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Agronomic, Energetic and Environmental Aspects of Biomass Energy Crops Suitable for Italian Environments

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Abstract

The review, after a short introduction on the tendencies of the European Community Policy on biomasses, describes the agronomic, energy potential and environmental aspects of biomass crops for energy in relation to the research activity carried out in Italy on this topic, differentiating crops on the basis of the main energy use: biodiesel and bioethanol (which refers to "first generation biofuel"), heat and electricity.

Currently, many of the crops for potential energy purposes are food crops (wheat, barley, corn, rapeseed, soybean, sunflower, grain sorghum, sugar beet) and their production may be used as biofuel source (bioethanol and biodiesel) since their crop management aspects are well known and consequently they are immediately applicable. Other species that could be used, highly productive in biomass, such as herbaceous perennial crops (*Arundo donax*, *Miscanthus* spp., cardoon), annual crops (sweet sorghum), short rotation woody crops (SRF) have been carefully considered in Italy, but they still exhibit critical aspects related to propagation technique, low-input response, harvest and storage technique, cultivars and mechanization.

Crops for food, however, often have negative energetic indices and environmental impacts (carbon sequestration, *Life Cycle Assessment*), consequent to their low productivity. Conversely, crops which are more productive in biomass, show both a more favourable energy balance and environmental impact.

Key-words: energy biomass crops, energetic indices, *Life Cycle Assessment*, CO_2 balance, VII Framework Program.

1. Introduction

The European Union foresees two key targets by 2020 (Commission of the European Communities, 2008 23.01.2008):

– at least a 20% reduction in greenhouse gases (GHG)
– a 20% share of renewable energies in EU energy consumption.

The European energy policy in biomass sector (Commission of European Communities, 2005) seems to be more oriented towards cereal and oil crops for biofuel production (biodiesel and bioethanol), since electricity and heat may derive from non-agricultural sources as well, such as forestry and waste biomass. In 2005, 1.8 million hectares in Europe were destined to biofuel crops, oil crops in particular for "biodiesel" production. Nevertheless, in order to reach the 10% biofuel target foreseen by the "Impact assessment of the Renewable Energy Roadmap" (Commission of the European Communities, AGRI G-2/WM D, 2007) 17.5 million hectares of energy crops or 15% of the total arable land in the EU are required.

At the present stage of development, the above-mentioned bioenergy chains can be fed by the most widespread crops cultivated in Italy (wheat, barley, corn, rapeseed, soybean, sunflower, grain sorghum, sugarbeet), with economic, technical and social strong points since these are traditional and consolidated crops. Other proposals are entirely new, as for example giant reed (*Arundo donax* L.), a wild species

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widespread in all Italian areas, or miscanthus (*Miscanthus* spp.), a species originating in highly different environments with respect to Italian and more generally European ones, introduced initially for ornamental uses.

The most commonly adopted classification for bioenergy crops is based on the prevalent biomass usage: oil for biodiesel production, carbohydrates for fermentation for bioethanol production, lignocellulose for heat and electricity production.

In the present review, an overall evaluation of biomass crops for energy production has been carried out, taking into account the agronomic aspects (novel crops and cropping systems in relation to the European Agricultural Policy directives), the energy aspects (energetic indices) and the environmental objectives, since positive implications on emission reduction, with particular reference to carbon dioxide into the atmosphere, must consider sustainable agriculture criteria.

2. Agronomic aspects

2.1 Bioethanol chain

Crops traditionally used are those for food which cumulate starch or sugars for fermentation in plant storage organs: wheat (*Triticum* spp.), corn (*Zea mays* L.), sweet and grain sorghum (*Sorghum bicolor* (L.) Moench), sugarbeet (*Beta vulgaris* L.), etc. By considering the well-known agronomic management for most of these crops, the European research is primarily focused on sweet sorghum. This species is characterized by a high yield potential and a great resistance to long drought periods; for this reason, it can be cultivated throughout Europe (Dalianis, 1996; AIR CT92 0041, 1995; FAIR CT96-1913, 1996). In Italy, its productivity under optimum soil water conditions is around 30 t ha^{-1} d.m., but it can exceed 40 t ha^{-1} d.m. in southern regions (Cosentino et al., 1996; Foti et al., 1996; Cosentino et al., 1997; Patanè et al., 1997; Mastrorilli et al., 1999). The variability depends on climatic and soil conditions, input levels, water applied and/or soil water storage, but also on cultivar and sowing time. Field experiments conducted on sorghum highlight the highest productivity of late genotypes, which have fermentative sugar contents higher than 16% of fresh stalk biomass and sugar yields up to 18 t ha^{-1} (Copani et al., 1989; Perniola et al., 1999; Cosentino et al., 2003a). Moreover, early sowings seem to be advantageous in terms of biomass yield as compared to late sowings. The latter, however, are interesting for Southern areas since they may permit saving irrigation water, moving part of the growing season to autumn and allowing the use of early autumnal rainfall (Mantineo et al., 2005). These rainfalls could allow the "ratooning" of the crop in order to have two crops in one year (Mastrorilli et al., 2002). The posibility of anticipating sowing time by means of seed osmopriming or by the use of cultivars resistant to low temperatures have been investigated by Foti et al. (2002) and Patanè et al. (2006). The advancing of the growing season could also be obtained leaving the ratoon after the harvest which can re-grow the following year (Cosentino et al., 2007c).

The advantages of cultivating sweet sorghum for energy purposes mainly derive from the easy introduction of the crop into current cropping systems by applying ordinary crop management and farm machinery. The difficulty in finding seed represents a weak point. Other problems are: the irrigation requirement in Southern areas, lodging susceptibility which is possible to prevent either by agronomic management (fertilization, irrigation, plant population) or by cultivar selection. To this end, a wide research activity has been conducted in Italy through breeding programs for new genotypes selection (fiber types) resistant to low temperatures, to lodging and drought (Lorenzoni et al., 2005). From a technical point of view, the presence of a large amount of silica in leaves has been reported to reduce the burning chamber efficiency (Venturi and Bentini, 2005).

2.2 Biodiesel chain

Biodiesel chain is widespread throughout Italy since the crops involved are largely well-known and cultivated for food uses. These are annual species such as sunflower (*Helianthus annuus* L.), rapeseed (*Brassica napus* L. var. *oleifera* D.C.), soybean (*Glicine max* L.) and other food and non-food *Brassicaceae*, belonging to *Sinapis*, *Crambe*, *Brassica* genera. Within perennial crops, artichoke (*Cynara cardunculus* var. *scolymus* L.) and cardoon (*Cynara cardunculus* var. *altilis* D.C.) may also be used for achene oil extraction.

Rapeseed is not widely grown in Italy when compared to the broad diffusion in North Europe; however, this crop benefits from an agronomic research which has successfully investigated and solved the main problems met when this crop was first introduced. In the three geographic areas of the country, yield reported in the scientific literature changed considerably: between 1.2 and 4.1 t ha^{-1} in North Italy and between 0.7 and 4.9 t ha^{-1} in Central Italy; in the South, yields similar to those obtained in North Italy alternate with yields lower than 1 t ha^{-1} (0.8-3.8 t ha^{-1}) (Tab. 1) (Toniolo et al., 1992; Abbate et al., 1993; De Mastro et al., 1999; Mazzoncini et al., 2002; Onofri et al., 2005; Zanetti et al., 2005; De Mastro et al., 2006). Seed oil content is slightly higher in Central-North than in the South of Italy (39-48% against 34-44%).

From the 1990s onward, attention has been focused on *Brassicaceae* with long-chain fatty acids such as erucic acid (C22:1), which is highly interesting for the engine and lipochemical industries. To this end, cultivars and lines of *Brassica napus* L. var. *oleifera* D.C. HEAR (High Erucic Acid Rapeseed), *Brassica carinata* A. Braun, *Brassica juncea* L. Czern, *Brassica rapa* L., *Sinapis alba* L. and *Crambe abyssinica* Hochst ex Fries were studied. Field experiments conducted in Italy (Mosca 1998; Venturi et al., 1998; Copani et al., 1999; De Mastro et al., 1999.; Errani et al., 1999; Fontana et al., 1999; Lazzeri et al., 1999; Mazzoncini et al., 2002; Cosentino et al., 2004; Di Candilo et al., 2005a; Zanetti et al., 2006) pointed out good yields of *Brassica napus* cultivars. *Brassica carinata* exhibited good adaptation especially in Southern areas, for its flowering earliness, resistance to pod shatter and lodging, biotic and water stress resistance, which involve a higher yield stability as compared to rapeseed (Mazzoncini et al., 2002; Zanetti et al., 2006). Seed oil concentration and oil erucic acid concentration were almost always lower in *B. carinata* than in *B. napus*, but oil yield was similar to that of rapeseed. Difficulties, in relation to crop environment, were encountered by *Crambe abyssinica*, *Brassica juncea* and *Sinapis alba*. In particular, poor resistance to low temperatures has been observed in Crambe, which suggests spring sowings in Central-North areas (Lazzeri et al., 1998; Fontana et al., 1999).

Sunflower, for its morphological and physiological traits, may be suited to scarce and irregular rainfall conditions and high summer evapotranspiration; it is mainly cultivated in "sunflower belt" environments which range from Tuscany to the Adriatic regions (Monotti, 2002) and in low water availability areas of the North. For the biodiesel chain, high oleic genotypes are suggested (cultivars and hybrids primarily selected abroad), with an acid concentration ranging from 45 to 52% (Monotti, 2002). Early sowings at the end of winter and/or early cultivars are preferred. Conventional crop management allows achieving a seed yield higher than 3.0 t ha^{-1} in the Centre of Italy, with a reasonable variability within genotypes, close to 2.7 t ha^{-1} in the North of Italy and higher than 4 t ha^{-1} in the South of Italy but with no limitation of water supply (Tab. 1).

In cardoon, the seed represents approximately 30% of head dry biomass (around 26% in artichoke) (Foti et al., 1999; Curt et al., 2002) and 10% of total dry biomass; seed oil content is about 25%. Oil composition is similar to that of sunflower (Fernandez and Curt, 2005). Both species (artichoke and cardoon) originate from the Mediterranean basin and therefore are suitable to drought conditions of the Centre and South Italy where they are cultivated in autumnal-winter growing season and harvested in late summer (Foti and Cosentino, 2001; Cosentino et al., 2005b). Seed yield is higher in cardoon and wild types (*Cynara cardunculus* L. var. *sylvestris* Lam) than in artichoke, but with a high variability (between 0.4 and 2.8 t ha^{-1}) (Tab. 1). The biomass yield usually decreases from the second year of cultivation onward (Foti et al., 1999; Gherbin et al., 2001a). The number of genotypes available is higher in artichoke than in cardoon.

2.3 Lignocellulosic chain

After a first selection among different lignocellulosic crops at the end of the 1990s, through research programs supported by EU (FAIR CT96-2028, 2001; AIR CT92-0294, 1997; FAIR CT96-1704, 1998; AIR CT93-1089, 1999), more attention has been paid towards giant reed (*Arundo donax* L.), miscanthus (*Miscanthus* spp.), switchgrass (*Panicum virgatum* L.), cardoon (*Cynara cardunculus* var. *altilis* D.C.), fiber sorghum (*Sorghum bicolor* L. Moench) (Foti and Cosentino, 2001; Venturi and Bonari, 2004). In recent years, this list has been enriched with that of short rotation forestry (SRF) species (Bonari, 2001, 2005; Bonari and Villani, 2004;

Table 1. Agronomic aspects of oil crops and bioethanol crops studied in Italian environments.

Species		Italian regions	Sowing or transplant (month)	Harvest (month)	Yield (t ha^{-1} d.m.)	Oil or sugar content (%)	References
Bioethanol chain							
Sweet sorghum	Seed	Northern	V	XI-XII	16-38	44%ϒ	Cosentino et al., 2005b
		Central	V		28		Dolciotti et al., 1998
			V	IX	18-26		Barbanti et al., 2006
			IV-V	IX	20-34		Cosentino et al., 2005b
		Southern	VI	XI	6§-28*		Foti et al., 2004
			V-VII	X-XI	14§-45*		Cosentino et al, 1996
			IV-V	X	30-32•		Mastrorilli et al., 1999
			VI	IX-XI	22-34•	9-18%√	Copani et al., 1989
			V - VI	X	30•		Abbate and Patanè, 1996
			V		15-36•	8.8-14.4√	Patanè et al., 1997
			V	IX-X	20§-42*	12-16.9√	Cosentino et al., 1997
Biodiesel chain							
Rapeseed	seed	Northern	IX-X	VI	2.4-3.2❑	42-44	Zanetti et al., 2005
					3.2-3.5♥		Zanetti et al., 2005
			X	VI	2.5-2.6	40-45	Toniolo et al., 1992 (revised data)
			IX	VI	1.2-4.1	40-48	Onofri et al., 2005
		Central	X	VI	2.0-2.9	40-47	Toniolo et al., 1992 (revised data)
			X	VI	0.7-1.9❑	39-42	Zanetti et al., 2005
					1.3-2.4♥		Zanetti et al., 2005
			IX	VI	3.6-4.2		Zanetti et al., 2005
			X	VI	1.1-2.0		Onofri et al., 2005
			X	VI	3.2-4.9	38-43	Onofri et al., 2005
					2.3-3.2	39-44	Mazzoncini et al., 2002
		Southern	X-XI	V-VI	0.8-3.1	34-44	Toniolo et al., 1992 (revised data)
			X-XI	V-VI	1. 0-3.8		Abbate et al., 1993
					1.6-2.2	41-43	Mazzoncini et al., 2002
					2.5♣-2.9♦		De Mastro et al., 2006
			Autumn		2.1±0.8	33	De Mastro et al., 1999
			Spring		1.6±0.9	32	De Mastro et al., 1999
Brassica juncea	Seed	Northern	IX	V-VI	0.8-2.9	30-42	Zanetti et al., 2006
		Central			1.67-2.20	31-39	Mazzoncini et al., 2002
		Southern	X	V-VI	1.2	34	Cosentino et al., 2004
			XI-XII	VI	0.7-2.1	31-42	Copani et al., 1999
			Autumn		1.6±0.7	31	De Mastro et al., 1999
			Spring		0.9±0.7	29	De Mastro et al., 1999
Brassica carinata	Seed	Northern	IX	V-VI	0.4-3.1	32-38	Zanetti et al., 2006
		Central			3.2-3.3	33-39	Mazzoncini et al., 2002
		Southern	X	V-VI	2.7	34	Cosentino et al., 2004
					1.9-3.5	34-38	Mazzoncini et al., 2002
			Autumn		3.4±1.0	31	De Mastro et al., 1999
			Spring		3.5±0.6	30	De Mastro et al., 1999
Crambe abyssinica	Seed	Northern	IV	V-VI	1.0	26	Zanetti et al., 2006
					1.0	26	Mazzoncini et al., 2002
			III	VII	1.3-3.0	33-37	Lazzeri et al., 1999
		Central	III	VII	1.4-2.2	27-28	Di Candilo et al., 2005a
			III	VI	2.4-3.5	33-38	Fontana et al., 1999
					1.9-2.6	35	Mazzoncini et al., 2002
		Southern			1.5-2.1	33-34	Mazzoncini et al., 2002
			XII	V	1.6	30	Copani et al., 1999
			Autumn		2.4±0.9	33	De Mastro et al., 1999
			Spring		1.0±1.0	21	De Mastro et al., 1999
Sunflower	Seed	Northern	Spring		2.1♣-2.7♦	44-56	Baldini et al., 2005
		Central	Spring		3.0-3.3	45-52	Monotti et al, 2005
		Southern	Spring		5.5	41-45	Anastasi et al., 2001
			Autumn		4.1-4.6	45-53	Anastasi et al., 2001
Cardoon	Seed	Southern	VII	VII	1.1-2.8	24-27	Foti et al., 1999
			V	VIII	0.4-1		Gherbin et al., 2001a
			V-XI		0.4- 1.4	18-23	Piscioneri et al., 2000

• irrigated; # dry; § 25% ETM; * 100% ETM; ϒ % of d.m.; √ % of f. m.; ♣ organic management; ♦conventional management; ❏ t ha year high inputs; ❑ t ha year low inputs.

Bonari et al., 2005). These are mostly crops which have not yet been introduced into the current cropping systems.

Taking into account the ontogenesis of the species for its agronomic implications, the species could be distinguished in annual (sorghum) or perennial (all other species). The research was addressed towards fiber sorghum (which, when compared to sweet sorghum, cumulated mainly cellulose fibers instead of soluble sugars in stalks) for the same reasons as those indicated for sweet sorghum (bioethanol chain). When compared to this last, the specific advantages of fiber sorghum are the easy seed availability, which at present is produced and distributed in Europe, and the lower susceptibility to lodging, which is one of the main objectives of the genetic improvement carried out in Italy (Lorenzoni et al., 2005).

Perennial species may contribute to agronomic and environmental sustainability, since they limit soil tillage and act positively in protection of soil against erosion, enhancement of soil fertility and reduction of CO_2 emission; they require a low use of pesticides, herbicides in particular; they have low nutritional requirements, due to nutrient "recycle" in species with a rhizomatous root (Foti and Cosentino, 2001; Monti et al., 2002; Lewandowski et al., 2003; Venturi and Bonari, 2004; Cosentino et al., 2005b); they also allow an annual biomass harvest, unlike the SRF. The main drawbacks revealed up to now are the low biomass yields in transplanting year (Angelini et al., 2005a; Cosentino et al., 2006a) and the difficult mechanization in giant reed, cardoon and *Miscanthus*, with particular reference to the lack of harvesting machines (Venturi and Bentini, 2005) and the availability on the market of propagation material for giant reed and *Miscanthus* which can be propagated only by rhizomes, stem cuttings, micro-propagated plants (Cosentino et al., 2003b).

In terms of thermal conversion, a relevant problem is represented by the high ash content, which leaves sediments in the burning chamber and limits the normal functioning of the boiler; to this end, heating value of biomass has been estimated to decrease by 0.2 kg MJ kg^{-1} for each 10 kg kg^{-1} ash increase (Monti et al., 2005). The highest ash content occurs in cardoon (8 to 14%), followed by giant reed (4 to 7%), switchgrass (3 to 6%), *Miscanthus* (2 to 3%). In Table 2, a comparison of ash content within annual, perennial and SRF species is reported.

The research on perennial herbaceous plants in Italy has been conducted throughout the entire country. Germplasm collections of giant reed (39 genotypes) (Cosentino et al., 2006a), *Miscanthus* (5 genotypes) (Cosentino et al., 2006b, 2007a) and cardoon (17 genotypes) (Gherbin et al., 2001) have been constituted. The main issues of agronomic management, such as plant density (Angelini et al., 2005a), propagation methods (Cosentino et al., 2003b), nitrogen fertilization and irrigation (Cosentino et al., 2005b; Cosentino et al., 2007a) have been studied, together with the physiological matters connected with water stress (Foti et al., 2003) and the effects of some of these factors upon mechanical characteristics of giant reed (Cosentino et al., 2003c).

Cardoon is an autumn-sown and summer-harvested species. In relation to harvest time and cultivation environment, biomass presents a moisture content ranging between 16 and 62% (Tab. 2); it does not normally require irrigation, but like other plants which grow with the rainfall availability only, yield depends on the amount of water stored in the soil. Good performances occur with 450 mm water availability in the period ranging from shoot emission to heads differentiation (Fernandez and Curt, 2005). Yield may vary between 6 and 36 t ha^{-1} d.m. in relation to cultivation environment and nitrogen applied with fertilization (Ceccarini et al., 1999; Foti et al., 1999; Piscioneri et al., 2000; Gherbin et al., 2001a; Cosentino et al., 2005b; Monti et al., 2005; Nassi o di Nasso et al., 2006). Biomass production rises up to the third and decreases in the subsequent years (Gherbin et al., 2001a; et al., 2005b; Nassi o di Nasso et al., 2006).

Giant reed and *Miscanthus* transplanting and switchgrass sowing are made in spring; harvest is normally carried out at the end of winter when moisture content decreases down to < 40% in *Miscanthus* and switchgrass and < 50% in giant reed. Irrigation is required at transplanting and during growing season (June- September) depending on geographical area.

Giant reed exhibited the highest yields and productive stability in all environments. Within the 2nd and 3rd year, the yield in the South areas varies between 26 to 37 t ha^{-1} d.m., with 25% and 75% of evapotranspiration-ETc restoration, respectively (Cosentino et al., 2005b). Yields ranging from 20 to 41 t ha^{-1} d.m. are reported by Angelini et al. (2005a) between the 2nd and

Table 2. Agronomic aspects of energy crops studied in Italian environments (Giant reed, *Miscanthus* and cardoon yields begin from II year).

Species		Italian regions	Sowing or transplant (month)	Harvest (month)	Yield ($t\ ha^{-1}$ d.m.)	Humidity (%)	Ash (%)	References
Lignocellulosic chain								
Fibre sorghum	Seed	Northern	V	XI-XII	16-28	35-41		Cosentino et al., 2005b
		Central	IV-V	IX	29-32	65-68		Cosentino et al., 2005b
			V	IX	18-26			Barbanti et al., 2006
			IV	X	29	65-73	4.5	Di Candilo et al., 2005b
			IV-VI	VIII-IX	24-26•			Monti et al., 2002
			Spring.	VIII-IX	27	60-70	6.0	Angelini et al., 1999
		Southern	V-VI	VIII-IX	20§-24☆	70-73	6.0	Cosentino et al., 2005b
			V-VI	IX-X	16§-31☆			Cosentino et al., 2002
					17-24§ 25-37*	70-75		Gherbin et al., 2001b
			V-VI	XI	34•			Abbate and Patanè, 1996
Miscanthus	Rhizomes	Northern	V	XI-XII	14-24	28-48		Cosentino et al., 2005b
		Central	Spring	IX-X	22-48	52-56	2.8	Ceccarini et al., 1999
			IV	X	17-24#	65 leaves		Ercoli et al., 1999
					17-34•	47 stems		
			III	I-II	14-29	42-50		Cosentino et al., 2005b
				II	30-32	42-46	2-3	Di Candilo et al., 2005b
		Southern	IV	II	11-24§ 19-30☆	30-48		Cosentino et al., 2005b
								Cosentino et al., 2007b
			VI	II - III	14-21§ 15-27*			Cosentino et al., 2007a
			III		13-15•			Abbate and Patanè, 1996
Giant reed	Stem cutting, rhizomes	Northern	V	XI-XII	33-51	33-47		Cosentino et al., 2005b
		Central	III	X-XI	20-41	58		Angelini et al., 2005a
				I-III	23-37	52	5.0	Angelini et al., 2005b
			III	I-II	25-42	42-55		Cosentino et al., 2005c
			III	Autumn	29-31		7.0	Monti et al., 2005
			IV	Winter	42-44	52-58	4-6	Di Candilo et al., 2005b
			Spring	IX-X	41-53	52-63	5.0	Ceccarini et al., 1999
		Southern	IV	II	26§ 37☆	50-53		Cosentino et al., 2005b
			III		33-48•			Abbate and Patanè, 1996
Cardoon	seed	Central	III	Autumn	6-9		8.0	Monti et al., 2005
			III	VIII-IX	9-13	16-40		Cosentino et al., 2005b
	transplant		Spring		8-21	56-62	13.9	Ceccarini et al., 1999
	seed	Southern	V	VII-VIII	14-21§ 23-26☆	35-55		Cosentino et al., 2005b
	transplant		VII	VII	27-36			Foti et al., 1999
				VII-VIII	5-14			Gherbin et al., 2001a
	transplant		V		7-13	15-20		Piscioneri et al., 2000
	transplant		V		19-22			Abbate and Patanè, 1996
Switchgrass	seed	Central	IV	Autumn	9-23		6.0	Monti et al., 2005
			V	Winter	8-21 average 6 years		3-5	Monti et al., 2004
			V	II	11-12	25-40	4-6	Grigatti et al., 2004
				VII	17	55	6.0	
		Southern	VII	XII-I	0,8-16•	14-71		Piscioneri et al., 2001
				Spring	0,9-26•			Sharma et al., 2003
Poplar		Northern			3-25			Facciotto et al., 2005
		Central			1-25			Facciotto et al., 2005
			Winter	Winter	17❑ - 22♥			Bonari, 2005; Bonari et al., 2005
					9❏, 15◊, 22≥			
			IV		14 yearly average	56-58	2-4	Di Candilo et al., 2005b
Willow		Northern			3-26			Facciotto et al., 2005
		Central			1-19			Facciotto et al., 2005
			IV		13 yearly average	53-56	2-4	Di Candilo et al., 2005b
Robinia		Central			10 average	41-48	2-3	Di Candilo et al., 2005b

• irrigated; # dry; § 25% ETM; ☆ 75% ETM; *100% ETM; ϒ % of d.m.; √ % of f.m.; ❑ t ha year low inputs; ♥t ha^{-1} year high inputs; ♣ organic management; ♦ conventional management; ❏ t ha^{-1} $year^{-1}$ yearly turn cut; ◊ t ha^{-1} $year^{-1}$ two year turn cut; ≥ t ha^{-1} $year^{-1}$ three year turn cut.

6th year from transplanting. At Bologna and Udine, rising yields have been recorded from the 1st to the 3rd year, with maximum values of 42 and 51 t ha^{-1} d.m., respectively (Cosentino et al., 2005b).

Miscanthus x giganteus also provides good productions in South Italy; under irrigation conditions its productivity ranges between 11 and 30 t ha^{-1} d.m. biomass yields between 14 and 34 t ha^{-1} in Central Italy and between 14 and 24 t ha^{-1} d.m. in North Italy have been recorded (Ercoli et al., 1999; Cosentino et al., 2005b; Cosentino et al., 2007a). Other species and varieties of *Miscanthus* were studied in South of Italy such as: *Miscanthus sinensis* (cv. Goliath, Poseidon, Clone 11, Roland) and *Miscanthus floridulus.* A promising species adapted to the dry Mediterranean environment, belonging to the same family of *Miscanthus*, *Saccharum spontaneum* L. subsp. *aegyptiacum* (Willd.) Hackel, collected in the eastern coast of Sicily, has been also studied (Cosentino et al., 2006b).

Yield of *Miscanthus* genotypes, on average, was equal to 1 kg dry matter m^{-2} in the 2nd year and doubled in the 3rd year (2.1 kg d.m. m^{-2}), with great differences among the genotypes. *M. sinensis* Clone 11 and cv. Poseidon genotypes produced 2.7 and 2.8 kg d.m. m^{-2}), while *M. floridulus* 2.2 kg dry matter m^{-2}. *S. aegyptiacum* showed a remarkable productivity level in the 2nd year (5.0 kg d.m. m^{-2}), confirmed at the 3rd year (5.3 kg d.m. m^{-2}) to be ascribed both to the stem density (121.5 stems m^{-2} at the 3rd year) and stem weight (56.2 g $stem^{-1}$ at the 3rd year).

Short Rotation Forestry (SRF) refers to the cultivation, for energy biomass production, of fast growing forest species (poplar, willow, robinia, eucalyptus, etc.) lasting 10 to 20 years, with a high plant population (over 10,000 plants ha^{-1}), coppiced and repeatedly harvested (every two or more years). In Italy the research activity carried out on SRF is rather recent and lacking in information, if the studies conducted by a few scientific institutions such as ENEL and the Scuola Superiore Sant'Anna of Pisa (Bonari and Villani, 2004) are excluded. However, the agronomic aspects related to the selection of the most suitable species and cultivars to the different climatic conditions and to crop establishment (plant density), management (cut interval) and mechanization (Bonari and Villani, 2004) still have to be assessed.

The species selection depends on crop growth rate, stump regrowth capacity, suboptimal conditions adaptability both in terms of soil and biotic stress resistance (Bonari, 2001). The most suitable species are poplar (*Populus alba* L., *P. nigra* L., *P. deltoides* Marshall, *P.* x *euramericana* (Dode) Guinier) already cultivated in Padana plain as traditional wood crop, willow (*Salix alba* L.) suitable for Po area, eucalyptus (*Eucaliptus globosus* Labil., *E. bicostata* Maiden, *E. camaldulensis* Dehnh.) for Central-South regions, and robinia (*Robinia pseudoacacia*) in marginal lands of hilly South and North areas (Bonari, 2001). Experiments in Tuscany on poplar (*Populus deltoides* cv. Lux) demonstrated how the highest yields are obtained with 10,000 - 13,500 plants ha^{-1}. The best cut interval seems to be the three-year one (21.7 t ha^{-1} against 9 t ha^{-1}, with three-year and annual cut, respectively) (Tab. 2). Problems concern the decreasing productivity from 3rd-4th cut, probably due to an increase in diseases and to the high stumps mortality (close to 50% in the 7th year from transplanting) (Bonari and Villani, 2004).

3. Energy parameters

3.1 Energy content

Among the energy ligno-cellulosic species, giant reed achieves an energy content ranging from 14.6 MJ kg^{-1} (Di Candilo et al., 2005b) to 19.1 MJ kg^{-1} (Ghetti et al., 1995) (Tab. 3). For *Miscanthus* spp. values range from 14.6 MJ kg^{-1} (Di Candilo et al., 2005b) to 17.7 MJ kg^{-1} (Venturi and Venturi, 2003); in cardoon, energy content results lower than, that of the other two species varying from 14.1 MJ kg^{-1} (Nassi o Di Nasso, 2006) to 16.8 MJ kg^{-1} (Venturi and Venturi, 2003). For fiber sorghum, values between 14.1 MJ kg^{-1} (Di Candilo et al., 2005b) and 16.9 MJ kg^{-1} (Cosentino et al., 2002; Venturi and Venturi, 2003) have been reported. Energy content in swicthgrass reached approximately 17.4 MJ kg^{-1} (Venturi and Venturi, 2003).

Referring to liquid biofuel crops, grain energy content ranged from 25.0 MJ kg^{-1} (Baldini et al., 2005) to 27.2 MJ kg^{-1} (Venturi and Venturi, 2003) for sunflower. Rapeseed, soybean and sugarbeet, achieved 24.0 MJ kg^{-1}, 20.5 MJ kg^{-1} and 16.9 MJ kg^{-1}, respectively (Venturi and Venturi, 2003). If we consider the oil energy

Table 3. Energy parameters of some bio-energy crops studied in different Italian environments.

	Output (GJ ha^{-1})	Input (GJ ha^{-1})	Specific energy (MJ kg^{-1})	Energy yield (GJ ha^{-1}) (O-I)*	Energy ratio (O/I)*	References
Solid biofuels						
Giant reed	294.6✰-473❏	14.9✰-10.5 9❏	18	280✰-463❏	20.5✰-77❏	Angelini et al., 2005b
	285.8❑-531.1♥	39.2❑72.4♥	17.7	345 (II year)	7.36 (II year)	Cosentino et al., 2007b
	240-600		14.6	118-592	11-75	Venturi and Venturi, 2003
			19.1			Ghetti et al., 1995
Miscanthus	179.1❑-351.6♥	39.2❑-72.4♥	17.1	198.7 (II year)	4.5 (II year)	Cosentino et al., 2007b
	260-530		17.6-17.7	238-522	5-20	Venturi and Venturi, 2003
		12.8-26.5✰	16.5	291❑-564♥	22-47	Ercoli et al., 1999
		4.1-17.9 (from the 2nd year)	14.6			Di Candilo et al., 2005b
Cardoon	179.1❑-351.6♥	28.9❏-48♥	16.5	312	9.43✰	Cosentino et al., 2007b
		8-22	15.5-16.8	133-344	7-31	Venturi and Venturi, 2003
		13.2	14.1-15	180		Nassi o Di Nasso et al., 2006
Fiber sorghum	270❑-524♥	31.4-71.1	16.7-16.8	238❑-453♥	6.8-8.5	Cosentino et al., 2002
				245-300	16.5-20	Monti and Venturi, 2003
	334-507	13-25	16.7-16.9	309-494	13-39	Venturi and Venturi, 2003
			14.1			Di Candilo et al., 2005 c
Swicthgrass	174-435		17.4	152-427	8-54	Venturi and Venturi, 2003
Poplar		14.2 per year			13	Balsari and Airoldi, 2002
Liquid biofuels						
Sweet sorghum	337❑-423♥	31.4-71.1	16.7-16.8	295❑-365♥	6-11.7	Cosentino et al., 2002
	132.5❑140.6♥	13.8❑-19.1♥		118.7❑-121.5♥	7.4❑-9.6♥	Monti and Venturi, 2003
	250-422	13-25	16.7-16.9	225-409	10-32	Venturi and Venturi, 2003
Rapeseed	16.6-18.8❏ 65.2-45.3♥	14.7-14♦ 39.1-33.4♥		54.8♦-56.3♣	4.8♦-13.4♣	De Mastro et al., 2006
			24.0	3.8-44.4	1.38-2.21;	Venturi and Venturi, 2003
					1.36❑-1.67♥	Cardone et al., 2003
	69 (29.7 oil; 39.3 meal)	16.1		52.9 (with meal) 13.6	4.3 (with meal) 1.8	Bona et al., 1999
Brassica carinata	38.2❑ 31.8-48.7♥	23.5-24.2❑ 29.4-36.6♥			1.6♥-1.2❑	Cardone et al., 2003
Sunflower						
				10-20	0.68-1.79	Bona et al., 1999
					1.03 (with meal) 0.7	Bona, 2001
			25	51.5-57.3	5	Baldini et al., 2005
			27.2	-6.4-30		Venturi and Venturi, 2003
Soybean			20.5	-0.6-38.8	0.96-2.11	Venturi and Venturi, 2003
Sugarbeat		33.3	16.9	45-130	2.8-3.2	Venturi and Venturi, 2003
Corn				10-110	1.4-3.8;	Venturi and Venturi, 2003
					3.5	Baldini et al., 2005

* O = output; I = input; ♣ organic management; ♦ conventional management; ❑ tha^{-1} $year^{-1}$ low inputs; ♥ high input; ✰ I year; ❏ II-VI years.

content, this is equal to 37.4, 38.4 and 36.4 MJ kg^{-1} for rapeseed, sunflower and soybean, respectively (Venturi and Venturi, 2003).

3.2 Energy yield

Energy yield is the difference between the energy content of the harvested biomass (output) and the energy used throughout the whole growing season for soil tillage, sowing, fertilizers, chemicals, etc. (input). In *Arundo donax*, this difference resulted equal to 280 GJ ha^{-1} in the 1st year crop (Angelini et al., 2005b), but reached 592 GJ ha^{-1} from the 2nd year onward (Venturi and Venturi, 2003).

In the year of transplanting, *Miscanthus* attained 200 GJ ha^{-1}, with a maximum value of 564 GJ ha^{-1} when 200 kg ha^{-1} of nitrogen fertilisation and irrigation were employed. In cardoon, energy yield ranged between 133 and 344 GJ ha^{-1} (Venturi and Venturi, 2003). Energy yield of fiber sorghum varied between 238 GJ ha^{-1} (Cosentino et al., 2002) and 494 GJ ha^{-1} (Venturi and Venturi, 2003) and that of sweet sorghum between 118 GJ ha^{-1} (Monti and Venturi, 2003) and 409 GJ ha^{-1} (Venturi and Venturi, 2003).

In swicthgrass, an energy yield between 152 and 427 GJ ha^{-1} was indicated (Venturi and Venturi, 2003). Energy yield of rapeseed was approximately 52.9 GJ ha^{-1}, considering the oil cake as well. It decreases to 13.6 GJ ha^{-1}, if only oil is considered (Bona, 2001). Moreover, rapeseed, in relation to cropping systems adopted, ranged between 3.8 GJ ha^{-1} (Venturi and Venturi, 2003) and 56.3 GJ ha^{-1} (De Mastro et al., 2006) for conventional and organic management, respectively. For sunflower and soybean, negative energy yields are reported by Venturi and Venturi (2003) equal to, respectively, -6.4 GJ ha^{-1} and -0.6 GJ ha^{-1}, which would increase to 57.3 GJ ha^{-1} for sunflower (Baldini et al., 2005) and 38.8 GJ ha^{-1} for soybean (Venturi and Venturi, 2003), using low input levels of cropping systems.

3.3 Energy efficiency

Energy efficiency is expressed by the ratio between the entire energy content of biomass yield (output) and the energy utilised in the cropping system (input).

In *Arundo* energy ratio resulted 7.4 in the 2^{nd} year irrigation (Cosentino et al., 2007b) and 77 corresponding to the year of maximum productive level (Angelini et al., 2005a and b). In *Miscanthus*, the ratio varied between 4.5 in the 2^{nd} year with the use of irrigation (Cosentino et al., 2007b) and 47 (on average from the second to the fourth year) (Ercoli et al., 1999). In cardoon, ratios ranging between 7 and 31 in relation to different crop management are indicated (Venturi and Venturi, 2003). Energy efficiency it ranged between 6.8 (Cosentino et al., 2002) and 39 (Venturi and Venturi, 2003) in fiber sorghum, between 6 and 32 in sweet sorghum, between 8 and 54 in swicthgrass (Venturi and Venturi, 2003).

With regard to rapeseed cultivated in conventional, low energy level and organic cropping systems, values of energy ratios from 4.8 to 13.4. are reported (De Mastro et al., 2006). Lower values, 1.67 and 2.21, are indicated by Cardone et al. (2003) and Venturi and Venturi (2003), respectively. On sunflower, Baldini et al. (2005) indicated an energy ratio of 5, whilst Bona (2001) reported a value equal to 1.03.

Balsari and Airoldi (2002) calculated an energy ratio of approximately 13 in a poplar Short Rotation Forestry.

4. Environmental aspects

Positive environmental impact is often mentioned for biofuel use instead of fossil fuels. It is usually assumed that bioenergy has a neutral CO_2 balance because of the CO_2 emitted during its combustion is recycled by the photosynthetic activity of the energy crops.

4.1 CO_2 saved

CO_2 saving by burning biomass instead of fossil fuels may contribute to limiting the greenhouse effect and so the global warming of the earth. This may be considered the most important aspect, because of the attention given to limiting CO_2 emissions according to the Kyoto protocol and to European and national directives (Ministero dell'Ambiente, 2002). In order to calculate the CO_2 saved, CO_2 fixed in the biomass is considered positive input and CO_2 emissions during the entire production process, both during agricultural and industrial phases, is considered negative output. Liquid biofuels had shown a saving of CO_2 emission lower than that of the solid bio-fuels. Rapeseed methyl- ester for road transport production and oil cake and residual biomass for heat production showed CO_2 savings ranging between 15.8 and 7.5 t CO_2 equivalents ha^{-1}, respectively in Northern and Southern Italy, with difference due to higher yields obtained in more favourable environmental conditions in North Italy (Tab. 4).

The production of ETBE from sugar and heat from bagasse and residual biomass, both using the entire plant of sweet sorghum, showed CO_2 savings ranging between 14.4 and 27.40 t of CO_2 equiv. ha^{-1}, respectively for Southern and Northern-Central Italy (Cosentino et al., 2005a).

In the case of biodiesel production, despite the industrial phase does not lead to high emission of CO_2, the production is substantially low (2-3 t ha^{-1} of seeds); in the case of ETBE, on the other hand, despite the high biomass pro-

Table 4. Life Cycle Assessment, CO_2 "saved" and CO_2 balance.

Impact categories Differences between impact categories values of thermal, biodiesel and ETBE chains and corresponding fossil chains (negative values indicate an advantage of biofuels and vice versa)							CO_2 "saved" (t CO_2 equiv. ha^{-1})	CO_2 balance (t ha^{-1})
Biofuel	Use of fossil fuels (MJ MJ^{-1})	Greenhouse effect (g CO_2 equiv. MJ)	Acidification (g SO_2 equiv. MJ^{-1})	Eutrophication (g NO_3^- equiv. MJ^{-1})	Land use $m^2t^{-1}y^{-1}$	Agriculture phase incidence (%)		
Biomass	-1.12	-76	0.13	0.20-0.29		5.3□-28.4▲		
Giant reed					167-227		37.7	31.1-46.3
Miscanthus					229-646		17.5	11.2-29.4
Cardoon					229-737		19.1	31.6-41.7
Fiber sorghum					265-416		25.1	
Biodiesel								
Rapeseed	-1.36	-80.9	0.40	0.81	452-842	29.7	15.8-7.5	2.55
Sunflower								2.73
ETBE								
Sweet sorghum	-4.06	-157.9	0.07	1.13	308-488	6.6□-14.1▲	14.4-27.4	18.9-33.0

Life cycle assessment (data by Cosentino et al., 2005a).
CO_2 "saved" = CO_2 fossil emitted – CO_2 biofuel emitted (data by Cosentino et al., 2005a).
Balance CO_2 = CO_2 fixed – CO_2 emitted (data by Bona, 2001).
□ low input; ▲ high input.

duction of sweet sorghum, the industrial phase produces high levels of CO_2.

The CO_2 saved per hectare gave remarkably high values for the solid biofuels used for the production of heat and electricity. Giant reed showed 37.7 t ha^{-1} of CO_2 per year not emitted to atmosphere, followed by fibre sorghum (25.1 t CO_2 ha^{-1} per year), cardoon (19.1 CO_2 ha^{-1} per year) and *Miscanthus* (17.5 CO_2 ha^{-1} per year) (Cosentino et al., 2005a).

4.2 Life Cycle Assessment

Life Cycle Assessment (LCA), among the different applied methodologies for the evaluation of environmental impact, has raised the greatest interest. Within the framework of a project of the Italian Ministry of Agriculture "Sustainable innovative techniques for energy and no food crops" coordinated by Istituto delle Colture Industriali of Bologna, this methodology was applied using data obtained in experimental field researches carried out between 2001 and 2004 in Northern, Central and Southern Italy, to study the CO_2 balance and the environmental impact of energy crops for the production of biodiesel, ETBE and heat and electricity (Cosentino et al., 2005a).

Without giving a specific "weight" to each impact categories, the categories "use of abiotic resources" and "global warming" have shown significant advantages with respect to the use of fossil fuels deriving these impact categories are, at present, widely accepted as the most important ones to be considered in the comparison of biofuels from different sources (for example sugar cane, corn, sugarbeet, rapeseed, palm oil, etc.). The reduction of the "use of abiotic resources" allows the safeguard of the agroecosystem and also the diversification of energy sources. Because of the high energy demand of fossil fuels to generate 1 MJ of mechanical energy, ETBE with the addition of heat generation from bagasse and residual biomass shows, on average, an energy saving almost four-fold higher than the other solid biofuels (4.06 MJ MJ^{-1} mechanical energy for ETBE against 1.12 MJ MJ^{-1} heat and 1.36 MJ MJ^{-1} mechanical energy for RME-Rapeseed methyl-ester with the addition of heat generation of by-products). "Global warming", linked to carbon cycle, was discussed in the previous paragraph.

A series of impact categories resulted favourable to fossil fuels (acidification of the atmosphere, water eutrophication, ozone depletion), to be ascribed to some crop management. Taking into consideration that the reduction of the agronomic inputs may contribute to reduce the overall impacts of the above said categories, a deep analysis with an eventual updating of some agricultural techniques could contribute to the reduction of the impact of these activities.

Other impact categories (ecotoxicity, human toxicity, summer smog) for bio-energies differ little in comparison with those recorded for fossil fuels. In any case, these impact categories must be analysed in order to evaluate their actual significance and weight, in relation to their potential effect on ecosystems and human health.

5. Perspectives of the research

The Biomass Action Plan of the European Union (Commission of the European Communities, 2005) and the following analysis on biofuels (Epobio, 2006; European Conference on Biorefinery Research, 2006) introduce the distinction between the "first generation biofuel", such as bioethanol and biodiesel, which are basically produced by food crops (sugar cane, sugar beet, wheat and corn) and "second generation biofuels" such as the bioethanol obtained from cellulose and hemicellulose and the second generation biodiesel obtained from vegetable oils, as it is a synthetic gas composed by monoxide of C (CO) and H. The new concept of "biorefinery" has been introduced, which tends to affirm the idea of the complete exploitation of crop biomass, in order to obtain a wide range of products, from food to polymers, chemical products, biofuels, heat, etc.

Within the framework of the dedicated crops, the general objective is to develop suitable energy crops to each conversion process, specific for each geographic area, which could assure sustainability and environmental quality. One of the priorities of the VII Framework Programme (2007-2013) is represented by the research on biomass for the production of energy. Among the proposed topics the first calls reports on:

- development of new tools and processes to support R&D in crop plants: molecular breeding;
- genomics for cereal improvement for food and non-food;
- novel forest tree breeding;
- energy plants: novel plants for energy production;
- green oil: plants providing oils of the future;
- forest products: new forest based products and processes;
- biopolymers: biological Polymers from plants;
- future crops: technical, socio-economic, geographic and regulatory aspects of future non-food crop systems in particular related to co-existence and safety of agri-food chains;
- biomass supply: identification of optimal terrestrial and aquatic biomass and waste for bioproducts.

5.1 Topics for future research

In the framework of the above mentioned indications, the themes of the research may be outlined as follows:

First generation biofuel crops

- Assessment of stress tolerant local species with focus on starch and biomass yield;
- breeding and selection of transgenic and non transgenic varieties with specific traits;
- development of alternative crops with proven potential for the production of bioethanol for irrigated and non irrigated environments (i.e. sweet sorghum);
- improvement of the traditional crops based on the production of sugar (sugarbeet);
- low input cultivation to maintain sustainability;
- composition of the biomass to maximize bioethanol production;
- biomass suitable for the present processing technologies.

Second generation biofuel crops

- Understanding plant Cell Walls for optimizing biomass potential;
- developing efficient enzyme systems for deconstructing cell walls;
- high cellulosic biomass yield under low input production;
- existing energy crops for the production of biomass;
- newly developed energy crops, e.g. perennial grasses such as *Miscanthus* or switch grass;
- breeding of local species for different regions and soil and climatic conditions;
- improvement of radiation use efficiency;
- optimizing biomass production and lignocellulosic biomass yield;
- improvement of the water and nutrients use efficiency;

– development of techniques for a sustainable production;
– lignocellulosic biomass quality – low content of N, P, S and micro nutrients (ash).

Other aspects:
– Multiple crops; agricultural and forest systems, annual and perennial species; herbaceous species, shrub and trees;
– from a traditional agriculture to a multifunctional agriculture;
– sustainability of the crops; environmental impact, biodiversity, soil erosion;
– logistic: harvest, pre-treatments, storage of the products in relation to the humidity content logistic of the crops to attain at multifunctional agriculture;
– strategies for the use of territory;
– social acceptability.

6. Conclusions

The review on the agronomic, energetic and environmental aspects of the energy crops shows an articulated framework on the perspectives of the energetic chains for the production of energy in Italy. The production of biofuels (bioethanol and biodiesel) could at present be assured by food traditionally cultivated crops. However, their cultivation requires high energy inputs; they have an unfavourable "output/input" ratio; the environmental impact compared to fossil fuels, with the exceptions of greenhouse gases emissions and energy saving, is sometime negative; lastly, the biomass yield transformable in biofuel is limited. Moreover, biofuel represents only a fraction of the total biomass and the annual crops intercept only a fraction of the solar energy.

The lignocellulosic chain for the production of heat and energy may be realised through the use of highly productive perennial crops (Short rotation coppice, *Arundo donax, Miscanthus*, Cardoon). These crops could achieve further favourable energy and environmental indices compared to the food crops, but their introduction into cropping systems requires more research on cropping techniques, as well as genetic and logistic aspects.

The analysis of the environmental impact through the "Life Cycle Assessment" highlighted the advantage of the energy obtained by these crops compared to fossil fuels in the categories "energy saving" and "greenhouse gas balance". In particular, it could be proven interesting to utilise the amount of CO_2 saved which these crops allow to obtain, in order to be considered among the mitigation measures requested by "Kyoto protocol" for the reduction of CO_2 emissions.

The main perspectives of the research regard, therefore, the increase of the energy of the crops used for the production of the "first generation biofuels" through the breeding and molecular biology, the study of new lignocellulosic species (short rotation coppice, *Miscanthus*, *Arundo donax*, cardoon, etc.) also in relation to the "second generation biofuels". The reduction of the agronomic inputs, the evaluation of the environmental impact, the new possible cropping systems for non-food uses, the logistic problems and the use of the land also need a specific attention of the research activity.

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