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PRODUCTION PROCESS EVALUATION OF WASTEWATER-IRRIGATED PLANT BIOMASS THROUGH LIFE CYCLE ASSESSMENT

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ABSTRACT In this study the Life Cycle Assessment (LCA) of *Arundo donax* production process for energy purpose is proposed. The cultivation of this type of herbaceous biomass, irrigated with urban wastewater, was carried out in an experimental field, located in eastern Sicily (Italy). The analysis by LCA makes it possible, among other things, to evaluate the potential environmental impacts related to each phase of the process. In this study sensitivity analysis of the LCA results were carried out by varying the process stages. Furthermore the incidence of each process stage on the damage categories by varying the cultivation-cycle length was evaluated. The stages constituting the *Arundo donax* production process, considered in this assessment, regard seedling production, agronomic practices, irrigation, and transport to boiler. The functional unit used in the analyses was 1 ton of biomass and crop productivity values were derived from literature. The analyses allowed the identification of the most significant stages of the *Arundo donax* production process related to the experimental field. In detail, this study highlights that seedling production and irrigation stages contributed most of all to the overall environmental burden, whereas agronomic practices stage showed a minor influence on the process.

Keywords: *Arundo donax*, Environmental performance, Damage categories.

INTRODUCTION The basic principles of Life Cycle Assessment (LCA) were defined in USA and in Europe between the Sixties and the Seventies, and from the Eighties studies on LCA received a new stimulus on a worldwide scale with the aim to quantify the resources needed for goods production and for enhancement of production processes as well as for evaluating the related emissions to the environment. The LCA makes it possible, in fact, to evaluate the energy and environmental burdens associated to a process or to a product in relation to the energy and to the materials used and to the emissions released to the environment. The assessment concerns the whole life cycle (‘from cradle to grave’), included ‘the extraction and the treatment of raw materials, the manufacturing process, the transport, the distribution, the use, the reuse, the recycling and the final disposal’.

The LCA of a product or a process is generally developed to highlight critical points of a production process in order to reduce consumption of energy, raw materials and emission/waste production as well as to evaluate environmental or energy performance of a product/process in comparison to an analogous product/process and identify possible improvements to be done towards the achievement of environment sustainable development. LCA is an objective analysis technique which, on the basis of quantifiable parameters and specific phases, makes it possible to direct policy actions inherent environmental problems.

In 1990 SETAC (Society of Environmental Toxicology and Chemistry) began an extensive activity aimed at reaching agreement at international level about the definition of guidelines and methodological recommendations about LCA. This activity led to the definition of the SETAC Code of practice (Russell *et al.*, 2005). The standardization process continued then with the drafting of ISO standards. At present, in fact, the current standards ISO 14040:2006 (UNI, 2006a) and ISO 14044:2006 (UNI, 2006b) derive from ISO 14040:1997 (UNI, 1997), and from ISO 14041:1998 (UNI, 1998), ISO 14042:2000 (UNI, 2000a) and ISO 14043:2000 (UNI, 2000b), respectively.

In detail, ISO 14040:2006 describes the general criteria of the methodology identifying its main phases: goal and scope definition, inventory analysis, life cycle impact assessment, life cycle interpretation. The LCA procedure is iterative and interactive, i.e. requirements, objectives and/or application field can be modified after data collection (UNI, 2006a). Standard ISO 14044 analyzes the phases of LCA identified by ISO 14040. In detail, in the first two phases it is necessary to: describe the system which is the object of the study, and list data categories to be analyzed; define the characteristics of product/process performance, quantifying them by defining the functional unit which all input and output data must be referred to; identify and quantify the input and output fluxes of the system, structuring this activity in data collection, computation process and interpretation of results. In the third phase of LCA the results of the inventory analysis are elaborated to obtain information about the potential damages associated to human health, resources depletion, and environmental degradation. Finally, the standards allows to carry out data interpretation also by comparing different products with the aim to find out the best one from the point of view of the environmental sustainability. Further supports to the application of the Standards derive from some ISO technical reports: ISO/TR 14047 (UNI, 2003) details examples of impact evaluation; ISO/TS 14048 (UNI, 2002) defines standardized data format to show the results of the LCA study; ISO/TR 14049 (UNI, 2000c) illustrates a set of examples regarding the inventory analysis according to ISO 14041.

Within production processes of energy crops, LCA makes it possible to evaluate the overall environmental burden of the biomass supply chain, i.e. from the biomass production to its combustion in boiler. By analyzing LCA results, decisors could derive suggestions for strategic choices aiming at reducing environmental risks.

In this paper LCA was applied to the biomass production from *Arundo donax* crop grown in an experimental field and irrigated with urban wastewater. The study aimed to highlight possible weak points of the production process, in relation to raw material-and-energy fluxes through the system, and variability of *Arundo donax* productivity in a life cycle of 10 years.

MATERIAL AND METHODS

2.1 Description of the experimental field The experimental field, sited in the Municipality of San Michele di Ganzaria, in the province of Catania (Italy), at an altitude of 490 meters above the mean sea level, is composed of two parcels of 486.5 m^2 (17.5 m × 27.8 m). The experimental field has a micro-irrigation system which distributes urban wastewater, stored in a reservoir, after phytodepuration. The water distribution system is composed of the storage reservoir of about 40 m^3 and a micro-irrigation plant constituted by the following components: a vertical multi-stage pump (2.2 kWh), a disk filter, PE pipelines having different diameters (16 mm for dripping pipes and 40 mm for water main distribution), T-shaped joints, ring joints, closing and calibration valves, volumetric meters, manometer and accessories. All these elements were taken into consideration in the LCA. In detail, all the works needed to build the reservoir were considered (excavation, soil compaction, waterproofing, etc.), and production processes of the micro-irrigation plant components were analyzed. Some of them are considered to be replaced during a life cycle of 10 years. In detail, due to mechanical harvesting of the biomass, ϕ16 pipes are considered to be substituted every year, whereas for ϕ40 pipes this is done every 5 years. The irrigation volumes actually distributed in the field are monitored by volumetric meters placed near to the distribution point of each sector and the irrigation need is computed by using a microclimatic station composed of dataloggers and sensors for the estimation of plant evapotraspiration. Wastewater is analyzed to determine the chemical-physical properties (BOD5, COD, SST, Nitrogen in different forms and total Phosporous content) (Barbera *et al.*, 2009). The *Arundo donax* plants transplanted in the experimental field were purchased from a nursery which utilizes the micropropagation technique. Therefore in the LCA the three main subprocesses which compose the production process of *Arundo donax* seedlings were considered: micropropagation, subcultivation and greenhouse nursery growing.

2.2 Application of the LCA methodology to the case study According to UNI 14040, the goal and the scope of the LCA were firstly defined. In detail, the objective is the evaluation of the incidence of the different stages of the process on the overall environmental burden due to *Arundo donax* production. This evaluation was carried out with the aim to identify possible weak points in the process and acquire a wider knowledge suitable to suggest, together with further investigation and research, different scenarios of biomass production with a low environmental impact. The scope of the analysis was referred to the functional unit of 1 t of biomass of fresh matter. The choice of this functional unit, instead of the unit of energy (1 MJ) comes from data availability. In fact, in this study productivity data were taken from literature. Therefore, if also literature data would have been taken for energy characteristics, uncertainties related to both energy and productivity would have caused a higher approximation of the results. A more accurate inventory analysis would result as soon as biomass production data and its energy characteristics will be available from the experimental field results.

Data regarding *Arundo donax* biomass production in Sicily is about 10 t/ha of dry matter (D.M.) for the first year and 22 t/ha D.M. for the second year (Cosentino *et al*., 2006). Preliminary results from the experimental field are comparable (Barbera *et al*., 2009). Literature shows that production increases in the next years reaching values higher than 20 t/ha D.M. (Angelini *et al*., 2005; Angelini *et al*., 2009). Therefore, in the analyses a minimum value of field productivity equal to 15 t/ha of fresh matter (F.M.) was considered for the first year whereas a productivity of 45 t/ha F.M. for the next years.

The production stages and the related subprocesses used to describe *Arundo donax* production are shown in Fig. 1 by using a block diagram (Bidini *et al*, 2006). In this study the environmental burden associated to the whole biomass production process was evaluated considering the specific contribution of the different stages. Moreover, the saved resources were evaluated in terms of avoided environmental burden due to the use of wastewater instead of conventional resources and fertilizers. Thanks to soil clay nature and stratigraphy in the area under study, it is possible to neglect the percolation of the part of wastewater nutrients incompletely absorbed by the crop. The wastewater treatments developed before the storage reservoir was considered outside system boundaries as these treatments are carried out independently from the subsequent use of the wastewater yet to comply with the regulations in force concerning the disposal of wastewaters. Also the combustion in the boiler was considered outside the system, as experimental-test results concerning the energy characteristics of the biomass and the emissions associate to combustion process are in progress.

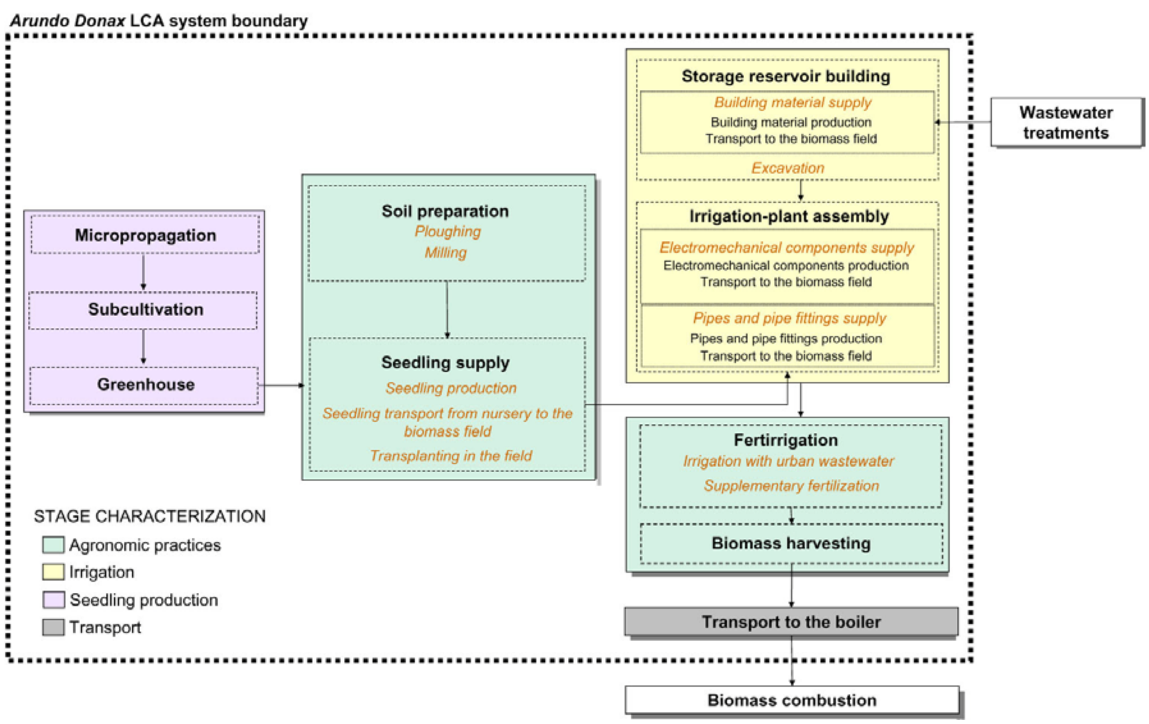

Figure 1. Block diagram of *Arundo donax* production.

In the proposed analyses the environmental burden related to the first year of biomass cultivation (1st scenario) and that associated to a production cycle of 10 years (2nd scenario) were considered with the aim to evaluate the reduction over time of the burden due to the initial agronomic practices and to find out the incidence of some yearly operations on the overall burden. Furthermore, other two scenarios were considered with the aim to highlight production-stage burden variation due to an increase of crop productivity. In detail, a 3rd scenario was carried out considering only the first year of cultivation fixing a maximum value of production equal to 65 t/ha F.M., whereas a 4th scenario was built by fixing a maximum value of production equal to 25 t/ha F.M. for the second year until the end of the 10-year life cycle.

To identify the production stages which determine the highest impacts, the incidence of the following production-stage subprocesses were considered for each scenario:

- *Seedling production* stage: micropropagation, subcultivation and greenhouse nursery growing (included the transport from the nursery to the field, which was considered to be carried out at a regional scale, i.e. a distance of 250 km).

- *Agronomic practices* stage: soil preparation, seedling transplanting in the field, irrigation with urban wastewater, harvesting. In this study, harvesting is a yearly subprocess carried out by using a blade brush cutter.

- *Irrigation* stage: storage reservoir building, irrigation-plant component supply (PE pipes, pumps, and pipe fittings).

- *Transport to the boiler*: transport activity from field site to boiler was considered to be carried out at a regional scale, as for seedling production subprocess.

In this work the disposal of materials used in each subprocess was considered.

According to the second phase of LCA in the standards, data collection was carried out by identifying the fluxes of raw materials and energy for each subprocess within system boundary. Collected data were elaborated by using the software Simapro 7.1 with Ecoinvent 99 database which assembles all the most requested data on materials, production processes, energy generation, product disposal, etc. The computation method used for the analyses carried out in this study is Ecoindicator 99. This method is based on a damage-oriented approach. In detail, three typologies of environmental damage are considered (human health: HH, ecosystem quality: EQ, resources: R) which in turn are subdivided in 11 impact sub-categories (Prè Consultants, 2008a). Ecoindicator 99 method refers to parameters at European level, and damages are normalized with reference to the damage caused to a European citizen in a year. For each scenarios an index, named ‘single score’ is computed and applied to the three damage categories and to the whole process. The value of single score increase with damage raise. In this study the hierarchic weight defined within Ecoindicator99 was applied (Prè Consultants, 2008b). Hierarchic method considers all the damaging substances in a medium-term perspective, with a weight incidence, associated to the damage categories, distributed as follows: HH 30 % - EQ 50 % - R 20 %.

RESULTS The single scores of the 10-year life cycles related to the minimum and maximum productivity results equal to 604 Pt and 395 Pt, respectively. The values, expressed in percentage, of the rate between the single score of the considered subprocess and that of the whole process in the considered scenarios are reported in Tables 1-2. In these tables, on the basis of EcoIndicator 99 method, burden values were subdivided into damage categories (Human Health, Ecosystem Quality, Resources). In detail, each production stage was subdivided into subprocesses having different environmental impacts according to the considered scenario.

	SEEDLING PRODUCTION						AGRONOMIC PRACTICES								IRRIGATION								TRANSPORT TO THE BOILER	
																			Pipes					
	Micropropagation		Subcultivation		Greenhouse		Soil preparation		Seedling transplanting (biomass fiel)		Irrigation with urban wastwater		Harvesting		Storage reservoir building		Irrigation plant components (except pipes)		Φ 40 mm		Φ 16 mm			
DAMAGE CATEGORY	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle
Human Health (%)	3,776	3,101	4,401	2,660	4,496	3,167	0,117	0,083	0,328	0,231	0,404	1,138	0,007	0,020	1,643	1,157	1,711	1,205	0,197	0,185	1,441	4,061	0,299	2,110
Ecosystem Quality (%)	0,705	0,563	0,799	0,497	0,842	0,593	0,024	0,017	0,044	0,031	0,069	0,195	0,004	0,011	0,799	0,563	0,508	0,358	0,014	0,013	0,105	0,295	0,079	0,554
Resources (%)	14,880	12,319	17,487	10,483	20,698	14,581	0,190	0,134	0,366	0,258	1,306	3,681	0,019	0,054	10,801	7,609	2,804	1,975	0,939	0,882	6,864	19,344	0,833	5,871
Total	**19,361**	**15,983**	**22,687**	**13,640**	**26,036**	**18,342**	**0,332**	**0,234**	**0,737**	**0,519**	**1,779**	**5,014**	**0,030**	**0,085**	**13,243**	**9,329**	**5,022**	**3,538**	**1,150**	**1,080**	**8,410**	**23,699**	**1,212**	**8,535**

Table 1. First and second scenarios of *Arundo donax* LCA.

	SEEDLING PRODUCTION						AGRONOMIC PRACTICES								IRRIGATION								TRANSPORT TO THE BOILER	
																			Pipes					
	Micropropagation		Subcultivation		Greenhouse		Soil preparation		Seedling transplanting (biomass fiel)		Irrigation with urban wastwater		Harvesting		Storage reservoir building		Irrigation plant components (except pipes)		Φ 40 mm		Φ 16 mm			
DAMAGE CATEGORY	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle	First year	10-year cycle
Human Health (%)	3,746	2,439	4,366	2,843	4,460	2,904	0,117	0,076	0,325	0,212	0,401	1,164	0,007	0,021	1,630	1,061	1,697	1,105	0,195	0,176	1,430	4,154	0,495	3,224
Ecosystem Quality (%)	0,699	0,455	0,793	0,516	0,835	0,544	0,024	0,016	0,043	0,028	0,069	0,200	0,004	0,011	0,792	0,516	0,503	0,328	0,014	0,013	0,104	0,301	0,130	0,847
Resources (%)	14,761	9,613	17,347	11,296	20,532	13,371	0,189	0,123	0,363	0,236	1,296	3,765	0,019	0,055	10,714	6,977	2,781	1,811	0,931	0,840	6,809	19,784	1,378	8,973

Table 2. Third and fourth scenarios of *Arundo donax* LCA.

In all the scenarios analyzed, it resulted that seedling production and irrigation stage determined, over the whole process, the highest impacts in percentage, with values ranging between 43.98%÷68.08% and 27.60%÷37.65%, respectively. In detail, the percentages related to damage categories show that the highest values are reached by resource damage category (34.28÷53.07%) within ‘seedling production’ stage, followed by human health damage category (21.24÷29.81%) within ‘irrigation’ stage. The EQ damage category, instead, is always characterized by lower values ranging between 2.35% and 0.08% within the whole process.

The comparison between the results obtained for the first year of cultivation and those obtained in the 10-year life cycle shows that the raw materials (saved conventional resources and fertilizers, and pipes), incoming energy into the system (electricity needed to pump functioning), and yearly activities (harvesting and transport of the biomass), which are carried out during the whole period of plant growth, determine in all scenarios higher impacts (in percentage) in the 10-years life cycle than in the first year of cultivation (Tables 1-2). For instance, in maximum production scenarios, the construction of the storage reservoir decrease in incidence from 13.1% to 8.5% when the considered life cycle goes from 1 year to 10 years, whereas the substitution of the ϕ16 pipes every year produces an impact increase from 8.3% in the 1-year cycle to 24.2% in the 10-years cycle, respectively. This result shows that a different irrigation system should be designed to reduce the environmental impact of biomass production.

As regards seedling production stage, in maximum productivity scenario related to the first year of cultivation (Tab. 2), for instance, micropropagation, subcultivation and seedling growth under greenhouse have incidences over the total impact of 19.21%, 22.51% and 25.83%, respectively. Therefore, under the hypothesis of using rhizomes of spontaneous plants the overall impact would reduce of 41.72%. With reference to the high contribution which micropropagation and subcultivation confer to the whole environmental burden, the choice of micropropagated plants is acceptable if a productivity increase is attained in comparison to the use of plants rooted under greenhouse or rhizomes of spontaneous plants. Furthermore, by highlighting a high sensitivity of the single score to crop productivity, the results show that crop productivity constitutes a crucial parameter to correctly determine the process environmental burden. In this regard, further improvements could be obtained by defining a more appropriate *Arundo donax* yield curve through long-term experimental trials.

The agronomic practice stage affects to a minor extent the overall burden and, therefore, it can be regarded as a less significant stage in the assessment of biomass production process and in the research of possible modification of the process. Greater attention must be given to this stage when considering a wider field for a large-scale biomass production.

CONCLUSION The LCA of the production process carried out in this study, regarding biomass for energy purposes irrigated with wastewater, made it possible to identify the most significant stages affecting the environmental assessment. The results showed that the production of *Arundo donax* seedlings and the irrigation plant contributed most of all to the overall environmental burden. These analyses allowed to make suggestions regarding modification of some subprocesses, also in dependence on crop productivity scenarios.

Further research would concern the analysis of a large-scale production process and the comparison between the production processes of different biomass carried out in the experimental fields belonging to the research project. As this study highlighted a high sensitivity of the biomass production process assessment to crop productivity, further investigation could be based on experimental results regarding *Arundo donax* yield curve, as well as biomass energy yield obtained by laboratory trials could allow to refer the process to an energy functional unit.

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