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Environmental Assessment of Flax Straw Production for Non-Wood Pulp Mills

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Nowadays, there is an increasing interest for using non-woody fibres as raw materials for production of paper´s pulp. The present work aims to identify and quantify the environmental impacts associated with the production of flax fibres, through 3-year field experiment, carried out in Bologna and Pisa representative of the pedoclimatic characteristics of central Italy. Life Cycle Impact of “a one ton of fibre ready to be processed in a pulp mill” was assessed taking into account: farming, straw process (drying, scutching and baling) and transport. Inventory data for agricultural inputs and outputs were obtained directly from field experimentation and from bibliographic data about heat, transport and electricity consumption on straw processing. An economic allocation approach to assign impacts within flax seed and processed straw has been used. The CML baseline 2000 methodology was selected to quantify the potential environmental impact associated to the crops. Specifically, global warming (GWP), acidification (AP), eutrophication (EP) and photochemical oxidant formation (POP) were evaluated together with energy use (EU). Major impacts contribution arise from fertilizers use and straw processing. Cultivation phase of flax fibre at Pisa reported higher values (approximately 3 times greater) for all the impact categories. The lower impact in the flax cultivation scenario at Bologna was due to no use of mineral fertilizer and the higher flax-straw yield. It resulted also a strong reduction of the impacts with respect to those of hemp pulp in Spain as well as to the impacts of the conventional wood-pulp reported in Simapro. Furthermore, LCA tool aided to identify the materials and process that most affected the impacts: fertilizers use, diesel consumption and straw processing were identified as hot spots in both crops. Finally, non-wood pulp derived from Bologna´s Flax straw represents an opportunity to replace conventional wood pulp in Italian paper industry.

Keywords: Flax fibre; LCA; pulp mill.

1. Introduction

The potential of implementing a flax biorefinery chain is assessed in the context of local and imported feedstock with similar uses, the best available technological processes and market demand trends. Nowadays, lignocellulosic crops and residues of forestry sector are attractive feedstock for biorefineries specially when they are integrated into a pulp and paper mill because they do not compete with food crops for fertile land and relies on larger biomass yields (Moshkelani et al., 2013). Wood-pulp for paper manufacturing is the first non-food industrial utilization of plant biomass (wood and straw) in North America and Western Europe, particularly in Spain, Italy and Portugal (González-García et al., 2010; Sarma, 2014). Furthermore, wood fibres constitute the main virgin source of paper pulp raw materials in developed countries (Peng et al., 2015; Madakadze et al., 2010). However, in the last years the pulp and paper sector has been facing several problems related to the shortage of forest industry traditional resources and water pollution (González-García

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et al. 2010). Consequently, there is an increasing interest in non-wood fibres (i.e. Flax, Hemp, Cotton, and Bamboo).

The concept of sustainability is becoming increasingly important in the pulp and paper industry around the world (Hermann et al., 2007; Lopes et al., 2003). In order to improve its environmental performance, this industry has made important investments, not only in the production process itself, but also in the flue gases and liquid effluents treatment systems. Besides this concern regarding pollution prevention, one of the issues of most relevance in the context of sustainability is replacing wood pulp mills with non-wood ones (Kissinger et al., 2007; Dickson et al., 2014). In 2015, producers in Italy manufactured a total of 8.8 million tons of paper and paperboard equivalent to a 2.2% rise in production compared to 2014 according to Assocarta, opening a great business opportunity for non-wood fibres producers in Italy. In this regard, it become very important to assess alternative feedstock for paper industry, particularly that can reduce its environmental burden and increase the local production of alternative feedstocks, consequently improving coproducts (non-wood fibres) economic value. In this regard, it become very important to assess alternative feedstock that could able to reduce environmental burden of paper industry and increase their local production. The purpose of this LCA study is to determine if flax fiber cultivated in central Italy is suitable to be used as raw material in high quality paper pulp manufacturing. In this regard, this work assesses the use of flax fibre produced at Bologna and Pisa along three years (2013-2015), analysing the life cycle (LCA) of products and by-products (seeds and straw).

2. Materials and methods

The data used for LCA was taken from a three-year (2013–2015) research carried out within the project *“Materie prime Agricole italiane per Bioprodotti e Bioenergie”*, by a research team including: *Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria* (CREA), the University of Bologna, the University of Florence and the University of Pisa. All trials were conducted in the experimental fields located in Budrio at Bologna and San Piero at Pisa. Cultivation techniques are in line with the ‘state of the art’ of low impact agriculture practices and were considered as standard scenarios for flax production in central Italy. These farm practices in particular do not contemplate the use of irrigation and pesticides. The flax specie considered was *Linum usitatissimum var. Sideral*. Hypogeal and epigeal biomasses were estimated by sampling uprooting plants, cutting at root collar and weighting them. Experimental results are expressed as a three-year mean. Straw processing phase data was complemented with bibliographic sources (Lloveras et al., 2006; Turunen et al., 2006). Farming phase data is shown in Table1.

Table 1: Inputs and output flows of farming phase referred to the production of a hectare (mean values of seasons 2013-2015).

Agro-Inputs			**Bologna**		**Pisa**	
Characteristics		**Units**	**Mean**	**RSD**	**Mean**	**RSD**
Works	Human	Hours/ha	8,00	0,00%	8,00	0,00%
Organic Fertilizers	Organic N (Urea)	Kg/ha	16,00	35,15%	0,00	0,00%
Inorganic Fertilizers	Inorganic N (Anhydrous ammonia)	Kg/ha	22,33	40,20%	82,67	10,00%
	P2O5	Kg/ha	0,00	0,00%	53,33	46,19%
	K2O	Kg/ha	0,00	0,00%	53,33	49,14%
Phytosanitary	Pesticide	Kg/ha	0,00	0,00%	0,01	0,00%
Fuels	Diesel	Lt/ha	167,00	1,00%	118,67	17,00%
Seeds		Kg/ha	30,00	0,00%	38,00	3,00%
Outputs						
Grains	Output	ton/ha	1,53	30,52%	1,57	7,00%
Straw	Output	ton/ha	6,23	22,47%	3,87	12,66%
Total Biomass	Output	ton/ha	8,56	25,61%	5,81	21,57%

The agricultural system under study is focused on the production of non-wood pulp fibre and cold pressed flax oil assumed as representative of fibres production system supplying an Italian pulp mill industry. The system functional unit was then be defined as “one ton of fibre ready to be processed in a pulp mill”. which is in agreement with other agricultural LCA studies (Kong et al., 2014; González-García et al., 2010). The system boundaries included all the life cycle stages from the flax cultivation to the pulp mill gate. Although the specific period of flax crops growing is quite short (2–5 months), a year seasonal period has been considered. As regard transport from farm to pulp mill plant, 100km of transportation per ton (9,27 kg CO_2eq) and the consumption of 414,88 kWh has been assumed. As reported in González-García (2010) and the impacts of transformation of fibre into pulp was obtained from Kissinger (2007). All infrastructure impacts (building, plant and machinery) were not considered.

The impact assessment phase was carried out following the CML baseline 2000 methodology (Guinée et al., 2002) and in particular the impact categories usually used in an agricultural LCA (global warming (GWP), acidification (AP), eutrophication (EP) and photochemical oxidant formation (POP)) were analyzed as well as the use of non-renewable energy resources. The selection of these impact categories seems to be suitable for the evaluation of crops related to industrial products (van der Werf and Turunen 2008; Kissinger et al., 2007). SimaPro 8.1 (PRé Consultants) was used to perform the impact assessment. Impact allocation among coproducts has been considered, using their economic value for allocation according to several case studies and recommendations (Ardente and Cellura, 2012; Sarma, 2014).

3. Results and discussion

Considering farming phase, there are several differences in Bologna and Pisa requirements as shown in Table 1. The N-fertilizers used was greater in Pisa than Bologna influencing directly to N_2O emission. Moreover, only in Pisa super phosphate and potassium oxide were applied, increasing its environmental burden. Despite the great fertilizer use in Pisa, grain yield is basically the same while straw yield was considerably lower (almost a half) affecting directly the environmental performance of Flax produced in Pisa (see Figure1). On the other hand, Bologna had a greater diesel consumption, 40 % higher than Pisa. As highlighted in Figure 1, Bologna has lower impacts in all categories considered. Comparing the impacts of both cases with the Ecoinvent values assumed as a reference it may be noticed that, except the eutrophication for Pisa, all others are lower (very lower in the case of Bologna).

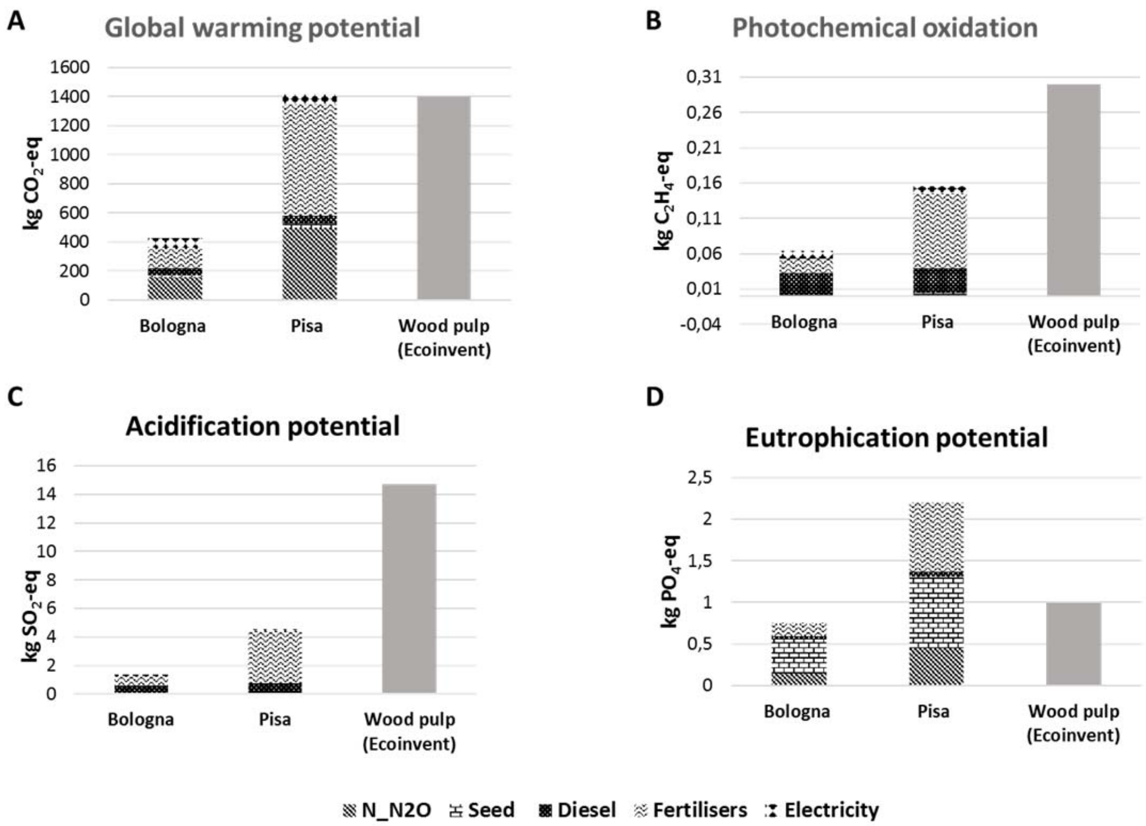

Figure1: Comparison of Flax pulp Impacts (per pulp ton) assuming Ecoinvent wood pulp values as a reference.

GWP (due to CO_2, CH_4 and N_2O emission) is mainly caused from fertilizers use (ranging 60-80%) followed by diesel consumption; Considering crop location, Pisa has shown almost triple GWP (approximately 1400 kg of CO_2eq/ton) in contrast with Bologna (See Figure1 A). N_2O emissions are principally leaded by N-Fertilizer affecting negatively Pisa cultivation GWP impact.
Photo-oxidants are formed in the troposphere under the influence of ultraviolet light by means of VOCs and CO in the presence of NOx. In Pisa, farming phase contributes to 50% of POP as shown in Fig. 1B. Fertilizers use involves almost the 40% of total contributions, specifically P-based fertilizer production. POP shows important contributions from energy-related emissions (SO2 and CO2). Moreover, Bologna POP is noticeable lower that wood pulp (Ecoinvent) that is over four times low. It is, beside GWP, one of the most relevant results concerning the environmental burden of paper pulp mill.
In Pisa, acidification (Figure 1 C) is mainly due to mineral based fertilizers (super phosphate and ammonium nitrate) while in Bologna is diesel consumption. Acidification Potential results has explained that it could be reduced from 14 to 2 kg SO_2-eq/ton replacing wood pulp with flax non-wood pulp (produced in Bologna).
Eutrophication covers all potential impacts related to high level of macronutrients, specifically nitrogen and phosphorus emissions to air, water, and soil. In Pisa, the use of fertilizers is the principal source to this impact category (Figure 1 D). Nitrate (NO_3^-) leaching, nitrogen and phosphate emissions have contributed to approximately 90% of the whole effect. Compared to the reference impact of Ecoinvent wood pulp it results an increment of 1,2 kg of PO_4-eq/ton for Pisa and a reduction of 0,3 kg of PO_4-eq/ton for Bologna.
Regarding fossil energy use, the highest value was that of Pisa, mainly due to mineral-based fertilizers consumption added to that of diesel. The comparison (Figure 2) highlights that Bologna has a lesser impact (9,5 GJ/ton) with respect the reference value of wood-pulp while Pisa is higher (13,2 GJ/ton). The results are in agreement with those of studies done over flax in Mediterranean zone (González-García et al., 2010), in other zones it was reported ranging 11- 13,3 GJ/ton. (Manda et al.,2012; Peng et al., 2015).

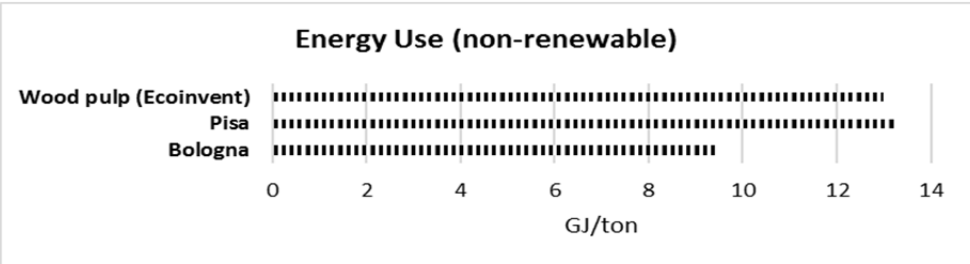

Figure 2: Comparison of energy use for Bologna and Pisa with Ecoinvent wood pulp reference value.

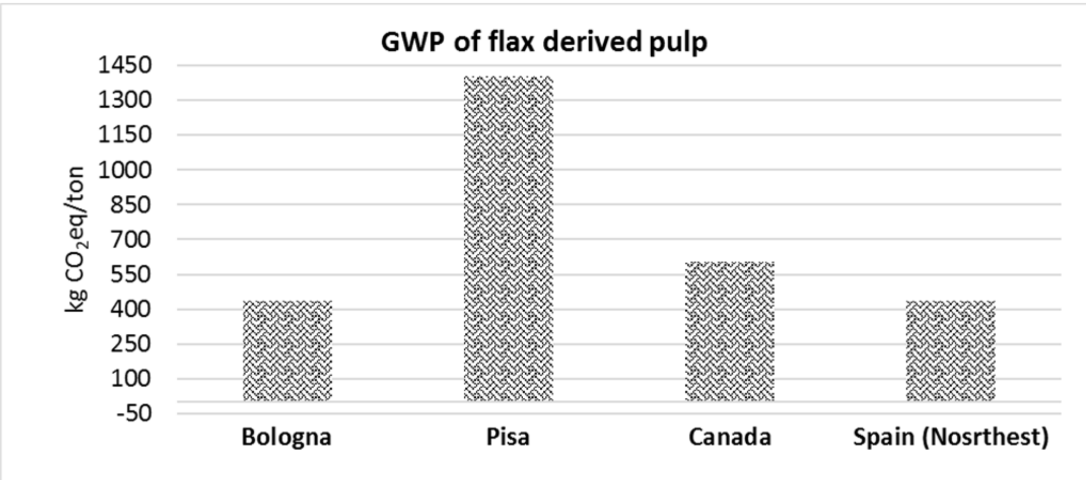

Figure 3: Comparison of Global warming potential for Bologna and Pisa crops with González-García (2010) and Kissinger (2007) reported in Spain and Canada respectively.

Flax-straw pulp produced in Bologna has evidenced a reduction of almost three times the GWP with respect to eucalyptus (Hermann et al., 2007; Lopes et al., 2003), hemp (González-García et al., 2010) and Ecoinvent wood-pulp reference value. With respect to GWP impact of flax-straw pulp our results are similar to those evaluated in Canada (Kissinger et al., 2007) and Spain (González-García et al., 2010), ranging 400-650 kgCO_2eq/ton (see Figure 3). Pesticides use was zero for Bologna crop and minimal for Pisa crop (lower than 0,01 kg/ha), amount that is lower than the value reported in similar studies (González-García et al., 2009; Warrand et al., 2005).
Finally, straw yields resulted considerably lower in Pisa than in Bologna (almost 40%) which strongly affected the pour environmental performance of Pisa flax-straw pulp production chain. These values compared with those of several studies (Lloveras et al., 2006; Turunen and van der Werf, 2006) shone that straw yield in Pisa is significantly lower.

4. Conclusions

Flax is an oilseed crop with a short growth cycle, high oil content and low agronomic inputs requirements, recognized as a good feedstock for bio-refinery. The LCA results have shown that Flax straw as feedstock to produce pulp mill in Bologna reduces impacts compared with Pisa and conventional wood-pulp production chain.
At the agricultural stage, three factors show higher influence over emissions: seed and straw yield, fertilizers applied, and diesel consumption, these two are the inputs to take under control in order to reduce the environmental burden associated to flax pulp production. Compared with wood pulp mill, flax-straw pulp produced in Bologna can reduce CO2eq emission from 1400 to 450 kg/ton.
In general, using Bologna flax straw leads to a considerable reduction of environmental impacts compared with eucalyptus wood-pulp and with Ecoinvent wood-pulp reference value.
In the last few years, it is important to point out new perspectives in green chemistry to revalue the flax by-products (seeds and straw) as feedstock. In our case, non-wood pulp derived from Flax straw represents an opportunity in order to replace conventional wood pulp in Italian paper industry due to its better environmental performance (Bologna crops).

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