)	n.a.	CML 2 and Eco-indicator 99	GWP, OLD, Ac, Eu, T-t, MW-t, FW-t, H-t, A-d.
12	Herbaceous Perennial-Giant reed							
13	Herbaceous Perennial-*Miscanthus*							
14	Herbaceous Perennial-Cardoon							
15	Herbaceous Annual-Fibre *Sorghum*							
16	Herbaceous Perennial-Giant reed	Forte et al. (2015)	Marginal	Cradle-to-farm gate	1 kg of dry matter	n.a.	ReCiPe midpoint (H)	CC, OD, TA, FE, ME, POF, PMF, TET, FET, MET, WD, FD

(continued)

Table 8.1 (continued)

	Feedstock	Paper	Land	System boundary	FU	Allocation	LCIA-M	Impact category[a]
17	Herbaceous Perennial-Giant reed	Zucaro et al. (2015)	Marginal	Cradle-to-farm gate	1 kg of dry matter	n.a	ReCiPe midpoint (H)	CC, OD, TA, FE, ME, POF, PMF, WD, FD
18	Herbaceous Annual-Fibre *Sorghum*							
19	Herbaceous Perennial-Giant reed	Bosco et al. (2016)	Fertile	Cradle-to-plant gate	1 ha and 1 t of dry biomass	n.a.	CML	Energy balance, gross and net greenhouse gas emissions, eutrophication potential, acidification potential, ozone layer depletion potential, photochemical ozone creation potential
20	Herbaceous Perennial-Giant reed		Marginal	Cradle-to-plant gate		n.a.	CML	
21	Herbaceous Perennial-Cardoon	Zucaro et al. (2016b)	Marginal	Cradle-to-farm gate	1 kg of dry matter	Economic	ReCiPe Midpoint (H)	CC, OD, TA, FE, ME, POF, PMF, WD, FD

(continued)

Table 8.1 (continued)

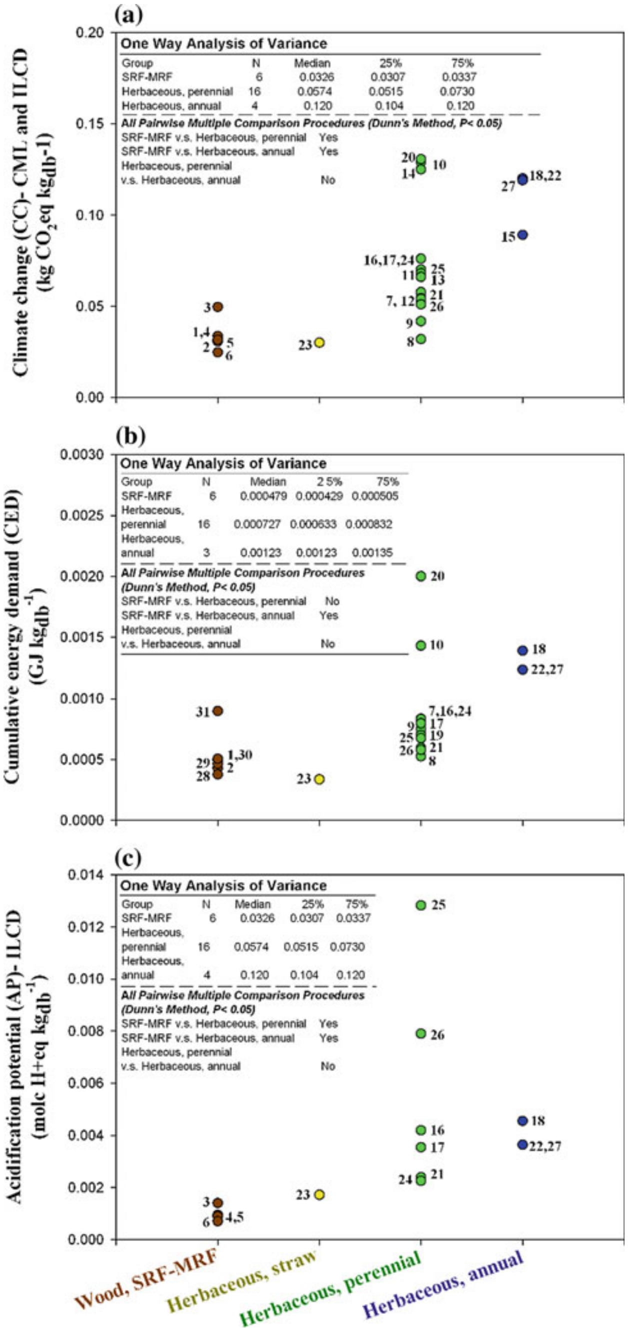
	Feedstock	Paper	Land	System boundary	FU	Allocation	LCIA-M	Impact category[a]
22	Herbaceous Annual-Fibre *Sorghum*							
23	Herbaceous Straw-Wheat straw	Forte et al. (2016)	Fertile	Cradle-to-farm gate	1 kg of dry matter and 1 kg of bio-based 1,4-Butanediol	Economic	ReCiPe midpoint (H)	CC, OD, TA, FE, ME, POF, PMF, WD, FD n
24	Herbaceous Perennial-Giant reed	Zucaro et al. (2016a)	Marginal	Cradle-to-wheel	1 kg of dry matter and 1 km driven	n.a.	ReCiPe midpoint (H)	CC, OD, TA, FE, ME, POF, PMF, WD, FD
25	Herbaceous Perennial-Giant reed high-input	Zucaro et al. (2018)	Marginal	Cradle-to-farm gate	1 kg of dry matter	n.a.	ReCiPe midpoint (H)	CC, OD, TA, FE, ME, POF, PMF, WD, FD
26	Herbaceous Perennial-Giant reed low-input							
27	Herbaceous Annual-Fibre *sorghum*	Forte et al. (2017)	Marginal	Cradle-to-farm gate, cradle-to-wheel	1 kg of dry matter and 1 km travelled	n.a.	ReCiPe Midpoint (H)	CC, OD, TA, FE, ME, POF, PMF, WD, FD
28	Wood SRC-Poplar/Willow Casale Monferrato	Djomo et al. (2015)	Fertile	Cradle-to-farm gate	Hectare based	n.a.	Energy output and balance	Energy ratio, net energy yield

(continued)

Table 8.1 (continued)

	Feedstock	Paper	Land	System boundary	FU	Allocation	LCIA-M	Impact category[a]
29	Wood SRC-Poplar Ostiano							
30	Wood SRC-Poplar Pisa							
31	Wood SRC—Poplar Bagni di Tivoli							

[a] Acronyms LCIA-M: life cycle impact assessment method, FU: functional unit, for ILCD impact categories: climate change (CC), ozone depletion (OD), human toxicity, cancer effects (HTc), human toxicity, non-cancer effects (HT), particulate matter (PM), photochemical ozone formation (POF), acidification (A), freshwater eutrophication (FE), terrestrial eutrophication (TE), marine eutrophication (ME), freshwater ecotoxicity (FEx) and mineral, fossil and renewable resource depletion (MFRD), acronyms for CML impact categories: global warming potential (GWP), ozone layer depletion (OLD), rainfall acidification (Ac), water eutrophication (Eu), terrestrial ecotoxicity (T-t), marine water ecotoxicity (MW-t), fresh water ecotoxicity (FW-t) human toxicity (H-t), abiotic depletion (A-d). acronyms for ReCiPe impact categories: climate change (CC); ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), photochemical oxidant formation (POF), particulate matter formation (PMF), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), water depletion (WD), fossil depletion (FD)



(a)

One Way Analysis of Variance

Group	N	Median	25%	75%
SRF-MRF	6	0.0326	0.0307	0.0337
Herbaceous, perennial	16	0.0574	0.0515	0.0730
Herbaceous, annual	4	0.120	0.104	0.120

All Pairwise Multiple Comparison Procedures (Dunn's Method, P< 0.05)

SRF-MRF v.s. Herbaceous, perennial	Yes
SRF-MRF v.s. Herbaceous, annual	Yes
Herbaceous, perennial v.s. Herbaceous, annual	No

(b)

One Way Analysis of Variance

Group	N	Median	25%	75%
SRF-MRF	6	0.000479	0.000429	0.000505
Herbaceous, perennial	16	0.000727	0.000633	0.000832
Herbaceous, annual	3	0.00123	0.00123	0.00135

All Pairwise Multiple Comparison Procedures (Dunn's Method, P< 0.05)

SRF-MRF v.s. Herbaceous, perennial	No
SRF-MRF v.s. Herbaceous, annual	Yes
Herbaceous, perennial v.s. Herbaceous, annual	No

(c)

One Way Analysis of Variance

Group	N	Median	25%	75%
SRF-MRF	6	0.0326	0.0307	0.0337
Herbaceous, perennial	16	0.0574	0.0515	0.0730
Herbaceous, annual	4	0.120	0.104	0.120

All Pairwise Multiple Comparison Procedures (Dunn's Method, P< 0.05)

SRF-MRF v.s. Herbaceous, perennial	Yes
SRF-MRF v.s. Herbaceous, annual	Yes
Herbaceous, perennial v.s. Herbaceous, annual	No

Fig. 8.1 **a** CC, **b** CED and **c** AP impacts of the different lignocellulosic feedstock. The inset table shows the results of the ANOVA-one way analysis of variance ($p < 0.05$)

Table 8.2 Kruskal-wallis one way analysis of variance on ranks ($p < 0.05$) for the key agronomic input (N, P and K fertilizer and diesel) required per 1 kg of dry biomass produced through SRF-MRF, herbaceous perennial and herbaceous annual cultivations

N-fertilizer input (kg kg^{-1} of dry biomass)				
Cluster	Number	Median	25%	75%
SRF-MRF	12	0.000234	0.00223	0.00323
Herbaceous, perennial	23	0.00522	0.00381	0.00667
Herbaceous, annual	7	0.00667	0.00428	0.00811
All pairwise multiple comparison procedures (Dunn's method, $p < 0.05$)				
SRF-MRF versus Herbaceous, perennial		Yes		
SRF-MRF versus Herbaceou, annual		Yes		
Herbaceous, perennial versus Herbaceou, annual		No		
P-fertilizer input (kg kg^{-1} of dry biomass)—$p = 0.978$				
Cluster	Number	Median	25%	75%
SRF-MRF	12	0.000297	0.000252	0.000297
Herbaceous, perennial	23	0.000416	0.0000483	0.00107
Herbaceous, annual	7	0.000554	0.000	0.00164
K-fertilizer input (kg kg^{-1} of dry biomass)—$p = 0.197$				
Cluster	Number	Median	25%	75%
SRF-MRF	12	0.00109	0.00084	0.00109
Herbaceous, perennial	23	0.000178	0.000	0.000985
Herbaceous, annual	7	0.00046	0.000	0.00254
Diesel input (kg kg^{-1} of dry biomass)—$p = 0.249$				
Cluster	Number	Median	25%	75%
SRF-MRF	12	0.00499	0.0024	0.0326
Herbaceous, perennial	23	0.00415	0.00308	0.0064
Herbaceous, annual	7	0.00825	0.00612	0.0102

Table 8.3 Significant correlations among analysed environmental impacts and key N, K, P and diesel inputs per kg of dry biomass produced (pearson product-moment test)

Impact	N-fertilizer (kg kg_{bd}^{-1})	P-fertilizer (kg kg_{bd}^{-1})	K-fertilizer (kg kg_{bd}^{-1})	Diesel (kg kg_{bd}^{-1})
CC (kg CO_2 eq kg^{-1}_{bd})	0.752*** (27)	0.613*** (26)	0.439* (27)	0.823*** (27)
CED (MJ kg^{-1}_{bd})	0.832*** (22)			0.821*** (22)
POF (kg NMVOC eq kg_{db}^{-1})		0.624* (14)	0.542* (14)	
OD (kg CFC-11 eq kg_{db}^{-1})	0.813*** (23)	0.636** (23)		0.826*** (23)
PM (kg PM2.5 eq kg_{db}^{-1})	0.752** (14)			0.753** (14)
TE (molc N eq kg_{db}^{-1})	0.666** (14)			0.620* (14)

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$. Sample size in parentheses

risk of soil erosion (Angelini et al. 2009); (iv) an increase in soil carbon content and biodiversity (Angelini et al. 2009). Although there is a general consensus on the importance of the below-ground biomass in withdrawing C from the atmosphere (Monti and Zatta 2009) only few studies provided quantitative data on roots of energy crops and the possible plant CO_2 uptake (Monti and Zatta 2009). Therefore, in this review the direct estimate of SCS were not included. For the perennial-giant reed (GR) crop preliminary measures of SCS have highlighted a potential clime change mitigation showing in some cases a net sink of atmospheric CO_2 (Forte et al. 2015; Zucaro et al. 2018).

The results achieved from the evaluation of the CED impact category underlined a significant difference between dedicated woody crops and annual herbaceous crops (Fig. 8.1b). The differences between the SRF-MRF group and herbaceous perennial or between herbaceous perennial and annual were not significant (Fig. 8.1b). In the first case the result was affected by the poplar feedstock cropped in Bagni di Tivoli (see Table 8.1 for additional details), subjected to an annual cultivation management comparable to the herbaceous perennial crops. For the second case, the GR cultivation on marginal soil (point 20, Table 8.1), in spite of higher rates of N fertilization, produced less than half biomass respect to the same GR crop on fertile soil (Bosco et al. 2016). This finding underlined that the high energy demand requested to produce fertilizers might not significantly affect long-term productivity (Cadoux et al. 2014; Djomo et al. 2015).

Table 8.3 shows a linear dependency between the CED impact and the required inputs of N-fertilizer and diesel per kg of dry biomass produced, with an average highest impact for the annual feedstock according to the average highest fuel consumption (Table 8.2). In this regard, the amount of fertilizers and choice of mechanical harvest

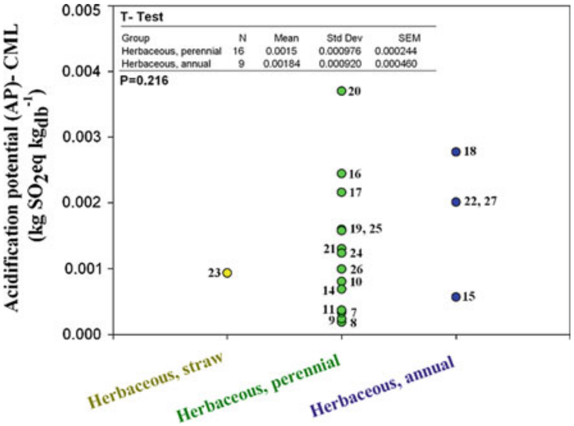


Fig. 8.2 AP of the herbaceous lignocellulosic feedstock. The inset table shows the results of the comparison of perennial versus annual feedstock

yard can largely affect the depletion of fossil resources (Bosco et al. 2016; Zucaro et al. 2018).

For the Acidification potential (AP), the statistical results by the ILCD methods (Fig. 8.1c) show significant differences between the SRF-MRF and the herbaceous groups (both annual and perennial), highlighting much lower impacts for woody crops. The comparative analysis by the CML method (Fig. 8.2) confirms the slight (not significant) differences between the AP impact generated by the herbaceous perennial and annual crops. Relevant tradeoffs may occur in the assessment of AP impacts with both IAMs, due to no clear assessment of Direct Field Emissions (DFE) as highlighted by several authors (Forte et al. 2015; Mbonimpa et al. 2016). Specifically, comparing the same crops in some of the reviewed papers (Monti et al. 2009; Fazio and Monti 2011) the contributions of both N fertilization and harvest operations were on the whole lower compared to the average share highlighted in the other studies (Forte et al. 2015; Zucaro et al. 2018). This was most likely due to differences in the DFE included and the chosen calculation methodology (Bessou et al. 2013; Forte et al. 2015); however only some of the studies at the national level reported the detailed accounting procedure of each DFE analysed (Forte et al. 2015, 2016; Bosco et al. 2016; Zucaro et al. 2016a, 2018). Therefore, no positive correlations emerged between the main hotspot inputs (fertilizers and diesel consumption) and the linked target AP impacts. Nevertheless, as highlighted by some authors (Forte et al. 2015 and Zucaro et al. 2018) the volatilized ammonia (NH_3) emissions, linked to N fertilization practices, highly influenced (up to 70–75%) the acidification impacts.

The results achieved for ozone depletion (OD) were shown in Fig. 8.3a. For both investigated IAMs, ILCD and CML, the OD impact was measured in kg CFC-11 eq. For this reason, the results were processed and presented together. The OD results show significant differences (Fig. 8.3a) among groups due to the higher dependency on the use of fertilizers and diesel consumption (Table 8.3) mainly linked to the upstream halocarbures emissions (Zucaro et al. 2018). Indeed, the constrained use of mineral fertilizers for woody crops (Table 8.2) has produced a lower OD impact, linearly related to the N-fertilizer input (Table 8.3).

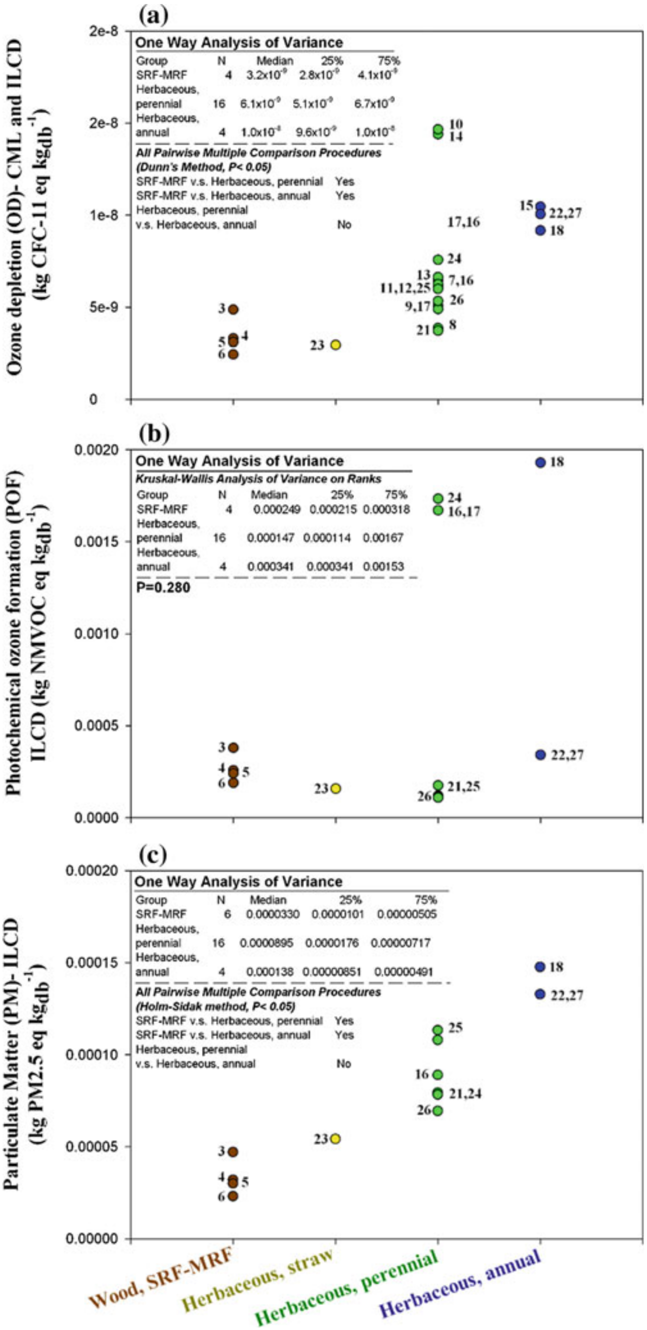
The results achieved for Photochemical Ozone Formation (POF) category (Fig. 8.3b) did not show a significant difference among clusters. The average POF value for woody crops was less than the herbaceous one. Indeed, whilst for the woody crops the mechanization of field operations (reaching almost 90% of impact) has been detected as the main responsible of POF impact (Bacenetti et al. 2016), for the perennial and annual crops the total POF impact was influenced by both upstream (from fertilizer and agricultural machinery productions) and downstream (from machinery on-field operations) emissions (Forte et al. 2017). The POF regression analysis (Table 8.3) highlighted the importance of upstream NO_x emissions emitted during fertilizer manufacturing showing a linear dependency in the use of P and K fertilizers. These results showed the importance in the assessment of the whole production chain, underlining how the different accounting of the indirect emissions might produce marked differences in the results evaluation.

The investigation of particular matter (PM) impact category pointed out a net separation among the investigated clusters (Fig. 8.3c). Nevertheless, the differences between herbaceous crops were not significant (Fig. 8.3c), also in this case due to the overlapping crop management for both perennial and annual lignocellulosic feedstocks. The PM correlation diagrams (Table 8.3) shows a clear dependence by: (i) the increase of N-fertilizer, mainly related to ammonia (NH_3) volatilization, due to the specific NH_3 emission factor (DFE calculation) and the scheduled fertilization rates (Bacenetti et al. 2016; Forte et al. 2017), (ii) the use of diesel in the agricultural machinery (reaching in same case 40–60% of PM impact) (Table 8.3). Therefore, more reliable estimate of NH_3 emissions from Mediterranean cropped lands (Sanz-Cobena et al. 2008) as well as the monitoring of the on-field mechanization (Zucaro et al. 2015) would be very beneficial.

The eutrophication potential (EP) was largely affected by the fertilizer application (Monti et al. 2009; Bacenetti et al. 2016; Zucaro et al. 2018) and to a lower extent by the sulphur dioxide emissions from the combustion of diesel fuel (González-García et al. 2013). In the ILCD method three different EP impact categories are considered: terrestrial (TE), freshwater (FE) and marine (ME) (Fig. 8.4).

For TE significant differences among SRF-MRF and the perennial and annual lignocellulosic clusters were highlighted (Fig. 8.4a). TE values for woody crops were lower than the TE impact generated by both herbaceous crops mainly due to the lower fertilizer inputs. TE impacts were driven by the N-fertilizer input (Table 8.3), due to the key role of NH_3 emissions (about 90%). Also the agricultural mechanization tuned the TE impact (Table 8.3) as highlighted by Bacenetti et al. (2016) and González-García et al. (2013).

The FE values for SRF-MRF cluster were higher than the FE impact generated by the herbaceous crops (Fig. 8.4b). For the annual and perennial herbaceous crops the P-fertilization (when applicable, see Table 8.1 for details) was the highest contribution (Forte et al. 2015). The difference between woody crops and perennial herbaceous was significant (Fig. 8.4b) showing a clear separation of the two clusters, but only for FE the SRF-MRF group displayed higher impact than the perennial one. Currently



One Way Analysis of Variance

Group	N	Median	25%	75%
SRF-MRF	4	3.2×10^{-9}	2.8×10^{-9}	4.1×10^{-9}
Herbaceous, perennial	16	6.1×10^{-9}	5.1×10^{-9}	6.7×10^{-9}
Herbaceous, annual	4	1.0×10^{-8}	9.6×10^{-9}	1.0×10^{-8}

All Pairwise Multiple Comparison Procedures (Dunn's Method, P< 0.05)

SRF-MRF v.s. Herbaceous, perennial	Yes
SRF-MRF v.s. Herbaceous, annual	Yes
Herbaceous, perennial v.s. Herbaceous, annual	No

One Way Analysis of Variance

Kruskal-Wallis Analysis of Variance on Ranks

Group	N	Median	25%	75%
SRF-MRF	4	0.000249	0.000215	0.000318
Herbaceous, perennial	16	0.000147	0.000114	0.00167
Herbaceous, annual	4	0.000341	0.000341	0.00153

P=0.280

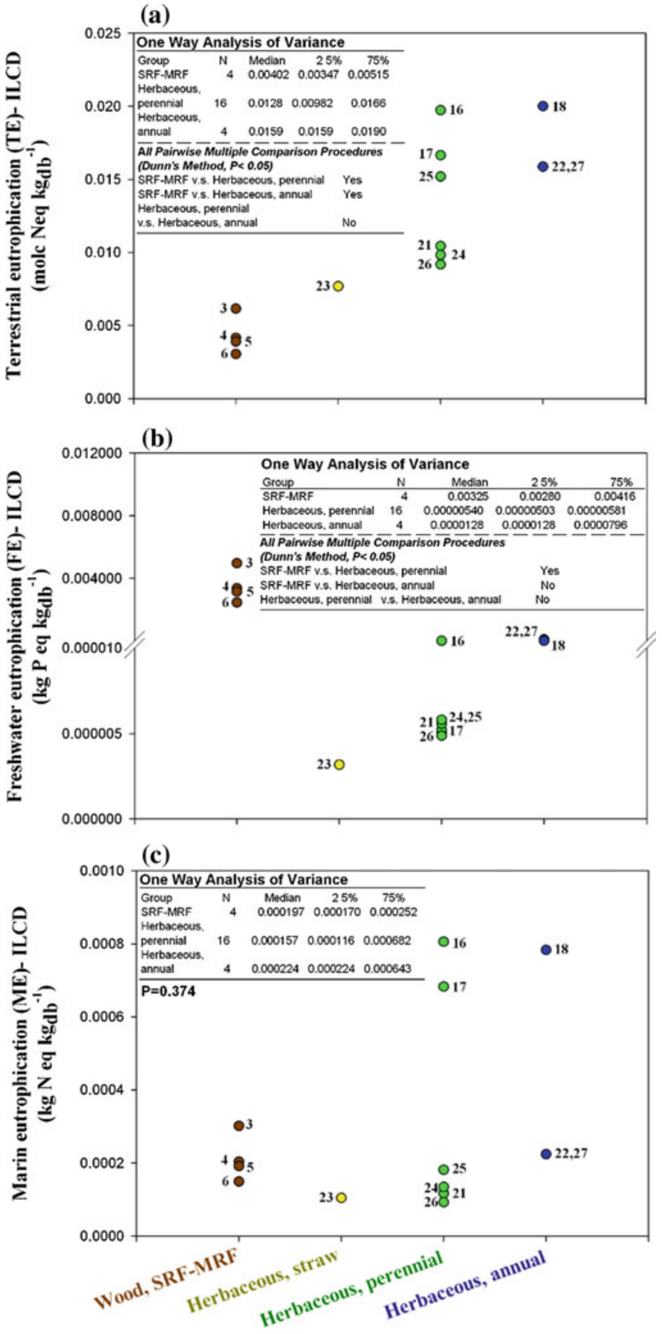
One Way Analysis of Variance

Group	N	Median	25%	75%
SRF-MRF	6	0.0000330	0.0000101	0.00000505
Herbaceous, perennial	16	0.0000895	0.0000176	0.00000717
Herbaceous, annual	4	0.000138	0.00000851	0.00000491

All Pairwise Multiple Comparison Procedures (Holm-Sidak method, P< 0.05)

SRF-MRF v.s. Herbaceous, perennial	Yes
SRF-MRF v.s. Herbaceous, annual	Yes
Herbaceous, perennial v.s. Herbaceous, annual	No

Fig. 8.3 **a** OD, **b** POF and **c** PM impacts of the different lignocellulosic feedstock. The inset table shows the results of the ANOVA-one way analysis of variance ($p < 0.05$)



One Way Analysis of Variance

Group	N	Median	2 5%	75%
SRF-MRF	4	0.00402	0.00347	0.00515
Herbaceous, perennial	16	0.0128	0.00982	0.0166
Herbaceous, annual	4	0.0159	0.0159	0.0190

All Pairwise Multiple Comparison Procedures (Dunn's Method, P< 0.05)

SRF-MRF v.s. Herbaceous, perennial	Yes
SRF-MRF v.s. Herbaceous, annual	Yes
Herbaceous, perennial v.s. Herbaceous, annual	No

One Way Analysis of Variance

Group	N	Median	2 5%	75%
SRF-MRF	4	0.00325	0.00280	0.00416
Herbaceous, perennial	16	0.00000540	0.00000503	0.00000581
Herbaceous, annual	4	0.0000128	0.0000128	0.0000796

All Pairwise Multiple Comparison Procedures (Dunn's Method, P< 0.05)

SRF-MRF v.s. Herbaceous, perennial	Yes
SRF-MRF v.s. Herbaceous, annual	No
Herbaceous, perennial v.s. Herbaceous, annual	No

One Way Analysis of Variance

Group	N	Median	2 5%	75%
SRF-MRF	4	0.000197	0.000170	0.000252
Herbaceous, perennial	16	0.000157	0.000116	0.000682
Herbaceous, annual	4	0.000224	0.000224	0.000643

P=0.374

Fig. 8.4 **a** TE, **b** FE and **c** ME impacts of the different lignocellulosic feedstock. The inset table shows the results of the ANOVA-one way analysis of variance ($p < 0.05$)

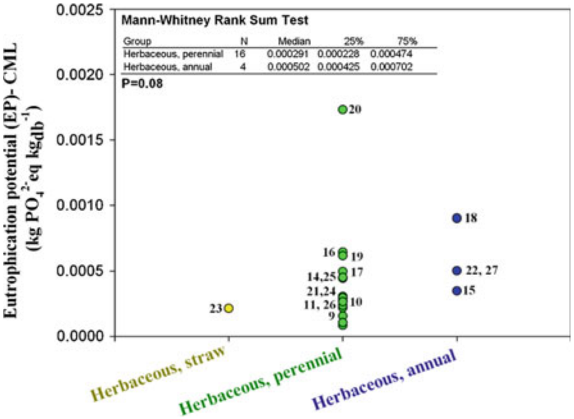


Fig. 8.5 EP impacts of the herbaceous lignocellulosic feedstock. The inset table shows the results of the comparison of perennial versus annual feedstock

the higher variability in the estimation of site-specific factors for P discharge and diffuse N emissions from soil to aquatic ecosystems (nitrate, NO_3^- leaching) may produce significant errors in the calculation of FE impact (Ortiz-Reyes and Anex 2018). The correct estimates of P discharges and nitrate losses to groundwater via leaching are a key challenge to be achieved.

Both emissions are dependent on local conditions, transport mechanisms, soil P concentrations, conservation measures such as managed riparian zones, and how fertilizer is incorporated into the soil (Ortiz-Reyes and Anex 2018). Therefore, also for this impact category the strongly dependency on agricultural management (e.g. fertilization rates) as well as on site-specific soil and climate conditions (Brentrup et al. 2004) requires appropriate DFE calculation procedure (Brentrup et al. 2004; Ortiz-Reyes and Anex 2018).

The combined effects of NH_3 emissions and the risk of nitrate losses considerably affected the ME impact (Forte et al. 2017; Zucaro et al. 2018) but also the mechanization of on-field operations cannot be neglected (Bacenetti et al. 2012; Forte et al. 2015). Nevertheless, the results of ME highlighted a less impact for willows and poplar crops compared to the other investigated lignocellulosic production showing not significant differences among groups (Fig. 8.4c).

The evaluation of EP impact category with CML method is shown in Fig. 8.5. The results achieved by the t-Test highlighted similar EP results for all investigated lignocellulosic herbaceous crops due to the comparable fertilization management. Two points are stand out: (i) the fibre sorghum cultivated in marginal land (point 18 Fig. 8.5 and Table 8.1) as combined results by the NH_3 volatilization after urea supply and the upstream and downstream emissions related to phosphorus input (Zucaro et al. 2015) and (ii) the GR cultivation on marginal soil (point 20 Fig. 8.5 and Table 8.1) producing about 170% higher EP impact compared to the same crop in fertile soil (Bosco et al. 2016). This finding highlighted the key role of biomass yield that can be considered as the main driver of environmental results of crop phase (Bacenetti et al. 2012; Bosco et al. 2016).

8.4 Concluding Remarks

The main findings achieved in this review can be useful for operators and stakeholders involved in the implementation of new bio-based supply chains, in particular regarding the choice of the best lignocellulosic feedstock to use from both a productive and an environmental point of view. Different management intensities have highlighted different environmental performance within the same group and in the cultivation of the same crop in different soils (marginal *versus* fertile). The choice of an applied method depends on the scope and objective of the study and the accounting of its limitations in results interpretation should be always discussed. Similarly, the calculation of the DFE emission needs to be clearly assessed considering the crop- and site- specific characteristics. The final outcome of this review has preliminarily highlighted for the investigated impact categories the SRF and MRF crops as the most promising lignocellulosic feedstock to supply bio-energy and/or biorefinery networks. Nevertheless, to routinely assess the environmental sustainability of bio-based processes a transparent environmental life cycle standardized procedure should be achieved.

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