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Review

Giant reed (*Arundo donax* L.): A weed plant or a promising energy crop?

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Giant reed (*Arundo donax*) is a perennial rhizomatous grass which is widely diffused in subtropical and warm temperate regions. From its native area, probably Eastern Asia, it has been dispersed all over the world by humans who use it for multiple purposes such as roof thatching, reeds in woodwind instruments, fishing rods, etc. Its spontaneous and rapid growth allows *A. donax* to be considered as an invasive weed. But more recently, due to its high biomass production and great adaptability to marginal land, it is being seen as one of the most promising energy crops for lignocellulosic bioethanol production. *A. donax* is a sterile plant because it is a hybrid with uneven ploidy or triploid specie. Therefore, its propagation is strictly agamic by rhizome fragmentation and sprouting from cane nodes. The lack of sexual reproduction is a negative characteristic when we consider *A. donax* as an energy crop, since it makes genetic improvement difficult, and this is further limited by the absence of genome sequence information and the lack of specific molecular tools. In this review we will summarize and discuss recent data on *A. donax*, specifically its origins, genetics and possible utilization as a source of biomass.

Key words: *Arundo donax*, vegetative propagation, polyploidy, energy crop, biomass, ethanol fermentation.

INTRODUCTION

Arundo donax is an erect, perennial, bamboo-like grass which has been present in the Mediterranean basin for thousands of years (Bell, 1997; Perdue, 1958) but its area of origin is still debated and is unclear because historical and archeological evidence indicates the presence of this plant since the ancient ages (Perdue, 1958; Gucel, 2010). *A. donax* has become globally dispersed by humans so, it is possible to find it in Asia, South Europe, North Africa, the Middle East and also in North and South America and Australasia (Bell, 1997; Perdue, 1958). The explanation of this intentional diffusion is that *A. donax* can be used for many purposes in the rural world. The culms are used to make lattices, fences, baskets, fishing rods (Figure 1A), stakes for plants (Figure 1B), roofs (Figure 1D), windbreaks, sun shelters, cereal bins, musical instruments, walking sticks and trellises. In vineyards, the stems and leaves are used for propping up and tying the vine plants. The apical inflorescence can be used to make brooms. In traditional medicine, it is utilized as a diuretic, sudorific and for dropsy treatment (Perdue, 1958; Shamel, 1917; Gucel, 2010; Guarrera, 2007). *A. donax* has been used industrially to produce cellulose, paper and rayon (viscose) (Perdue, 1958; Facchini, 1941).

From the past to the present day the reeds of woodwind musical instrument are made of *A. donax*, since its stem is excellent for elasticity, resilience and resistance to moisture (Figure 1C) (Perdue, 1958; Facchini, 1941).

BOTANY AND PHYSIOLOGY

A. donax L. is a plant well suited to warm-temperate to subtropical climates. It belongs to the Poaceae family of the Arundinae tribe and it is the most widespread among the species of the genus *Arundo* including also *Arundo*

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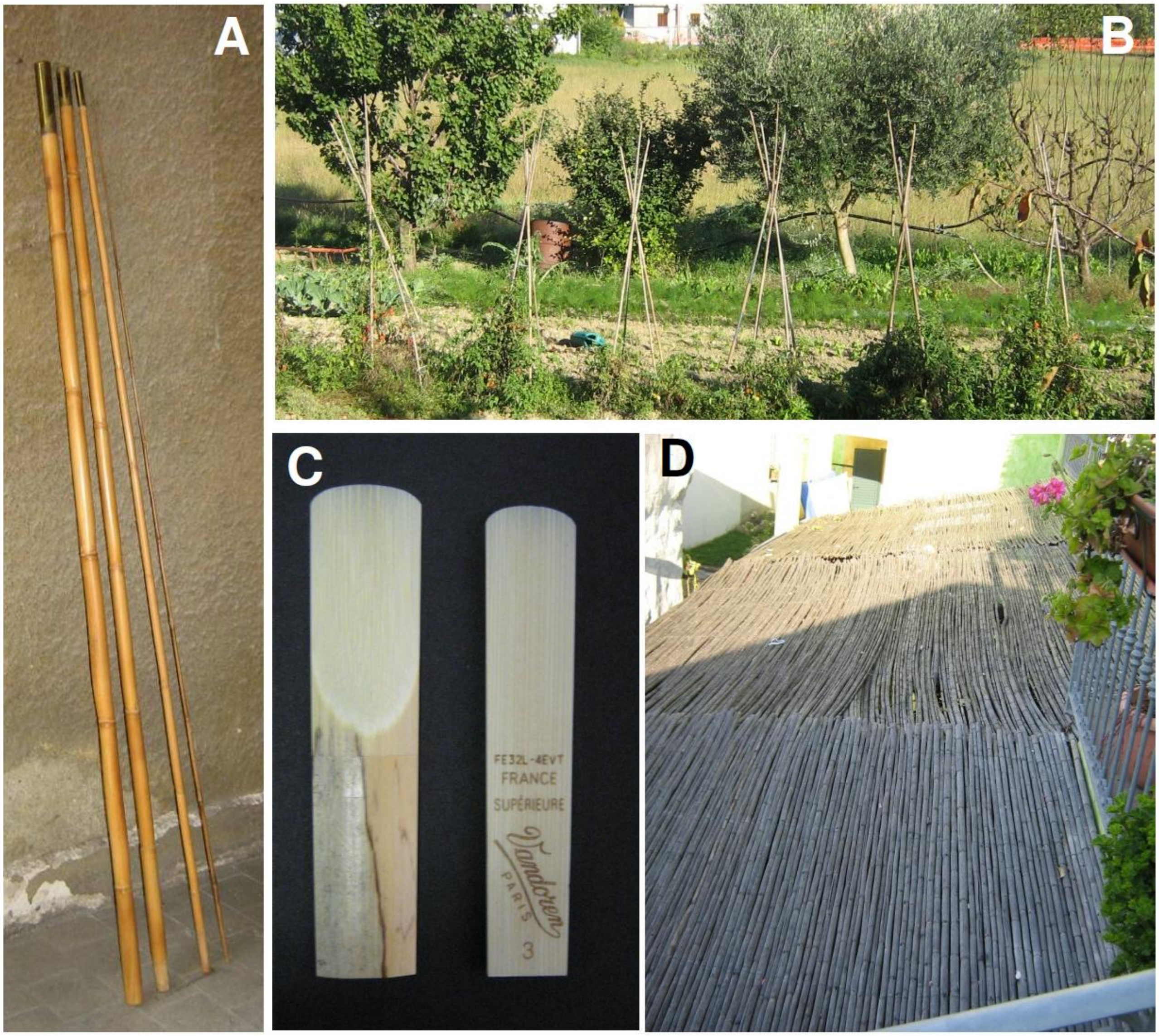

Figure 1. Canes utilization for different purposes: (A) Fishing rod; (B) Stakes for plants; (C) Reeds in woodwind instruments; (D) Roof thatching.

plinii, *Arundo collina* and *Arundo mediterranea*. It is considered one of the tallest herbaceous grasses because of its height that can reach more than 8 m under optimal growth conditions (Figure 2C) (Perdue, 1958; Mirza et al., 2010; Frandsen, 1997), with growth rates ranging from 4 to 7 cm per day (Perdue, 1958; Mirza et al., 2010; Frandsen, 1997). In fact, even thought *A. donax* is a C3 plant, it shows high photosynthetic rates and unsaturated photosynthetic potential compared to C4 plants (Papazoglou et al., 2005; Rossa et al., 1998).

A. donax is a perennial rhizomatous plant producing large fleshy rhizomes (from 5 to 50 cm in length) under the soil surface (Perdue, 1958; Spencer et al., 2006). The fibrous roots originating from the rhizomes are able to grow into the soil to 5 m in depth (Frandsen, 1997). The culms carry alternate leaves (5 to 8 cm wide and 30 to 70 cm long) that originate from the rhizome and are very hard and brittle with a smooth glossy green surface (Figure 2A) that turns golden-yellow at the end of the growing season (Figure 2B) (Perdue, 1958; Frandsen, 1997; Spatz et al., 1997). The *A. donax* stem is a hollow, segmented culm that measures from 1 to 4 cm in diameter and is able to branch (Figure 2E). The culms' walls range from 2 to 7 mm in thickness, and the internodes can reach 30 cm in length. This stem structure is able to support the erect position of such a tall plant, as its mechanical stability is not dependent on turgor pressure. In fact, cross-section analysis outlined a hypodermal sterome with sclerenchymatous fibers and a thick parenchymatous inner ring. This ring contains a

Figure 2. (A) *A. donax* flowering plants at maturity, at the end of summer; (B) In winter; (C) Single cane, reaching the height of 8 m, held by one of the authors; (D) Vegetative propagation by new rhizomes spreading from the old plants; (E) Young shoots sprouting from the nodes.

high number of vascular bundles, characterized by heavily lignified bundle sheaths, giving reinforcement in the longitudinal direction (Spatz et al., 1997). Stems and leaves are characterized by a relatively high content of silica, caused by the presence of silicaceous cells associated with vascular bundles in the epidermal layer (Perdue, 1958). Several stems grow from the rhizome buds (Figure 2D) during all the vegetative season, forming dense clumps (Figure 2C).

For these characteristics, *A. donax* is able to grow in a very wide range of soils, including apparently inhospitable and marginal land; after the first year of growth, it will became relatively insensitive to drought stress. It is also able to survive in sites of high moisture and salinity, including marshes, even if the best performances are obtained in well-drained soils with good water availability (Perdue, 1958). While it withstands low temperatures during the winter, it is very sensitive to late frost in spring (Perdue, 1958). Its vigor makes *A. donax* an effective potential competitor for other plant species. Once established, *A. donax* tends to cover large areas with dense clumps, compromising the presence of native vegetation not able to compete. In the riparian zone, it can alter flow regimes. *A. donax* is also able to take advantage of extreme fire events, since thanks to the rhizome resistance and its fast growing rate, it can outgrow other species. This can result in lowering the biological diversity of the colonised areas (Bell, 1997; Coffman et al., 2010). Furthermore, in *A. donax* stems and leaves, there are several noxious chemicals (Bell, 1997); these compounds together with the thickness of the tissues can protect them from the attack of herbivorous insects and other grazers (Bell, 1997; Spencer et al., 2010).

The flowering season is at the end of summer to early autumn, the inflorescences are single panicles 30 to 100 cm long at the end of the stems, with scabrous branches, feathery with silky hairs. The spikelets are 8 to 16, containing 2 to 7 flowers; florets are bisexual (except the apical one) (Tucker, 1990; Lewandowski et al., 2003) and incapable to produce pollen. In fact, *A. donax* is reported to be a sterile specie, and the propagation of this specie is by agamic reproduction, occurring through regrowth of rhizome fragments and growth of shoots from stem nodes (Boland, 2006; DiTomaso and Healey, 2003).

The adaptability to extreme soil conditions combined with rapid and vigorous growth makes *A. donax* an interesting subject for environmental studies on phytoremediation treatments. The use of plants to remove contaminants from polluted water and soil can be an advantageous strategy, which can also be used to remove metals that usually cannot be efficiently biodegraded. Studies indicate that *A. donax* may have a potential use for phytoremediation purposes. The plant is able to efficiently transfer arsenic, absorbed from the growing medium and efficiently accumulate it into the shoots, showing good tolerance to the presence of the metal (Mirza et al., 2010). *A. donax* is a plant only slightly affected by the presence of metals (such as cadmium, nickel, arsenic and lead) in the rhizosphere, and because of this trait, it can be a potential crop for contaminated soil, capable of high biomass production in polluted areas (Papazoglou et al., 2005, 2007; Guo and Miao, 2010).

A. DONAX AS AN INVASIVE SPECIES

A. donax is considered a weedy and invasive plant in several countries (Frandsen and Jackson, 1994; Bell, 1997; Boose and Holt, 1999; Everitt et al. 2004; Spencer et al., 2005; Quinn and Holt 2008) and has been included in the 100 world's worst alien species (Lowe et al., 2000), and this judgment can compromise the future of *A. donax* cultivation on large scale for biomass production. The giant reed invasion has been observed in riparian and simplified ecosystems such as road side (Figure 3) where it can form monocultural stand along several kilometres (Rieger and Kreager, 1989). The invasiveness reached a dramatic gravity in California (Bell, 1997; Dudley, 2000; Spencer et al., 2005) and in Rio Grande Basin (Seawright et al., 2009; Goolsby and Moran, 2009; Tracy and DeLoach, 1999) where the local institutions are investing a lot of resources in giant reed control (Dudley, 2000). The giant reed causes negative effects on water supplies for agriculture (Moran and Goolsby, 2009), biodiversity (Herrera and Dudley, 2003), rivers access (Hughes and Mickey, 1993), wildfire risk (Coffman et al., 2010) and ecosystem conservation (Rossi et al., 2010; Coffman et al., 2010). The high vegetative vigor and the great propagules production are the most *A. donax* competitive vantages with respect to native species, especially after extreme events such as fires and deforestations. When a great disturbance hits an ecosystem, the native vegetation is not able to reach the high *A. donax* relative growth rate; *A. donax* quickly occupies the canopy and rapidly removes nutrients, light and water from the other plants. The success of *A. donax* in diffusion is due to the rapidity of its vegetative propagation, the new shoots rise remarkably before the seedlings of the native plants with sexual reproduction (Herrera and Dudley, 2003). The stem and rhyzome fragments are carried out by floodwater and by humans. Humans significantly contribute in propagules diffusion accidently, through bulldozer activity (Boland, 2008) and voluntarily by propagating this species for domestic purpose. The herbivores *Melanaphis donacis* (Passerini), *Tetramesa romana* (Walker) (Hymenoptera: Eurytomidae), *Rhizaspidiotus donacis* (Leonardi) (Hemiptera: Diaspididae), *Cryptonevra* sp. (Diptera: Chloropidae) and *Lasioptera donacis* (Coutin and Faivre-Amiot) (Diptera: Cecidomyiidae), have been evaluated as candidates in *A. donax* biological control (Seawright et al., 2009; Goolsby et al., 2009; Moran and Goolsby, 2009; Dudley et al., 2008). Among these, *T. romana* (Arundo wasp) and *R. donacis* showed the most promising features as biological control agents and show host specificity for giant reed (Goolsby and Moran, 2009).

Arundo wasp has a short generation time, a prolific asexual reproductive capacity, and it increases the *A. donax* shoots mortality (McClay and Balciunas, 2005; van Klinken and Raghu, 2006). Although an Arundo wasp of Spanish genotype has been selected as the mostly suitable for a mass field releases (Moran and Goolsby, 2009), this insect seems to be unable to reduce significantly the total giant reed biomass (Dudley et al., 2008). The same tendency has been observed in *R. donacis* that negatively affects specifically the lateral shoots stems that are only minimally involved in total giant reed biomass (Cortés et al., 2011). Taken together these observations suggested that the combined used of *T. romana* and *R. donacis* could be successful only in greenhouse conditions (Cortés et al., 2011). The chemical control has been shown to be the most efficient system to control *A. donax* diffusion (Finn and Minnesang, 1990; Jackson, 1994; USDA Forest Service, 1993; Omori, 1996). This strategy consists of applying glyphosate herbicide to foliage between August and November (Bell, 1997; Spencer et al., 2008). A single late-season application is considered the best approach, minimizing both the costs and the negative environmental effects of the giant reed control (Spencer et al., 2008). The herbicide Rodeo, a trade name formulation of glyphosate, is currently labeled for wetlands in USA. Other herbicides useful to giant reed killing are Fusilade-DX (fluazapop-butyl) and Post (Sethoxidan) (Bell, 1997). When the *A. donax* invasion forms pure stands with > 80% canopy cover, the herbicides can be applied by helicopter with a spray apparatus that produces extremely fine droplets (400 μm) (Bell, 1997). To

Figure 3. Invasiveness of *A. donax* in Southern Italy.

decrease the quantity of the herbicide required, the fresh shoots grown after canes cutting could be treated. Therefore, this practice requires that the mature canes should be chipped and consequently disposed off. For this reason, the cutting is counseled in medium to low *A. donax* infestation (Spencer et al., 2008). The *A. donax* control foresees a serious prevention policy; the large scale cultivation should be avoided in areas characterized by water flood, and the propagules need chemical or mechanical treatment before their release in the ecosystems. Therefore, in non-riparian zone, it could be possible to cultivate *A. donax,* by sowing the plant at a minimum of 20 m from drainage lines and by adopting precautionary measures in harvest, transport and processing (Virtue et al., 2010).

ORIGIN AND GENETICS OF *A. DONAX*

Giant reed (*A. donax*), has an uncertain origin due, to its wide and ancient diffusion; its place of origin is still under discussion. Botanical and historical evidence suggest that *A. donax* and the related species *A. plinii*, *A. collina* and *A. mediterranea* originated from wild plants of the Mediterranean area (Zeven and Wet, 1982). An alternative hypothesis is that the *Arundo* genus originated in Eastern Asia in fresh water (Polunin and Huxley, 1987) and then *A. donax* diffused all over in Asia, Northern Africa, and Southern Europe and became naturalized in the Mediterranean regions (Lewandowski et al., 2003), where it was cultivated for thousands of years (Perdue, 1958; Zohary, 1962). From this area, *A. donax* was widely diffused by man in subtropical and temperate regions all over the world for multiple purposes (Perdue, 1958). It has been hypothesized that at the beginning of the nineteenth century, *A. donax* was introduced from the Mediterranean area into North America, starting from Southern California, to keep erosion under control. Later on, it was used for roof thatching and reed for musical instrument production (Bell, 1997; Hoshovsky, 1987). In North America, *A. donax* became one of the most diffused weeds on the banks of rivers, where it supplanted native species and modified ecological and successional processes (Bell, 1994, 1997; Dudley, 2000; DiTommaso and Healey, 2003).

A. donax was a successful invasive species at least in part, because of its rapid clonal spread, through rhizome extension and flood dispersion of rhizome and stem fragments (Dudley 2000; DiTommaso and Healey, 2003),

Figure 4. (A) Inflorescence of *A.donax*; (B) Particular showing dehiscent anthers.

that make its removal difficult.

A. donax produces flowers but no vital seeds were found in the area where it was introduced (Perdue, 1958), North America included (Dudley 2000; DiTommaso and Healey, 2003). In Italy too, giant reed seems to be sterile; its inflorescence, that can reach nearly one meter in length, does not produce pollen and consequently seeds (Figure 4). Our studies, carried out on more than one hundred clones sampled on Italian territory, and kept in a collection at the farm Angelo Menozzi of the University of Milano, confirm the sterility of the giant reed (unpublished data).

The apparent lack of sexual reproduction and the low level of expected genetic variability are considered to be good parameters when we think of *A. donax* as a weed and consider its biological control as the problem to be solved (Tracy and DeLoach, 1999). In fact, generally, asexual weeds are controlled by biological agents more effectively than weeds with sexual reproduction (Burdon and Marshall, 1981), probably because the lack of adaptive genetic variability in asexual populations limits the capability to evolve the resistance to pathogen and herbivorous attacks (Muller-Scharer and Steinger, 2004). A recent study based on molecular markers, showed the presence of minimal genetic variability among the populations of giant reeds in the American area, and the authors suggested that all the clones of this area originated from one single clone (Ahmad et al., 2008).

More recent studies showed a higher level of genetic variability among the clones of the Mediterranean area, thus strengthening the theory that the giant reed originated in South-Eastern Asia, then reached the Mediterranean area and diffused all over the world in relatively recent times (Mariani et al., 2010). It is possible to hypothesize that giant reed is phylogenetically a very recent species, and that its sterility can be explained by its origin if that was due to a cross between different species, allowing the production of an allopolyploid or an event of autopolyploidy. In the first case, the sterility would be certain because of the impossibility of having a correct pairing of homologous chromosomes during meiosis, leading to gametes with unbalanced and thus non-vital chromosome sets, while in the second case, complete sterility could be observed in autopolyploids with very numerous chromosome sets (6 N, 8 N, etc.). Actually, there are only a few papers about the chromosome number of giant reed, and even if the reported data are conflicting, they seem to be in agreement with the hypothesis that *A. donax* is a polyploid.

The first papers published on *A. donax* karyotype, dates from the 1930s (Avdulov, 1931; Hunter, 1934), and show quite conflicting data. The number of chromosomes found by Avdulov is 100 while the number reported by Hunter is 110. These data were revised and updated 30 years later by Pizzolongo (Pizzolongo, 1962). In this study, data of karyotypes of *A. donax* and *A. plinii* obtained from young inflorescences, caulinar apices and root apices of rhizomes, germinated in water, are presented. The observation of these samples, pretreated with colchicine and stained with feulgen, allowed the author to discover that the diploid chromosome number was 110. The main difficulties met in this research were the high number, the small size, and the close arrangement of the chromosomes.

We can thus hypothesize that *A. donax* is really a polyploid with a high chromosome number, higher than in species phylogenetically very similar such as *A. plinii*, whose chromosome number has been analysed by Pizzolongo, with the same techniques used for *A. donax* analysis, and found to be 2n = 72 with x =12.

Common reed *(Phragmites australis)* is a species very similar to giant reed and its chromosome number is different, depending on the geographic area considered: in Europe, 2n = 48 while in South-East Asia, x = 12 as for *A. plini* (Clevering and Lissner, 1999). In comparison with the related species, *A. donax* could be considered a polyploid that lost or acquired some chromosomes (aneuploid) either considering a basal chromosome set having x = 12 or a new chromosome set with x = 10.

As previously mentioned, giant reed is sterile and does not produce viable seeds (Dudley, 2000, Perdue, 1958; DiTomaso and Healey, 2003) and this is an advantageous trait for an energy crop because all the photosynthetic products are used to produce ligno-cellulosic biomass, instead of for seed production. On the other hand, sterility is a serious obstacle for breeding programmes which aim to improve both productivity and biomass quality for energy production. Sterility also implies that giant reed is propagated through asexual reproduction which causes a dramatic reduction of genetic variability in natural populations.

A serious drawback in breeding programmes is the lack of information on genome sequence, a key requirement to produce specific molecular tools. Until now, the genetic variation of *A. donax* has been investigated, using molecular markers that did not require species-specific sequence information (Ahmad et al., 2008).

A. DONAX AS AN ENERGY CROP

With the aim to tackle the problem of climate change and to reach the independence from fossil fuels, it is necessary to increase the use of renewable energies reducing direct Greenhouse Gases (GHG) emissions. Among the renewable energies, biomass is being increasingly used: the European Commission fixed the goal of 150 Million Tonne Equivalent of Petroleum (Mtep) from biomass energy within 2010 (Biomass action plan). Furthermore, in biofuel global market, the achievement of 5.75% for transportation has been established within 2010 (Directive 30/2003). So, the generation of biomass for energy production is becoming a real business opportunity for farmers all over the world, even thought the use of grains and other food is giving rise to ethical issues.

For this reason, the scientific community is supporting the energy production from rubbish and no-edible/low-input crops (Petrini et al., 1996; Ercoli et al., 1999) to:

1. Maximize the efficiency of energies production process;
2. Minimize the indirect GHG indirect emissions;
3. Avoid the decrease of food global availability.

Hence, in the quantification of the efficiency of biomass energies production processes, Energy returned on energy invested (Eroei) is an important parameter to be considered (Cleveland et al., 1984). In this contest *A. donax* showed the best potentially in Eroei value, thanks to the great yields reached in low input cultivation conditions, with respect to other herbaceous perennial species such as *sinensis* (Table 1) and *Panicum* that showed lower Eroei values and a lower adaptability to different pedoclymatic conditions (Takahashi et al., 2010).

A. donax shows the positive traits of both annual (high relative growing rate and high productivity) and polyennal crops (low input required and deep roots). The nitrogen fertilization to *A. donax* cultivation could be uneconomical because, the small increase in yield and the high energetic and economic costs of nitrogen would worsen the total energetic and economic balance (Angelini et al., 2005). For this reason, *A. donax* could be the ideal energetic crop being a rough plant suitable to marginal land (Lewandowski et al., 2003; Faix et al., 1989). The *A. donax* biomass found large application in energy production. It could be used as solid biofuel in direct combustion, gasification and pyrolisis (Ghetti et al., 1996), or used for anaerobic digestion to produce biogas, or subjected to alcoholic fermentation to produce bioethanol (Jeon et al., 2010). The alcoholic fermentation and anaerobic digestion requires chemical and physical biomass pretreatments that decrease the Eroei index of the processes. Upstream the future, *A. donax* shows also a great uncertainty in propagation and cultivation establishment strategy; giant reed cultivation on large scale does not exist at the moment but several experimental fields have been studied (Cosentino et al., 2005; Ceotto and Di Candilo, 2010). The cultivation starts with the transplantation of rhizome fragments or seedlings, obtained from stem nodes (20,000 rhizomes/

Table 1. Net energy yield and Eroei index during 12 years of cultivation of *A. donax* and *M. sinensis* (modified from Angelini et al., 2009).

Year	Net energy yield (Gj/ha)		Eroei	
	A. donax	*M. sinensis*	*A. donax*	*M. sinensis*
1	488	156	30	10
2	891	846	75	71
3	852	538	71	45
4	732	597	62	50
5	718	522	60	44
6	780	441	65	37
7	762	533	64	45
8	678	469	57	40
9	403	453	34	38
10	377	331	32	28
11	505	384	43	33
12	458	330	39	28
Mean	637±180	467±169	53±20	39±18

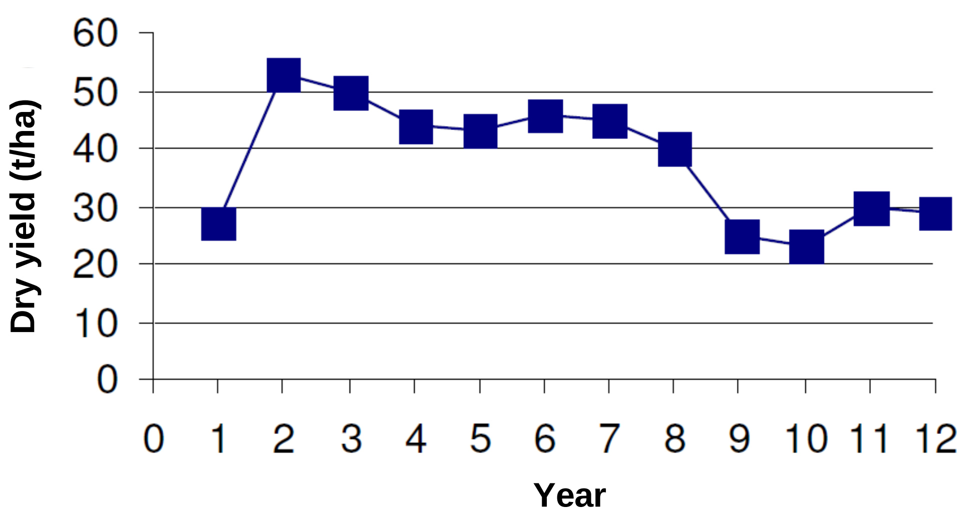

Figure 5. Biomass production (dry yield) of *A. donax* in a 12 years experiment (modified from Angelini et al., 2009).

seedlings per hectare), making this practice very expensive (about 1 euro for rhizome/seedling) (Ceotto and Di Candilo, 2010). The *in vitro* propagation methodology has been previously reported (Takahashi et al., 2010; Dhir et al., 2010) but this technique is not compatible with a low input energy crop; to maintain a favorable energy balance is necessary to develop a large scale methodology for propagation, where minimum hand-work and fossil fuels are required.

However, as reported in studies conducted in Italy, *A. donax* fields last about 10 to 12 years, with good performance without fertilization, weeding, irrigation and phytosanitary treatments, reaching a high Eroei value (Angelini et al., 2005).

As observed in Figure 5, *A. donax* cultivation is characterized by different yield-phases. In the first year, the dry matter yield is about 30 t/ha, in the second and third year, we observed the maximum of productivity (45 to 50 t/ha), between the fourth and eighth year the yield is steady (40 to 35 t/ha), and finally after the ninth year, we observed the minimum of yield (25 to 30 t/ha) (Angelini et al., 2009).

DIRECT COMBUSTION AS SOLID BIOFUEL

A. donax can be used as solid biofuel in direct combustion for heat production. The direct combustion to produce heat is the most efficient biomass technology for GHG emissions reduction because it

Table 2. Chemical analysis on chopped and pellettized *A. donax*.

Parameter	AD	PV	MI	PO
	% (d.b.)			
Ash	6.1	8.3	2.3	0.50
N	0.71	0.67	0.16	0.08
mg/kg (d.b.)				
Si	13920	14991	7305	< 400
Ca	3253	6555	1776	938
K	6497	12756	1446	484
Na	331	924	58	30
Mg	1627	2223	644	152
Al	919	763	82	n.a.
S	2160	735	390	73
Cl	2245	1511	880	53
Mj/kg (d.b.)				
GCV	19.8	17.8	19.6	20.3

AD: *Arundo donax*; PV: *Panico virgatum*; MI: Miscanthus; PO: Poplar; d.b.: dry basis; GCV: Gross calorific value (modified from Dahl and Obernberger, 2004).

Table 3. Chemical analysis on emissions of the combustion of *A. donax.*

Parameter	AD	PV	MI	PO
	mg/m^3			
Total dust	102	58	27	21
< 1 µm	67	50	16	16
NOx	363	368	187	106
HCl	67	18	59	3
SO_2	278	91	53	3
CO	443	145	55	1

AD: *Arundo donax*; PV: *Panico virgatum*; MI: Miscanthus; PO: Poplar. (modified from Dahl and Obernberger, 2004).

is characterized by few intermediate passages from biomass harvest to final energy utilization by burning in poly-annual crops (Hoffmann et al., 2010).

The very high Eroei index of *A. donax* biomass combustion, is due to its calorific value which is similar to that of woody materials (Dahl and Obernberger, 2004), the low inputs required in cultivation and high yield of dry matter per hectare (Cosentino et al., 2005; Angelini et al., 2005, 2009; Williams et al., 2008). Although, *A. donax* thermic transformation shows an excellent positive energetic balance as shown in Table 2, the biomass quality is rather poor for combustion utilization. Chemical analysis on chopped and pellettized *A. donax* have shown high quantity of total ash, chlorine, sulphur, nitrogen, silica and other metals, which may contribute towards shortening the life-cycle of the combustion power station (Dahl and Obernberger, 2004; Coulson et al., 2004). Furthermore, the emissions from combustion show high concentrations in both total dust and particles < 1 µm and produce some compounds harmful for human health and the environment, such as nitrogen oxides, hydrochloric acid, carbon monoxide and sulphur dioxide (Table 3) (Dahl and Obernberger, 2004; Coulson et al., 2004).

BIOETHANOL PRODUCTION

Lignocellulose material is an important feedstock to develop biomass energies, with the aim to reach gradual independence from fossil fuels in the transport sector. In particular, lignocellulose biomass represents the starting substrate for the production of second generation bioethanol (Chandel et al., 2007; Petrova and Ivanova, 2010). The second generation process shows higher efficiency (Williams et al., 2008; Hahn-Hagerdahl et al., 2007; Hayes, 2009) than bioethanol first generation production, and positive effects on the environment (Bull et al., 1992; Kheshgi et al, 2000) and society (Bevan and Franssen, 2006). The bioethanol of the first generation is produced, using cereals and starch crops. Starting from

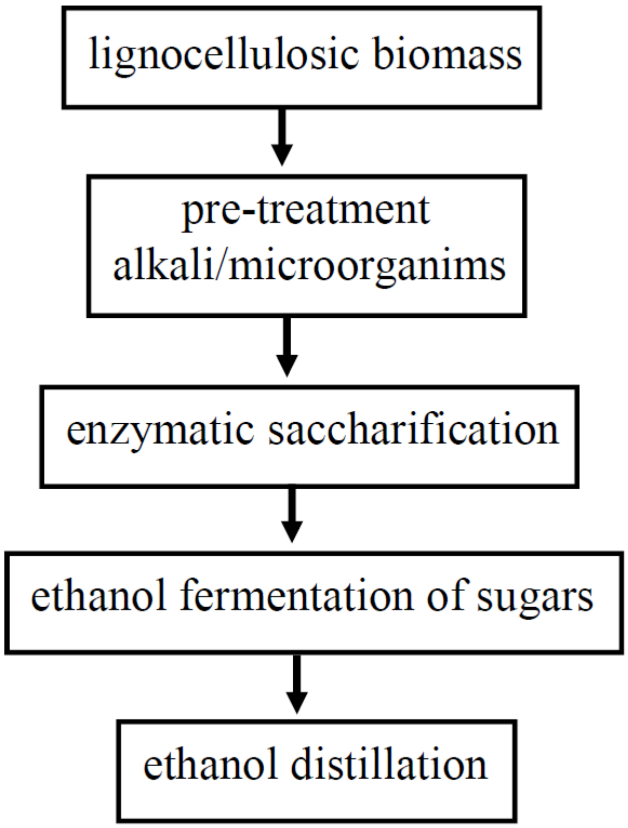

Figure 6. Scheme of bioethanol production by alcoholic fermentation of lignocellulosic biomass (modified from Chandel et al., 2007).

cereal kernels, the Eroei value is about 0.74 to 1.34 (Cleveland, 1984; Hattori and Morita, 2010) with a reduction in GHG of 12 to 18% (Farrell et al., 2006; Hill et al., 2006), while second generation bioethanol from poly-annual crops shows an Eroei index of 3.91 to 6.57, with a reduction of GHG emissions of 94% (Hattori and Morita, 2010).

The production of bioethanol from lignocellulose materials can be summarized in the following steps (Chandel et al., 2007) as shown in Figure 6:

1. Pretreatments of biomass with acid or enzymatic hydrolysis to decompose cellulose and hemicellulose to C5 and C6 sugars;
2. Alcoholic fermentation by microorganisms converting these molecules to ethanol;
3. Ethanol distillation.

The comparison among several fibrous biomasses showed an intermediate value for *A. donax* bioethanol yield, between the lowest value of woody and the highest values of herbaceous biomass, because of low sugar recovery yield and the presence after pretreatments of high concentration of acetate (4.8 g/l) (an inhibitory compound of alcoholic fermentation) (Jeon et al., 2010). The slightly lower efficiency in glucose release and bioethanol production could be due to high lignin stem content (16 to 22%) (Neto et al., 1997), high S : G lignin ratio (Seca et al., 2000) and higher microporosity and lower mesoporosity, with respect to other annual crops (Adani et al., 2011). Although, *A. donax* is not characterized by the best performance in bioethanol production process (Jeon et al., 2010), the high yield of dry biomass per hectare (Cosentino et al., 2005; Angelini et al., 2005, 2009; Williams et al., 2008) would suggest great potential for this crop.

CONCLUSION

A. donax could become an important energy crop due, to its high yield and capacity to grow in marginal land, therefore not competing with the arable land used for food production. The interest aroused recently by this crop, challenged the geneticists about how to improve this plant. The genetic improvement of this species, considering its high chromosome number and the complete sterility, will be a difficult goal and will be pursued by studying and selecting clones (ecotypes) with small phenotypic differences, by physical and chemical mutagenesis and by thinking about a genetic transformation method to produce a genetically modified reed (Takahashi et al., 2010; Dhir et al., 2010). Breeding programmes for this species would take into account traits such as biomass production per hectare, the capacity to propagate efficiently by rhizome and nodes, and the lignin content. From the agronomic point of view, better cultivation practices should be developed, in particular to lower the cost of rhizome management. For direct combustion of chopped and pelletized *A. donax,* it will be desirable to solve the problem of the low quality of emissions from combustion, while bioethanol production processes appear at the moment to be the best way to use the lignocellulose biomass obtained from this plant.

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