Chapter 1

Bioenergy from Perennial Grasses

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Abstract

In recent years, the establishment of perennial grasses as energy crops has emerged as a very viable option mainly due to their comparative ecological advantages over annual energy crops. Nonwoody biomass fuels have a great potential to replace fossil fuels and reduce greenhouse gas emissions. At the same time, their application in small-scale combustion appliances for heat production is often associated with increased operational problems such as slagging in the bottom ash or deposit formation, as well as elevated gaseous and particulate matter emission levels. To mitigate these problems, scope and limitation of blending raw materials owing to critical fuel composition with less problematic biomasses have been systematically studied during combustion experiments in a commercially available small-scale combustion appliance. Apart from traditional use, perennial rhizomatous grasses display several positive attributes as energy crops because of their high productivity and low demand for nutrient inputs, consequent to the recycling of nutrients by their rhizomes and resistance to biotic as well as abiotic stresses. Therefore, they are used to generate heat and electricity. In addition, grasses appear to be an economically and environmentally appropriate fuel for generating some local energy in rural areas. This chapter gives an overview on species characteristics, their soil-climate requirements, cultivation technology, yielding, and energy characteristics of lignocellulosic biomass of giant miscanthus (*Miscanthus* × *giganteus*), reed canary grass (*Phalaris arundinacea* L.), switchgrass (*Panicum virgatum* L.), and giant reed (*Arundo donax* L.).

Keywords: bioenergy, biomass, grasses, giant miscanthus, reed canary grass, switchgrass, giant reed, biomass yield

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1. Introduction

The search for an alternative fuel due to environmental concerns and depletion of fossil fuels has raised interest in sustainable energy systems. The utilization of biomass as renewable energy source is becoming increasingly important in the light of its potential for lowering global warming effects and sustainably securing fuel supply [1]. The main challenge in utilization of biomass as fuels would be a stable supply of raw materials [2]. In Europe, wood fuels (e.g., log wood, wood chips, and wood pellets) are the predominant biomass fuels for small-scale heating. However, in several regions, the rapid increase in wood pellet production resulted in shortage of raw materials [3, 4]. Wood assortments are also considered as promising raw materials for the growing biorefinery sector; therefore, this competition is expected to significantly increase in the future, resulting in an increase in raw material costs [5]. Thus, to fulfill the anticipated growth of biomass utilization, expected worldwide, a wider assortment of raw materials will be required including low-quality wood fuels (e.g., logging residues, short rotation coppice) and nonwoody biomasses [6]. Within the available biomass sources, there has been an increasing interest in the use of perennial grasses as energy crops. In order to achieve a positive energy balance, the condition for a plant species to be a potential energy crop is that its bioenergy yield must be produced with a low level of inputs that require minimal energy for their own production and utilization [7]. In this context, perennial rhizomatous grasses display several positive attributes as suitable energy crops. The characteristics which make perennial grasses attractive for biomass production are their high-yield potential and the high contents of lignin and cellulose of their biomass. The biomass of perennial grasses has higher lignin and cellulose contents than the biomass of annual crops [8]. These characteristics are desirable when used as solid biofuels, mainly because they have a high heating value associated with the high carbon content in lignin and, also, strongly lignified crops have the advantage of remaining stand upright with low water content. Therefore, its biomass has lower water content and a late harvest is possible to improve the quality of the biomass. From the point of view of crop management, high yields of biomass from perennial grasses are possible, but the quality of combustion is lower than that of wood products. Compared to stem wood, all these materials are usually characterized by higher ash content and a large variation in the composition of ash-forming elements. Therefore, the use of perennial grasses as fuel usually requires a greater maintenance of the boiler due to the particular characteristics of this type of biomass [9]. The chemical composition of the biomass is highly influenced by the date of harvest as well as by the procedure to make the bales, the condition of the soil, and the population of the plant. High ash content in the raw material will increase slagging tendency during combustion and also will cause high abrasions during the processes of grinding and densification. High contents of N, Cl, and S are mainly related to technical problems during the combustion process and to the increase of polluting emissions [9].

2. Characteristics and management of perennial grasses for energy production

Compared to other biomass sources, like woody crops and other C3 crops, C4 grasses may be able to provide more than twice the annual biomass yield in warm and temperate regions

because of their more efficient photosynthetic pathway [10]. Furthermore, the need for soil tillage in perennial grasses is limited to the year in which the crops are established, which is an advantage over annual crops. The advantages of the long periods without tilling are reduced risk of soil erosion and a likely increase in soil organic matter content. In addition, due to nutrient recycling by their rhizome systems, perennial grasses have a low nutrient demand [11]. Since they are affected by few natural pests, they may also be produced with little or no pesticide use. Furthermore, there are many environmental benefits expected from the production and use of perennial grasses. The substitution of fossil fuels by biomass is an important contribution to reduce CO_2 emissions.

Perennial grasses have many benefits as an energy crop. They are easy to grow, harvest, and process. Grasses is a "traditional agricultural crop" that does not need any special equipment, and the same could be used as for hay production. Perennial grasses are long-lived and thus do not need to be planted each year. In addition, it is not necessary to plow the soil every year, which leads to less soil disturbance. Grasses have several advantages as raw materials for fuels, since they conveniently occur throughout the world in a wide range of climates, geographies, and types of soils, and additionally, they sequester and store large amounts of carbon in the root systems and in the soil. Grasses can be grown on marginal lands unsuitable for continuous crop production or on open rural lands that currently are abandoned or underutilized. They yield more biomass per hectare and require much fewer inputs compared to annual crops that require more fertilizers, pesticides, and fuels. Perennial grasses are being used as a solid fuel in co-fired coal power plants and are also selected as the raw material for advanced biofuels such as cellulosic ethanol. The dry biomass of perennial grasses can also be densified and transformed into pellets and briquettes, which have uses as heating fuel to replace or supplement fuels made of wood fibers. The inclusion of a thermal component in the use of solid biomass for energy increases the efficiency of the combustion system more than three times [12].

In general, grasses grown as energy crop are managed for biomass yield rather than forage or nutritive quality. Grass biofuel requires minimum management expertise. It is as well suited to small farms as it is to large farming operations, and also works for all levels of management intensity. In fact, lower levels of nutrients such as N, S, K, and Cl may improve fuel quality and reduce emissions. The growth and yield of the grass crop depends significantly on several factors such as soil conditions, fertility, moisture, weed as well as pest control, and the timing of harvest. During the growing season of the grasses, the moderate use of fertilizers may be necessary to maintain soil fertility and to improve crop biomass production [13].

Good weed control in the first year of an establishment is critical to achieve a successful establishment. For example, switchgrass (*Panicum virgatum* L.) seedlings are slow to establish and are susceptible to competition from weeds. Emergence can take several weeks, depending on soil temperatures and moisture. It is critical that perennial weeds are eliminated from the fields prior to planting. To prevent competition from these species, it is important that cultural or chemical weed control is performed to ensure that the field is free of weeds. Nitrogen fertilizer is not recommended in the first year to reduce grass weed competition. Manure nutrients can be applied in the spring or anytime following grass harvest, as long as the grass is still actively growing.

The grass biomass should be harvested once per year, for which standard hay production equipment can be used. Grasses cut in the fall and left to overwinter produce less biomass, but have the advantage of leaching potassium and chlorine, two minerals that may create issues during combustion [13].

3. Grass biomass combustion

The combustion of grasses normally produces more ashes than the combustion of wood. The range in total ash content of grasses can be very wide, from 2% to greater than 20% [14]. Ash values higher than 10% in mature grasses are generally the result of excessive surface soil contamination. The issue of primary concern when burning grass is mineral composition that determines the melting point of ash and the potential for corrosion [15] and also elevated gaseous and particulate emission levels contributing to deposit formation or high-temperature corrosion as well as operational problems resulting from low ash-melting temperatures. High ash content or low ash-melting temperature poses technical issues through deposition, sintering, fouling, slagging, and corrosion. The latter can damage boilers and increase maintenance costs and can cause severe operation problems usually above 850–1000°C [14, 16]. Several indicators affect the ash-melting temperature such as nitrogen fertilizer used on the crop, meteorological conditions, and chemical composition [17]. The ash-forming elements potassium (K), phosphorus (P), chloride (Cl), silicon (Si), calcium (Ca), and sulfur (S) contribute to the abovementioned ash-related mechanical problems [18–20]. Silica is the major component of ash and is found in much higher concentrations in the leaf and inflorescence, compared to the grass stem [21], and the silicon content of the biomass ash may sum up to more than 90 wt% [18, 22, 23]. Silica can combine with alkali metals to form silicates that melt at lower temperatures [16]. K and Cl are the most problematic minerals, and both are consumed in high concentrations by the grasses. K is the most abundant alkali metal in grass biomass [24, 25]. This mineral reduces the melting temperature of the fuel and also contributes significantly to corrosion potential. Chlorine is a particularly undesirable component of grass biomass, as it acts as a catalyst for corrosion reactions and also increases the potential of chlorinated hydrocarbon emissions [26]. Sulfur reacts with alkali metals and forms deposits on heat transfer surfaces, and nitrogen content directly increases NOx emissions. Therefore, reduced concentration of all the abovementioned minerals in grass biomass is highly convenient. To enable and facilitate the utilization of a wide range of grasses in combustion systems, several strategies to mitigate the ash- and emission-related problems have been employed [25]. Appropriate harvesting time and fertilization application can all contribute significantly toward improvement of ash-melting behavior [27]. Potassium and chlorine can be reduced by controlling fertilization of these elements or by leaching them out of grass biomass [28, 29]. The content of some critical elements in fresh grass can be substantially reduced by mechanic dewatering [30]. Nitrogen concentration can be reduced by harvesting mature or overwintered forage. On the other hand, silica can be minimized by using warm-season grasses or by growing grass biomass on a sandy soil. Reduction of ash content and relative amount of critical elements can also be achieved by blending with less problematic biomass fuels such as wood, miscanthus, or peat [31].

Usually, additives are used in addressing the low ash-melting temperatures and the release of critical elements in the flue gas [32]. Using this strategy, slagging is reduced by the introduction of compounds that capture problematic ash components forming higher melting compounds or by diluting the ash with inert, high melting materials [33]. Zeng et al. [34] stated that significant reduction of the slagging risk during combustion of herbaceous fuels can only be achieved for high blending ratios with more than 70 wt% wood.

4. Densification of grasses

Grasses have low energy density (MJ m^{-3}) and low yield per unit area (dry tons ha^{-1}). Volumetric energy content of grasses used for biofuels is considerably lower than traditional fossil fuel sources, and this low energy density is due to low bulk densities of biomass materials [8]. Often, long distances have to be bridged between the biomass place of origin and the place of its utilization, resulting in expensive handling and transportation. Transportation costs of low-density grasses which increase the total cost of biomass processing are an important limitation to their use as an energy source [35]. To increase the bulk density of grasses, they can be densified into pellets using a mechanical process [35, 36]. Therefore, the densification of grasses is an important issue to improve the transport, storage, and handling capabilities of this lignocellulosic material. Densified biomass, especially pellets, has drawn attention due to its superiority over raw biomass in terms of its physical and combustion characteristics. With the international quality standard [37] for nonwoody biomass pellets, the foundation for an increasing commercial utilization of a wide range of biomass such as grasses was laid in 2014. Pellets have multiple end-use applications which range from smaller scale combustion for residential heating to an industrial scale where grass pellets could be co-fired with coal at power plants [38]. The increased demand of pelleted fuel sources in Europe and North America could allow for more nonwoody biomass resources such as perennial grasses to be used for pelletization. One of the most important variables in pellet production is moisture content, since this property will finally determine the durability and density of pellets [36, 39]. A less-expensive method of densification method (higher yield per hour) is by forming the grass into larger briquettes, also called tablets or cubes, which allows to manipulate and store the material easily, and they can also be transported economically and burned efficiently.

5. Description of the main perennial grasses

5.1. Miscanthus

5.1.1. Origin and distribution

It has been largely reported that miscanthus originated in East Asia, where it is found throughout a wide climatic range from tropical, subtropical, and warm temperate areas of Southeast Asia to the Pacific Islands as well as at both high and low altitudes [40]. The genotype widely used in Europe for biomass production is *Miscanthus* × *giganteus*, a natural hybrid

of *Miscanthus sinensis* and *M. sacchariflorus*. This natural hybrid is a giant, perennial warm-season grass native to Asia that is generating much enthusiasm for extremely high yields and very high cold tolerance.

5.1.2. General species description

Miscanthus × *giganteus* is a sterile hybrid that does not produce viable seed and therefore propagates vegetatively underground through its rhizomes (by planting underground stems). The rhizomatous C4 grass has been considered as a strong candidate as an energy crop due to its potential to deliver high biomass yields (up to 30 ton ha^{-1}) under low input conditions, and its economic as well as environmental benefits [41–44].

5.1.3. Ecological demands

Because of its C4 photosynthetic pathway and perennial rhizome, *M. giganteus* exhibits a very good combination of radiation, water, and N-use efficiencies for biomass production [44]. Boehmel et al. [45] compared the N-use efficiency of different annual and perennial energy crops and concluded that *M. giganteus* showed a higher N-use efficiency value of 526 kg DM kg^{-1} when compared to the N-use efficiency of maize (65 kg DM kg^{-1}). *M. giganteus* can be grown on a wide range of soils. The most important soil characteristic is the water holding capacity; therefore, sites with stagnant water are unsuitable. The highest yields have been reported in soils with a good water holding capacity. *M. giganteus* begins growth from the dormant winter rhizome when soil reaches temperatures of 10–12°C [46].

5.1.4. Biomass yields and characteristics

The production of aerial biomass depends on the duration of the growth period. After the first year, the start of the growing season depends on the last frost of spring. On the other hand, the end of the growing season depends on the flowering or the first autumn or winter, according to the date of harvest or location [47].

The lifetime of the crop lasts approximately 20 and 25 years [11], during which biomass is produced during two phases: a yield-building phase, which lasts for 2–5 years, depending on climate and plant densities, and a plateau phase where the yield is maintained [48]. When crop water supplies are not limiting, maximum crop yields are reached more rapidly in warmer climates than in cooler climates [47].

Miscanthus stands need between 3 and 5 years to become fully established and reach the maximum yield level [11]. Biomass yields above 30 t DM ha^{-1} have been reported in southern European locations with a high incidence of annual global radiation and high average temperatures, but only under irrigation conditions. Maximum yields of up to 49 t DM ha^{-1} have been observed in Europe during an autumn harvest of mature crops with irrigation. Harvestable yields in the spring are 27–50% lower than those in the autumn [49].

The main characteristics of miscanthus biomass as a fuel are listed in **Table 1**. The main problem of miscanthus biomass as fuel is its relatively low ash-melting point (1020°C). Biomass

Common name	Giant *Miscanthus*	Switchgrass	Reed canarygrass	Giant reed
Scientific name	*Miscanthus x giganteus*	*Panicum virgatum* L.	*Phalaris arundinacea* L.	*Arundo donax* L.
Photosynthetic pathway	C4	C4	C3	C3
Soils	Wide range. Not tolerant to flooding. No soil compactation	Wide range. Drought tolerant. Does not grow well in wet areas	Wide range. Drought tolerant, tolerant to wet areas	Wide range. Prefers well-drained soils with good water supply; also on saline soils
Day length	Long-day plant	Short-day plant	Long-day plant	Long-day plant
Biomass yields (t ha $^{-1}$)*	5–40	5–34	7–14	3–37
Moisture content at harvest (%)	15–60	15–20	10–23	
High heating value (MJ Kg $^{-1}$)*	17–20	17	17–19	15–19
Ash fusion temperature (°C)	1020	1016	1100–1650	1100
Ash (%)*	1.6–4.0	4.5–10.5	1.9–11.5	4.8–7.8

*Dry matter

Table 1. Perennial grasses species with potential as energy crop.

characteristics and quality of miscanthus are mainly a function of location and genotypes. For example, Lewandowski et al. [11] found that the ash contents of the biomass are correlated with high silt and clay content of the soil. In central Europe, miscanthus is harvested at the beginning of spring because the stems are dried during the winter and part of the ash, Cl, and K are leached by precipitation, which substantially improves the quality of the combustion. The most important management tool to improve biomass quality in miscanthus as a fuel is a delayed harvest.

5.1.5. Miscanthus as a bioenergy crop

The main advantages of *M. giganteus* as an energy crop are exceptional adaptability to different edaphoclimatic conditions; feasibility for growing on poor quality soils; high dry matter yields per unit surface; outstanding disease and pest resistance (application of pesticides is not necessary); very low fertilization requirements; herbicides are applied only during the first 2 years of establishment of the crop; and can be grown without any pest or weed control management once the crop is established [50, 51]. The main constrains of *M. giganteus* are its high establishment costs, its poor overwintering at some sites, and the insufficient supplies of water available in southern regions of Europe. It has been found that *M. giganteus* shows very little genetic diversity due to its sterility and vegetative mode of propagation. Most of the clones found in this species were obtained directly from the "Aksel Olsen" clone, as shown by isozyme and DNA studies [52, 53]. The small genetic base of *M. giganteus* is responsible

for the fact that the same clone has almost always been used in most studies or for cultivation. The sterility of *M. giganteus* is particularly interesting because it prevents the risk of invasion of the species; but on the other hand, it is a limitation to improve biomass production and to adapt it to a wide range of climatic conditions [47]. The sterile hybrid *M. giganteus* has to be propagated asexually using plantlets produced in tissue culture (micropropagation) or by rhizome divisions (macropropagation). The optimal planting density is one to two plants per square meter [11]. It has been reported that irrigation during the first growing season significantly improves the establishment rates.

Miscanthus does not respond to N fertilization at several sites in Europe; therefore, N fertilization is necessary only on soils with low N contents. Weed control in miscanthus in the year of planting is crucial for establishing a successful and healthy stand. The first 2 years are most critical, with little weed management thereafter. There are very few labeled herbicides for use on miscanthus crop, but various herbicides suitable for use in maize or other cereals can be used. It can be harvested only once a year, and the harvest window depends on the local conditions. The later the harvest can be made, the better the quality of the combustion, since it will decrease the moisture content and the mineral content of the biomass.

However, there is a trade-off between improving the quality and yield, since yield losses of up to 35% can occur between maximum yield and late harvest in early spring [54]. From an economic point of view, a late harvest with biomass water content lower than 30% is recommended in order to reduce the costs for harvesting and drying of the biomass [55]. Bilandzija et al. [1] state that harvest delays, from autumn to spring, had statistically significant influence on moisture, C, H, O, N, and S contents. They found that delayed harvest enhanced the quality of biomass in terms of combustion process, primarily through lowering moisture content, which is particularly important if biomass producers do not have drying systems.

Given its potential to be exploited for energy purpose, *Miscanthus* × *giganteus* is presently used mostly for electricity or heat generation in direct combustion [56], mostly in the form of wood chips, pellets/briquettes, and bales [57]. It is estimated that replacing fossil fuels with biomass from *Miscanthus* × *giganteus* can enable reducing the CO_2 emission by 75–93% [48]. However, because there is presently only one commercially available clone, *Miscanthus* × *giganteus*, it has some limitations such as a lack of winter hardiness during the establishment period [7] and it needs to be propagated vegetatively resulting in high field plantation costs.

5.2. Switchgrass

5.2.1. Origin and distribution

Switchgrass (*Panicum virgatum* L.) belongs to the Gramineae family. It is native to the North American tall grass prairies. Although generally associated with the natural vegetation of Great Plains and the western Corn Belt, it occurs widely in grasslands and nonforested areas throughout North America east of the Rocky Mountains and from southern Canada down to Mexico and Central America [58].

5.2.2. General species description

Switchgrass is one of the best herbaceous energy crops due to its habit of perennial growth, high yield potential on a wide variety of soil conditions, and compatibility with conventional agricultural practices [59]. Switchgrass has a deep rooting system that contributes to the accumulation of organic matter in the soil and, therefore, carbon sequestration [60]. In full development of the plant, the underground biomass is similar or even greater than the aerial biomass.

Switchgrass can be established through seeds; therefore, it has lower production costs that make it a practical option among the energy crops. However, the switchgrass biomass yield is considered to be lower than that of miscanthus [11].

Switchgrass can grow to more than 3 m height and develop roots to a depth of more than 3.5 m. The inflorescence is a typical open and diffuse panicle of 15–55 cm long. Each panicle consists of many to hundreds of spikelets at the end of long branches, with two dissimilar florets in each spikelet [61]. The expected life of a pasture would be 10 years or more if properly managed. Switchgrass is a cross-pollinated plant that is largely self-incompatible, and most cultivars are tetraploid or hexaploid [62].

5.2.3. Ecological demands

Switchgrass will grow best on well-drained good quality soils but will also sustain lower quality soils and shallow rocky soils. It can grow on sand to clay loam soils and tolerates soils with pH values ranging from 4.9 to 7.6 [63]. It is drought tolerant, but the grass does not grow in locations where precipitation is below 300 mm per year. Switchgrass can tolerate short-term waterlogging.

Switchgrass can be categorized into two groups or ecotypes classified by their habitat preference: the upland ecotype and the lowland ecotype. Upland ecotypes occur in upland areas that are not subject to flooding, while lowland ecotypes are found on floodplains and other areas that receive run-on water.

The upland ecotype is generally thinner stemmed and shorter than lowland ecotypes, is adapted to drier and wetter environments, and is generally derived from accessions collected in the northern regions of North America. Lowland plants have a later heading date and are taller with larger and thicker stems. Lowland ecotypes are tetraploids, while upland ecotypes are either octoploids or tetraploids. There are ecotypical differences among switchgrass ecotypes for important compositional features, such as fiber, nitrogen, and ash, among others. Dry matter produced by lowland ecotypes has higher cellulose and hemicellulose contents and lower N and ash contents than upland ecotypes, and dry matter produced by upland ecotypes contains higher lignin contents [64]. Upland and lowland tetraploids have been crossed to produce F1 hybrids that have an increase in yield of 30–50% over the parental lines. These hybrids are promising sources of high yield biomass cultivars [64]. Most seedlings of switchgrass will germinate after 3 days at 29.5°C. However, they germinate very slowly when the soil temperature is below 15.5°C [63].

5.2.4. Biomass yields and characteristics

The highest biomass yields per hectare can be obtained when switchgrass is harvested once or twice per year. In fact, one- or two-cut systems often provide similar average yields [65]. Wullschleger et al. [66] compiled 1190 biomass yield observations for both lowland and upland types of switchgrass grown on 39 sites across the USA, from field trials in 17 states, from Texas to North Dakota to Pennsylvania. In this study, it was found that much of the differences in biomass yields could be explained by the variation in the growing season, precipitation, annual temperature, nitrogen fertilization, and the type of switchgrass grown in a specific region. Annual yields averaged 12.9 t DM ha^{-1} for lowland and 8.7 t DM ha^{-1} for upland ecotypes. Some field sites in Texas, Oklahoma, and Alabama reported biomass yields greater than 28 t DM ha^{-1} using the lowland cultivars "Kanlow" and "Alamo."

The main characteristics of switchgrass biomass are listed in **Table 1**. Sladden et al. [67] compared eight switchgrass genotypes that were cut at the same maturity and found the six upland types did not vary much in their biomass composition. However, "Alamo" and "Kanlow" showed significantly lower N contents and higher fiber contents in their biomass which is explained by the later harvest date at maturity instead of differences in nutrient partitioning.

5.2.5. Switchgrass as a bioenergy crop

Switchgrass is established mainly by seeding. Successful stand establishment during the seeding year is essential for economically viable switchgrass as a bioenergy crop [68]. Stand failure as a result of poor seed quality or seedling physiology will have important implications on the cost of switchgrass biomass. However, weed competition is the major reason for switchgrass stand failure. Acceptable switchgrass production can be delayed by one or more years due to poor weed management and deficient stand establishment [69]. Switchgrass is readily established when high-quality seed of an adapted cultivar is used with the appropriate planting date, seeding rate, seeding method, and proper weed control. Switchgrass can be drilled in a conventional seedbed or by direct seeding methods. According to Sladden et al. [67], a row spacing of 80 cm is recommended because this led to higher yields in the second and third years than row spacing of 20 cm. Before planting, soil tests are recommended. N fertilizer is not recommended during the planting year since it will promote weed growth, increase competition for establishing seedlings, and increase economic risk and cost associated with establishment if stands should fail [70]. Economically viable yields will require N fertilization rates between 50 and 100 kg ha^{-1} $yr.^{-1}$ [71]. N fertilizer should be given in late spring. P and K can be applied before seeding to promote root growth and encourage rapid establishment. Switchgrass can tolerate moderately acid soils, but optimum germination of the seed occurs when the soil pH is between 6 and 8 [72].

Weeds can be an important obstacle for switchgrass establishment, especially summer annuals. Spraying herbicides to control broadleaf weeds is usually needed only once or twice every 10 years in established and well-managed switchgrass stands. One year before planting, the field must be plowed or chiseled [63]. A reduction of weed competition can also be achieved by cutting infrequently at 10 cm. In order to control grasshoppers, crickets, and other insects which may affect the new seedlings of switchgrass an insecticide may be needed [63].

Generally, a single harvest during the growing season maximizes biomass recovery, but harvest after a killing frost will ensure stand productivity and persistence, particularly when drought conditions occur, and reduce requirements of nitrogen fertilizers. Delaying the harvest until spring will reduce moisture and ash contents of the biomass; however, the yield loss can be as high as 40% compared to an autumn harvest [73]. With proper management, productive stands can be maintained for more than 10 years. It is not recommended to harvest switchgrass in summer or after flowering when there are drought conditions.

5.3. Reed canarygrass

5.3.1. Origin and distribution

Reed canarygrass (*Phalaris arundinacea* L.) is a member of the Poaceae family. It is a cool-season grass that is less productive than warm-season grasses. It is a sod-forming, perennial wetland grass, native to the temperate regions of Europe, Asia, and North America. It is usually found in wet areas such as lake shores and along the rivers.

5.3.2. General species description

Reed canarygrass is a tall, coarse, and erect grass with a C3 photosynthetic pathway, which reaches a canopy height of up to 300 cm. This grass has vigorous rhizomes that form 1 cm thick and short branches and a root system that reaches to more than 3 m [74].

Its inflorescence is a narrow and compressed panicle. The leaves are wide and flat with prominent nodes. The stems are robust, smooth, and occasionally branching at the nodes. Its ligules are membrane-shaped and obtuse and have a pointed-folded tip. Seeds are shiny brown. The seed production of the species is unreliable due to the seed shattering and occasionally the production of deficient panicles [11]. The presence of several types and concentrations of poisonous alkaloids has restricted the use of reed canarygrass as a forage crop [75]. The estimated life time of a reed canarygrass plantation is approximately 10 years [76].

5.3.3. Ecological demands

Reed canarygrass is a persistent species, which grows well on most types of soils, except droughty sands. It is one of the best grass species for poorly drained soils and tolerates floods better than other cold-season grasses. However, the highest yield can be obtained on organic soils. Reed canarygrass is adapted to and grows very well in a cool temperate climate and has also good winter hardiness. In order to induce flowering, this grass requires exposure to short days (primary induction) followed by long days for initiation of floral primordial and inflorescence development (secondary induction) [77].

5.3.4. Biomass yields and characteristics

There are considerable differences in yield between different soils. Kukk et al. [77] reported that soils with low N content produce yields of almost 1 t DM ha^{-1} in years with unsuitable weather conditions for plant growth. On the other hand, it is possible to achieve an average

dry matter production of up to 6–7 t DM ha^{-1} within limited years on soils with N contents of more than 0.6%. They found that fertilization increases the yield as well as decreases yield variability in soils with low organic matter content, but soils with high N content show an increase in production risks when fertilizer applications increase. Pociene et al. [78] have reported that under favorable climatic conditions reed canarygrass yields are 7–11 t DM ha^{-1}. Moreover, reed canary grass can produce over 15 t DM ha^{-1} in Canada [79], from 6 to 11 t DM ha^{-1} in Sweden [80].

The main biomass characteristics of reed canarygrass are listed in **Table 1**. During the combustion of the reed canarygrass biomass, problems of ash fusion or corrosion have been detected. However, in the delayed harvest system, these problems are almost eradicated. During the winter, there is a decrease in the content of elements such as K, Ca, Mg, P, and Cl. This change in chemical composition is mainly caused by leaching and loss of leaves during the winter, which significantly modifies the chemical and physical characteristics of the ash. It has been reported that the ash content and ash composition show considerable differences between different locations. The type of soil has a great influence on the quality of the biomass. For example, high ash contents have been found in reed canarygrass biomass grown on heavy clay soils and low contents of ash in biomass grown on humus-rich and organic soils [74].

5.3.5. Reed canarygrass as a bioenergy crop

Reed canarygrass is established mainly by seeding. The recommended seeding rate is 15–20 kg ha^{-1}. Seeds of reed canarygrass generally have a slow germination and show varying degrees of dormancy. Therefore, weed competition can reduce crop yields during the first year. Broadleaf weeds can be controlled with common herbicides. From the second year on, an established reed canarygrass stand becomes quite competitive, and as a result, weeds are no longer a problem. The number and timing of harvests during a growing season directly affect biomass yield of reed canarygrass and biofuel quality. Several studies have shown that reed canarygrass has higher than acceptable levels of silica [81], chlorine, and nitrogen [74]. However, delaying harvest of biomass from autumn to late winter or early spring, before regrowth begins can reduce the levels of undesirable components [76].

5.4. Giant reed

5.4.1. Origin and distribution

Giant reed (*Arundo donax* L.), also called giant cane, is a tall perennial grass of the family Poaceae. The area of origin of giant reed has been a subject of debate because the biogeographic and evolutionary origin of this species has been obscured through ancient and widespread cultivation [82]. As a result, there is no agreement on the location of the area where it originated. Botanical and historical evidence supports the hypothesis that the origin started from a pool of wild plants native to the Mediterranean region [83]. On the other hand, some authors suggest that Arundo genus originated in East Asia [84]. However, giant reed has been cultivated in Asia, Southern Europe, Southern Africa, Australia, and the Middle East for thousands of years [85]. The rapid spread of this species is probably attributed to its high productivity and multiple uses.

5.4.2. General species description

Giant reed is a tall, perennial C3 grass, and it is one of the largest of the herbaceous grasses that is widespread in the riparian areas of the Mediterranean and found over a wide range of subtropical and warm-temperate areas of the world [11]. The root system consists of tough, fibrous, lateral rhizomes and deep roots. The rhizomes form compact masses from which arise tough fibrous roots that penetrate deeply into the soil. The rhizomes usually lie close to the soil surface, while the roots are more than 100 cm long [86]. The stems arise during the whole period of growth from the large knotty rhizomes. It is reported that primary reproduction is asexual (sprouts from disturbed stems or rhizomes), due to seed sterility, caused by the failure of the megaspore mother cell to divide [87]. Due to the vegetative reproduction of giant reed, its genetic variability and the chances for finding new genotypes or varieties are low. However, according to the results from electrophoresis tests on some giant reed populations, there was a clustering of the selected populations in relation to their geographical origin, reflecting restricted migration of germplasm [11].

5.4.3. Ecological demands

Giant reed forms dense, monocultural stands and often crowds out native vegetation for soil moisture, nutrients, and space. It tolerates a wide variety of ecological conditions and, however, prefers well-drained soils with abundant soil moisture. It tolerates a pH in the range of 5.5–8.3 and soils of low quality such as saline ones. It can grow in all types of soils from heavy clays to loose sands and gravelly soils, but prefer wet drained soils [88]. Giant reed is a warm-temperate or subtropical species; however, it has little tolerance to survive frost, but when frosts occur after the initiation of spring growth, it is subject to serious damage [89].

Giant reed is commonly known as a drought-resistant species due to its ability to tolerate long periods of severe drought accompanied by low atmospheric humidity. This ability is attributed to the development of thick drought-resistant rhizomes and deeply penetrating roots that reach deep water sources [11].

5.4.4. Biomass yields and characteristics

Biomass yields in a study conducted in Spain showed 45.9 t DM ha^{-1} on average, ranging from 29.6 to 63.1 t DM ha^{-1} [90]. Angelini et al. [91] reported an average biomass yield of 37.7 t DM ha^{-1} in a study conducted in coastal Tuscany (Central Italy), and Di Candilo et al. [92] reported an average biomass of 39.6 t DM ha^{-1} in a study carried out in the Low Po Valley (Northern Italy). In Greece, the recorded average dry matter yields on irrigated plots for the first, second, third, and fourth growing periods were 15, 20, 30, and 39 t ha^{-1}, respectively. The high heating value of different aerial parts of a number of giant reed populations grown in Greece ranged from 14.8 to 18.8 MJ kg^{-1}. Depending upon the population and the growing period, the contents of ash ranged from 4.8 to 7.8%.

5.4.5. Giant reed as a bioenergy crop

Due to seed sterility, giant reed has to be vegetatively propagated from fragments of stems and rhizomes. This may limit large-scale cultivation, since it involves considerable cost and effort

and is time-consuming. Tissue culture is an alternative to conventional methods of vegetative propagation and may represent a useful tool for large-scale propagation in a bioenergy crop [93].

Giant reed has been reported to grow without irrigation under semiarid Southern European conditions [94]. However, it has been reported that irrigation had considerable effects on growth and biomass production since the plant used effectively any possible amount of water [95].

If the nutrient status of the soil is poor, a sufficient amount of K and P should be applied before establishing the giant reed plantation. Otherwise, moderate N fertilization of giant reed is favorable for both economic and environmental reasons. Due to its high growth rates, giant reed does not face significant weed competition from the second year onwards. However, herbicide application is recommended during the first year. Biomass can be harvested each year or every second year, depending on its use [86].

6. Conclusions

Perennial rhizomatous grasses can contribute significantly to the sustainable biomass production due to their high yield potential, low input demands, and multiple ecological benefits. Yields of more than 30 t DM ha^{-1} have been obtained from rhizomatous grasses. However, biomass yields strongly depend on local soil and climatic conditions.

The issue of primary concern when burning grasses is mineral composition that determines the melting point of ash and the potential for corrosion. Ash content needs to be minimized to avoid fouling problems. Appropriate harvesting time and fertilization application can contribute significantly toward improvement of ash content and ash-melting behavior. There is the possibility of using grasses biomass by blending it with other biomasses with low ash, K, and Cl contents. Further research is required to find the optimal blend of biomass.

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