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Review

Weed Management Practices to Improve Establishment of Selected Lignocellulosic Crops

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Abstract: Lignocellulosic biomass is one of the dominant renewable energy resources suited for the production of sustainable biofuels and other energy purposes. This study was focused on weed management strategies that can improve the establishment of six lignocellulosic crops. The studied crops included: giant miscanthus, switchgrass, giant reed, cardoon, sweet sorghum, and kenaf. Delayed planting, increased planting densities, and mulching techniques can suppress weeds in giant miscanthus. Weed competition is detrimental for switchgrass establishment. Seedbed preparation and cultivar selection can determine its ability to compete with weeds. Giant reed is unlikely to get outcompeted by weeds, and any weed control operation is required only for the first growing season. Competitive cultivars and increased seeding rates maximize the competitiveness of cardoon against weeds. Several cultural practices can be used for non-chemical weed management in sweet sorghum and kenaf. For all crops, pre-emergence herbicides can be applied. The available safe post-emergence herbicides are limited. Mechanical weed control during crucial growth stages can provide solutions for sweet sorghum, kenaf, and perennial grasses. Further research is required to develop effective weed management strategies, with emphasis on cultural practices, that can improve the establishment of these prominent lignocellulosic crops.

Keywords: *Miscanthus* × *Giganteus*; *Panicum virgatum* L.; *Arundo donax* L.; *Cynara cardunculus* L.; *Sorghum bicolor* Monech L.; *Hibiscus cannabinus* L.; biomass; bioethanol; weeds; cultural practices

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1. Introduction

Lignocellulosic biomass is the most abundant resource of organic carbon on Earth [1,2]. It can be obtained from the cultivation of various perennial and annual plant species and converted into liquid biofuels such as bioethanol [3,4]. Biofuels are expected to play a key role in solving the energy and environmental crises, as they are sustainable, renewable, and have a lower carbon footprint than conventional fossil fuels [5]. It should be noted that although food crops can also be grown for lignocellulosic biomass production, their cultivation for energy purposes causes conflicts with food production [6]. However, specific non-food crop species can produce large amounts of biomass in areas where food crops cannot be grown, relieving society of the fuel versus food debate [7]. As a result, these specific crops are expected to play a significant role in the energy landscape of the future.

This study focused on six herbaceous lignocellulosic crops whose biomass can be used as feedstock for the production of advanced biofuels such as bioethanol [8,9]. The perennial species in the group of selected crops were giant miscanthus (*Miscanthus* × *Giganteus* Greef et Deu.), switchgrass (*Panicum virgatum* L.), giant reed (*Arundo donax* L.), and cardoon (*Cynara cardunculus* L.). The annual species studied were sweet sorghum (*Sorghum bicolor*

(L.) Moench) and kenaf (*Hibiscus cannabinus* L.). The selection was based on evidence in the literature indicating these plants' adaptability under European soil and climatic conditions. Moreover, there are research data on the agronomic performance and productivity of these crops in European countries where field trials have been conducted in the past [10–15]. All these species are widely proposed to meet sustainability criteria and deliver suitable biomass products for the production of advanced biofuels and other energy purposes [8,16].

The selected lignocellulosic crops have wide adaptability and are resistant to various biotic and abiotic stresses [17–19]. As for their competitive ability against weeds, all these species can effectively suppress weeds. After a dense canopy is established, weeds are suppressed and weed control is no longer an issue [20–24]. However, before this stage, weeds can invade the stand and become a major obstacle to successful crop establishment [25]. Recent research studies have shown that interference by weeds in early growth stages can lead to significant yield losses. In Eastern Europe, competition from noxious broadleaf and grassy weeds such as *Chenopodium album* L., *Amaranthus retroflexus* L., *Echinochloa crus-galli* (L.) P. Beauv., and *Setaria glauca* (L.) P. Beauv. resulted in a 41% reduction in biomass yield of giant miscanthus [26]. Weed competition is the main reason for the failure of switchgrass establishment. Larson et al. [27] showed that one plant of *Setaria* spp. m^{-2} reduced switchgrass ground cover and biomass yield by up to 27%. The same authors found that ground cover of switchgrass was reduced by up to 73% when the density of *Setaria* spp. was increased to 10 plants m^{-2}.

Weed problems have also been reported for giant reed and cardoon. In Spain, *Conyza sumatrensis* (Retz.) E. Walker and *Conyza bonariensis* (L.) Cronquist were the dominant weeds observed in the field trials of Curt et al. [28]. These authors reported a loss of 55% of giant reed biomass yield when weeds were left uncontrolled [28]. In central Greece, Vasilakoglou and Dhima [15] recorded up to 66% losses in biomass yield of cardoon due to increased infestations of *Avena sterilis* L., *Papaver rhoeas* L., *Sinapis arvensis* L., and *Veronica hederifolia* L. Weeds are also a significant threat to the productivity of the annual species included in this study. Silva et al. [23] recorded a reduction in stem diameter and biomass yield of 25 and 50%, respectively, in sweet sorghum due to weed competition; the dominant weeds in their experimental field were *Eleusine indica* (L.) Gaertn., *Digitaria insularis* (L.) Fedde., and *Cyperus esculentus* (L.). The co-occurrence of broadleaf weeds and perennial grassy weeds (i.e., *Cynodon dactylon* (L.) Pers. and *Panicum maximum* Jacq.) under tropical climatic conditions resulted in 55, 70, 83, and 86% lower values for stem diameter, plant height, bast, and core fiber yield of kenaf, respectively [29].

The aim of this study is to present effective weed management strategies that can improve the establishment of the selected lignocellulosic crops. The general agronomic practices that create the optimal growth conditions for each crop are presented. Emphasis is given on cultural practices that can be adopted to suppress weeds. Available and safe herbicides are also presented.

2. Weed Management Practices to Improve the Establishment of Perennial Lignocellulosic Crops

2.1. Giant Miscanthus (Miscanthus × Giganteus Greef et. Deuter; Poaceae)

Giant miscanthus is a warm-season, perennial, rhizomatous grass with a C 4 photosynthetic pathway. The genus *Miscanthus* spp. is originated from East Asia. Giant miscanthus is a sterile hybrid between *Miscanthus sinensis* Andersson (1855) and *Miscanthus sacchariflorus* (Maxim.) Franch. It is a prominent lignocellulosic bioenergy crop for the production of cellulosic ethanol and other energy purposes [30]. Temperate areas are best suited for its cultivation [30]. Averaged over 22 years, its biomass yield production was 13.3 t DM ha^{-1} per year in Southern Italy [11]. In Germany, Iqbal et al. [31] observed that the mean annual biomass yield was 16.2 t DM ha^{-1}. The cultivation process requires fewer inputs than annual crops, and after establishment, the stands can remain fully productive for more than 20 years [32]. Weed competition is a factor of major importance for achieving successful establishment. Left uncontrolled, a weed infestation during the establishment year might turn into severe infestations during subsequent years [33]. Weeds caused 68%

plant mortality in a study by Haines et al. [34]. Given the slow growth rates of giant miscanthus during its early growth stages, weed control is necessary during the first growing season, and supplementary operations might also be needed during the second year [35].

Weed management relies first on the appropriate agronomic practices that ensure optimal growth for the crop. First, fields infested with perennial weeds should be avoided. Before planting, existing vegetation should be removed from the field [36]. Concerning its soil requirements, the crop has wide adaptability, but well-drained soils favor its growth. Selecting soils with sufficient water holding capacity is the most critical requirement [32]. The soil should be ploughed at 20–30 cm depth and harrowed before planting to eliminate weeds [22]. It was reported that ploughing the soil and hoeing before planting can decrease weed pressure by 35% compared to adopting minimum tillage systems [37]. Planting should take place after the frost period has passed. Planting densities can range between 1 and 4 plants m^{-2} [22,32]. Giant miscanthus is mainly propagated by planting divided rhizomes or pre-grown plantlets generated from rhizomes [22,38]. Rhizome length should be 10 cm or more [35,39,40]. For rhizomes, a planting depth of 10 cm has been found beneficial for maximizing aboveground biomass [41]. Irrigations during the first year are encouraged to increase establishment rates [32].

Cultural practices can be also adopted to suppress weed growth in newly planted giant miscanthus (Table 1).

Table 1. General agronomic practices and recommendations for giant miscanthus establishment, cultural practices to suppress weeds and direct weed control methods.

General Agronomic Practices/Recommendations for Establishment	Cultural Practices to Suppress Weeds	Direct Weed Control Methods
Well-drained soils/water holding capacity	Cold storage of rhizomes before planting	Interrow cultivation (1st and 2nd year)
Planting after the frost period	Delayed planting	Pre-emergence herbicides
Ploughing (20–30 cm) fb by harrowing	Compost mulching (2 cm)	Post-emergence herbicides (1st year) (Plant height: 40–50 cm)
Rhizome length: ≥10 cm	Increased planting density	
Planting depth: 10 cm	Mulching (biodegradable film)	
1–4 plants m^{-2}	Mulching (biomass)	
Irrigation (1st year)		

Davies et al. [37] found that cold storage of the rhizomes at 2 °C for two, four, and six weeks before planting resulted in 42, 72, and 65% lower weed ground coverage, respectively [37]. It should be noted that planting was delayed according to the cold storage period. Timing the planting to avoid weed competition was also suggested from Anderson et al. [42]. Davies et al. [37] noticed that planting along with compost mulching at 2 cm of depth can reduce weed ground coverage up to 48% when preferred over planting without implementing any mulching practice. Moreover, the biomass produced after the first growing season should be clipped and incorporated into the soil (i.e., mulching) with hoeing in early spring to inhibit weed emergence [38,43]. Biodegradable (and plastic) mulch films are another option to improve soil temperature, accelerate giant miscanthus growth, and suppress weeds. In relevant studies, mulching improved establishment rates, plant height, and biomass yield compared to conventional practices [44,45]. Planting density is another cultural practice recommended to suppress weeds and improve establishment. Von Cossel et al. [38] indicated that 1.66 plants m^{-2} suppressed weeds more effectively than 1.11 plants m^{-2}. Increasing planting rates from 2 rhizomes m^{-2} to 3 rhizomes m^{-2} has been reported to reduce the total weed biomass by approximately 17–31% at the five-leaf growth stage of giant miscanthus [46]. The greater levels of weed suppression resulted in a 24% higher biomass yield in a soil of low fertility, heavy mechanical composition, and unfavorable water–air properties. This is quite important given that this perennial grass is one of those crops representing the concept of developing low-input cultivation systems in marginal lands [9].

As for the available direct weed control methods, repeated passes with a rotary hoe between the crop rows for mechanical weed control is suggested for the first and second years if weeds remain an obstacle [11,42]. Concerning chemical control, the use of soil-applied herbicides with residual activity can provide a broad spectrum of weed control in the long term. Under real field conditions, pendimethalin at application rates of 1600–3200 g ai ha^{-1}, and *S*–metolachlor at 1785–3570 g ai ha^{-1} caused no injury when applied immediately after planting [47]. Mesotrione at 210 g ai ha^{-1} is another option if tank-mixed with the herbicides mentioned above [40]. These active ingredients are registered in Europe and can provide solutions. As for post-emergence applications, safe herbicides are mainly represented from auxinic herbicides such as 2,4–D (1060 g ai ha^{-1}), dicamba (560 g ai ha^{-1}), and bromoxynil (840 g ai ha^{-1}), which aim to control broadleaf weeds [48]. Such herbicides have been succesfuly applied when giant miscanthus plants were 40–50 cm high. On the contrary, the applications of ACCase- and ALS-inhibitors should be ignored. Although these herbicides can control troublesome grass weeds, their application can also cause unacceptable levels of crop injury [39,40,47].

2.2. Switchgrass (Panicum virgatum L.)

Switchgrass is another warm-season, perennial, rhizomatous, *C* 4 grass, native to North America. This species is a leading candidate among herbaceous species to be developed as a bioenergy feedstock for cellulosic ethanol production, direct combustion for heat, and other technologies [16]. There are two ecotypes, lowland and upland. The lowland ecotypes are preferable for the warm regions of Europe, whereas the upland ecotypes could be also grown in the cooler climatic zones [16]. In Greece, Alexopoulou et al. [10] found that the lowland ecotypes yielded 14.9 t DM ha^{-1} y^{-1} while upland ecotypes yielded 13.9 t DM ha^{-1} y^{-1}. A successfully established stand is persistent for more than 10 years. Weed competition is the major reason for establishment failure in switchgrass. Given the slow initial growth rates of the crop, the stand might be covered with weeds in the absence of any control practice. Weed biomass was negatively correlated with switchgrass plant height, tiller density, and biomass yield (R^2 = 0.52–0.81) in a recent study by An et al. [49]. Significant biomass yield reductions (up to 56%) were attributed to inadequate control of grass weeds such as *Setaria* spp. and *Panicum dichotomiflorum* Michx. by Miesel et al. [50].

Stand frequency above 50% indicates a successful stand, whereas stands with less than 25% frequency need to be re-established [51]. A series of agronomic practices need to be adopted to achieve sufficient levels of frequency in the stand and create the conditions for switchgrass to form a dense canopy and outcompete weeds. First of all, fields with perennial weeds are not recommended for switchgrass cultivation. Before sowing, proper weed control is required, and weed residues should be removed from the cultivated area [52]. Switchgrass has no special soil requirements and can be productive in shallow, rocky soils where other crops cannot be grown; well-drained soils favor its growth [32]. This perennial grass is propagated by seed. A very crucial point is to evaluate the germination of the seeds and select the appropriate seeding rates or break seed dormancy. Holding the seeds at 5–10 °C for a month followed by redrying is a method of stratification to relieve seed dormancy [52]. A well-prepared, firm seedbed is mandatory. The soil should be ploughed (30–35 cm), harrowed, and cultipacked before and after sowing to obtain good seed–soil contact [53]. A seeding rate of 2 kg ha^{-1} is recommended for seed lots of high-germination-rate seeds, while increased seeding rates (10 kg ha^{-1}) are required for seed lots of intermediate-germination-rate seeds [52]. Sowing should be carried out when the soil is warm enough (>15 °C), with 20–80 m row spacing at shallow depths (0.5–2.0 cm) given the small size of the seeds [54]. During the first year, unnecessary fertilization can increase weed density and should be avoided [49].

Although seedbed preparation is widely accepted as a fundamental point for achieving maximum emergence and productivity, the role of sowing in a non-tilled seedbed should be evaluated. Sadeghpour et al. [55] reported lower weed biomass in their non-tilled plots as compared to the conventional tillage system, especially when they used cover crops to suppress weeds. These authors noticed that the use of oat (*Avena sativa* L.) as a cover crop reduced weed biomass by 30–32% as compared to the weedy check and the use of (*Secale cereale* L.) as a cover crop. These interesting results were obtained in a field infested by noxious grass weeds, i.e., *Setaria glauca* (L.) P. Beauv. and *Digitaria sanguinalis* (L.) Scop. [55]. The role of cover crops needs to be further investigated. Another cultural practice for weed management is delayed sowing to avoid competition from early-emerging spring annual weeds. Competitive cultivars and mulching practices can be also used to suppress weeds in switchgrass (Table 2).

Table 2. General agronomic practices and recommendations for switchgrass establishment, cultural practices to suppress weeds and direct weed control methods.

General Agronomic Practices/Recommendations for Establishment	Cultural Practices to Suppress Weeds	Direct Weed Control Methods
Weed control before sowing Seed stratification Well-drained soils Ploughing (30–35 cm) fb harrowing Firm seedbed (cultipacking)	Increased seeding rates Non-tilled seedbed Cover crops (oat) Delayed sowing	Interrow cultivation (3 years) Mowing (30 cm height) Pre-emergence herbicides Auxinic herbicides (3 years) (Crop GS: 4–5 leaves)
Warm soil (soil T $\geq$ 15 °C) Seeding rates: 10 kg ha^{-1} Sowing depth: 0.5–2.0 cm Row spacing: 20–80 cm	Competitive cultivars Mulching (Biomass)	

Late sowing dates can reduce weed biomass by up to 56 and 73% in comparison to intermediate and early seeding dates, respectively, and biomass yields can benefit in turn due to the lower levels of weed pressure [56]. Parrish and Fike [52] also encourage farmers to delay the seeding process as far as possible. Increased seeding rates (10 kg ha^{-1}) were also reported to be an effective weed-suppressing strategy [56]. Variability can exist regarding the competitiveness of different cultivars [57]. In a study by An et al. [58], "*Cave-in-Rock*", an intermediate ecotype, was the only cultivar able to suppress weed growth during the whole cultivation period. The authors attributed this result to the higher photosynthetic rates and longer growing period of this cultivar compared to the others. This particular cultivar was also the most competitive against weeds and exploited any added nitrogen supply in a recent study conducted in established switchgrass [49]. Another interesting approach is to mulch the biomass of switchgrass to inhibit weed growth and emergence. Clipping plants in early spring of the second growing season and mulching the residue provided noticeable levels of weed control in the study by An et al. [58]. These researchers indicated the allelopathic effects of the residue against weeds.

Concerning direct weed control methods, interrow cultivation along with herbicide application can provide solutions [52]. In addition, a mowing operation designed to clip weeds that are taller than switchgrass is recommended [59]. Curran et al. [56] found that combined with delayed sowing, mowing at 8–10 weeks after sowing reduced weed biomass by 41–45% compared to the case where a single herbicide treatment was applied. Herbicide application is another option. Pre- and post-emergence applications of quinclorac were effective in the United States [50]; this active ingredient is not registered in Europe, however. Pendimethalin as pre-emergence at 1100 g ai ha^{-1} can have satisfactory efficacy against a broad spectrum of weeds without causing crop injury [57]. The use of seed safeners to avoid crop injury from pre-emergence applications of *S*-metolachlor has been successfully tested by Rushing et al. [60]. As for post-emergence chemical control, auxinic herbicides, e.g., 2,4–D, dicamba, and bromoxynil, can be safely applied to control broadleaf weeds when the switchgrass plants have four to five leaves [51]. On the contrary, herbicides with the potential to control grass weeds can be phytotoxic for switchgrass [48].

2.3. Giant Reed (*Arundo donax L.*)

Giant reed is a warm-season, perennial, rhizomatous grass. It has a *C* 3 photosynthetic pathway, but the plants exhibit high photosynthetic rates that are comparable to those exhibited by *C 4* plants [61]. It is native to India and widespread in the tropics and subtropics. Giant reed is one of the most promising bioenergy crops. Its biomass is suitable for the production of advanced biofuels (i.e., biogas and bioethanol), direct combustion processes, and multiple industrial uses [62]. This lignocellulosic crop is tailor-made for the semi-arid environments of the Mediterranean origin. In a 16-year field trial conducted in Northern Italy, the crop yielded 16.2–19.5 t DM ha^{-1} [14].

Once established, the stand is persistent for at least 15 years [24,62]. Giant reed is unlikely to get outcompeted by weeds, and the demands for weed control operations during its cultivation process are limited in the first growing season [24,63]. There are also reports where no weed control was needed [63,64]. As for the general procedures for establishment, giant reed is mainly propagated by rhizomes or stem cuttings planted in spring [14,65]. Giant reed does not tolerate low temperatures, so planting in very early spring should be avoided [66]. If directly planted, the rhizomes are placed at 10–20 cm soil depth [67]. Pre-grown plantlets are also widely used [63,64,68,69]. This crop is adaptable to various soil types and highly productive in marginal areas and polluted lands [68]. For optimal growth, giant reed most benefits from well-drained soils with sufficient humidity [66]. The usual planting density is 1–2 plants m^{-2} [64,65,70]. Before planting, existing vegetation should be controlled and removed from the cultivated area. For preparing a seedbed, ploughing operations are carried out at 40–45 cm soil depth and are followed by harrowing to ensure rhizome placement [14,67]. When plantlets are used, ploughing is carried out at lower depths [62].

There are no studies reporting the use of cultural practices focused on suppressing weeds in giant reed, mainly due to the highly competitive status of this crop (Table 3).

Table 3. General agronomic practices and recommendations for giant reed establishment, and direct weed control methods.

General Agronomic Practices/ Recommendations for Establishment	Direct Weed Control Methods
Well-drained soils with humidity Planting in spring after the frost period Ploughing (40–45 cm) fb harrowing Rhizomes/stem cuttings Planting depth: 10–20 cm 1–2 plants m^{-2}	Interrow cultivation (1st year) Mowing (1st year) Pre-emergence herbicides Post-emergence herbicides (1st year)(Crop GS: 40–50 cm)

Direct weed control methods include interrow hoeing [11,14,67]. Timely weed control is beneficial for the crop during the first year if highly competitive species (*Conyza* spp.) have invaded the stand. In particular, weeding in May resulted in 15, 25, and 34% higher values of plant height, number of shoots per plant, and dry weight per plant, respectively, compared to letting weeds compete with giant reed until June [28]. Danelli et al. [68] used mowing for weed control between the rows. Pre-emergence applications of *S*–Metolachlor and flumioxazin at 1390 and 71.5 g ai ha^{-1}, respectively, are safe according to Smith et al. [48]. As for post-emergence herbicides, Liu et al. [71] found that MCPA plus bromoxynil mixtures (420 g ai ha^{-1}), dicamba (280 g ai ha^{-1}), and chlorsulfuron (30 g ai ha^{-1}) did not cause phytotoxicity symptoms. Plant height was 40–50 cm when these herbicides were applied. On the other hand, ACCase-inhibitors such as sethoxydim (213 g ai ha^{-1}) can cause injury to the treated plants [48].

2.4. Cardoon (*Cynara cardunculus* L.)

Cardoon is originated in the Mediterranean region. Completely unirrigated, cardoon yielded 14 t DM ha^{-1} y^{-1} in Spain [72]. Its biomass is suitable for thermochemical processes to generate energy, while it is also a valuable source of sugars that can be fermented into bioethanol [73]. It is a perennial, *C* 3, herb, performing an annual growth cycle by re-sprouting every autumn. Once established, cultivation can last for more than 15 years [20]. During the establishment year, weeds can compete with cardoon. White and Holt [74] suggested that cardoon growth is severely affected due to competition with early-emerging grass weeds. The adoption of certain agronomic practices is important to create the conditions for optimal initial growth and minimize the effects of competition.

The stand should be established by seed or transplanting plantlets in autumn when the air temperature ranges between 20 and 25 °C [73]. Cardoon has a deep rooting system and needs to be cultivated in deep soils to enable the rooting system to develop properly [73] (Gominho et al. 2018). Soil preparation should include ploughing at 30–40 cm depth and harrowing [75–77]. Subsoiling (69 cm depth) followed by double harrowing is needed in the case of extremely heavy soils [78]. Harrowing before sowing or planting is required to control weeds [75,78,79]. The seeding rates are about 3–4 kg ha^{-1}, and the common row spacings are 70, 75, and 100 cm [15,77,80]. Sowing depth should be 2 cm [81]. In general, densities of 1–2 plants m^{-2} are required for a successfully established stand [73]. An irrigation (30 m^3 ha^{-1}) after planting can also improve the establishment rates [79].

The use of highly allelopathic and competitive cultivars is recommended as a cultural practice for effective weed suppression in cardoon (Table 4).

Table 4. General agronomic practices and recommendations for cardoon establishment, cultural practices to suppress weeds and direct weed control methods.

General Agronomic Practices/Recommendations for Establishment	Cultural Practices to Suppress Weeds	Direct Weed Control Methods
Weed control before sowing Deep soils Subsoiling in heavy soils Ploughing (30–40 cm) fb harrowing 1–2 plants m^{-2} Seeding rate: 3–4 kg ha^{-1} Sowing depth: 2 cm Row spacing: 75–100 cm Irrigation (1st year)	Increased seeding rates Competitive cultivars Allelopathic cultivars	Interrow cultivation (1st year) Pre-emergence herbicides

Averaged over three experimental years, Vasilakoglou and Dhima [15] observed that the presence of "*C12*" cultivar resulted in 10% lower sterile oat density compared to the presence of "*Bianco Avorio*" cultivar. The authors attributed this outcome to the faster canopy closure of "*C12*". In addition, a recent study highlighted the importance of adopting increased seeding rates for weed suppression in cardoon. In particular, Zenobi et al. [77] noticed that seeding at 1 m distance between rows and 0.5 m distance within rows reduced weed biomass by 65% compared to seeding cardoon at 1 m inter- and intrarow distances. To control weeds, hoeing between crop rows is widely suggested [73,82]. It should be noted that weed control is not always necessary. In their three-year field trials, Tsiaousi et al. [80] revealed that cardoon produced 19.70 t DM ha^{-1} without implementing any weed control method. However, if weeds remain an obstacle, pre-emergence herbicides are safe and effective. For example, Ierna et al. [76] applied oxyfluorfen (500 g ai ha^{-1}) between the crop rows. Moreover, Gominho et al. [73] suggested the combined use of pendimethalin as pre-emergence followed by interrow cultivation. Post-emergence herbicides may be phytotoxic to the crop.

3. Weed Management Practices to Improve the Establishment of Annual Lignocellulosic Crops

3.1. Sweet Sorghum (Sorghum bicolor (L.) Moench)

Sweet sorghum is a warm-season, annual grass with a *C* 4 photosynthetic pathway originated in Africa. Famous for its drought resistance and adaptability, it is cultivated in tropical, subtropical, and temperate areas [83]. It is one of the leading crops in the sector of bioethanol production. The plants have thick, long stalks with high soluble sugar content [84]. The biomass yield potential of this crop is high. Jankowski et al. [13] obtained yield values of 19.0 t DM ha^{-1} y^{-1} after 11 years of experimentation. To achieve high yields, weed management is mandatory.

Weed problems have been attributed to interference by noxious broadleaf weeds such as *Abutilon theophrasti* (Medic.) and *Amaranthus* spp. [85,86]. Infestations from grass weeds are also a very significant threat for *S. bicolor*. Common grass weed species that occur in sorghum include *Sorghum halepense* (L.) Pers. and *Sorghum bicolor* L. Moench. Given the botanical ties between *S. halepense* and sweet sorghum, it is not possible to control the perennial *S. halepense* with selective herbicides, and its initial infestations in the field evolve to severe infestations during the subsequent years [87]. The same can be noted for *S. bicolor* subsp. *drumondii*. Moreover, the strong botanical ties between the crop and its wild relatives enable gene flow between the crop and *S. halepense* as well as *S. bicolor* subsp. *drumondii*, with consequences including the spread of very competitive hybrids in the field [88]. Hence, to achieve successful establishment, it is key to avoid fields infested by these weeds and to control them in fallow areas near to the cultivated fields of sweet sorghum [89]. Besides this preventative measure, a well-prepared, firm seedbed is required to obtain a successfully established stand. The soil should be ploughed at 25–30 cm depth and then disk harrowed to further break clods [90]. The crop is propagated by seed in late spring to mid-summer for Europe [83]. Sowing should be performed at 2.5–3.5 cm depth and should be targeted to achieve a desired density of 12–20 plants m^{-2}. [83]. Row spacings can range between 35 and 105 cm [13,83]. In fact, row spacing is a useful cultural practice to suppress weed growth (Table 5).

Table 5. General agronomic practices and recommendations for sweet sorghum establishment, cultural practices to suppress weeds and direct weed control methods.

General Agronomic Practices/Recommendations for Establishment	Cultural Practices to Suppress Weeds	Direct Weed Control Methods
Avoiding fields infested with wild crop relatives	Narrow row spacing	Interrow cultivation between the 3- and 7-leaf GS Mowing between the 3-and 7-leaf GS
Well-drained soils	Increased seeding rates	
Ploughing (25–30 cm) fb harrowing	Competitive cultivars	
12–20 plants m^{-2} Sowing depth: 2.50–3.50 cm Row spacing: 35–105 cm	Allelopathic cultivars Intercropping	

Narrow row spacing of 25 cm between crop rows has been reported to reduce weed density by 24–45% compared to sowing in 51 and 76 cm-spaced rows, respectively [91]. The findings of other field trials carried out in the sweet sorghum crop were similar [92]. Narrow row spacing (≤50 cm) can increase the competitive ability of sweet sorghum against weeds and, subsequently, influence its productivity as well as its potential for bioethanol production [93]. Concerning the role of increased seeding rates, it must be mentioned that dense crop populations can rapidly achieve canopy closure and suppress weeds effectively [94–96]. Wu et al. [97] increased their seeding rates by 40% to limit the growth, biomass, and seed production of *Echinochloa esculenta* ((A. Braun) H. Scholz) by 22, 27, and 32%, respectively. In non-tilled sorghum, a significant decrease in weed population was attributed to increased sowing rates [98].

Furthermore, a study by Traoré et al. proved that the competitive ability of *S. bicolor* is a matter of hybrid selection, since taller hybrids were more competitive against *A. theophrasti* compared to shorter hybrids [86]. This study suggested growing tall (1.2–1.5 m) hybrids with increased Leaf Area Index (LAI) values as a promising weed management practice. In a study by Wu et al. [97], selecting a tall sorghum cultivar reduced *E. esculenta* density, biomass, and seed production by 19, 31, and 34%, respectively. The observations of Mishra et al. [99] regarding the increased competitiveness of taller hybrids were similar. There is also evidence that *S. bicolor* cultivars have excellent allelopathic potential, since they were reported to have suppressed noxious weeds such as *Cyperus rotundus* (L.) and *Ipomoea hederifolia* L. [100]. Recent research has established that allelopathic genotype cultivars provide suppression to noxious weed species such as *S. halepense*, *Echinochloa colona* L. (Link), and *Amaranthus retroflexus* L.; weed suppression was attributed to the presence of phenolic acids on the root exudates of the crop plants [94]. The establishment of biotypes with strong allelopathic effects, as well as their residues, inhibit weed growth not only in monoculture but also in a rotational view [101]. Intercropping with legume crops is another cultural practice with promising potential to enhance weed management options in sweet sorghum [102] Intercropping with cotton has also been reported to reduce the density and biomass of *C. rotundus* up to 96 and 97%, respectively [103].

In regard to direct weed control methods, the critical period for weed control in sweet sorghum ranges between the three- and the seven-leaf growth stages [23]. Very few herbicides can be used safely for weed control due to phytotoxicity concerns. For example, Silva et al. [104] detected severe injury symptoms in sweet sorghum after treatment with nicosulfuron at 40 g ai ha^{-1}. Moreover, injury levels above 98% were reported for an herbicide mixture containing flumioxazin and *S*–metolachlor [105]. However, mechanical weed control operations can alleviate weed pressure on sweet sorghum during the critical growth stages. In particular, weed density can be reduced by 31% by one hoeing operation between the crop rows at the three-leaf growth stage [95]. In a study carried out in Europe, the dominant weed species were *Amaranthus retroflexus* L., *Chenopodium album* L., and *Echinochloa crus–galli* (L.) P. Beauv. Mechanical weed control increased the biomass of the crop's plants by 30–33% [106]. Moreover, mechanical weed control can be integrated with row spacing manipulation. For example, in the case where rows are spaced at 53 cm, Donald [107] suggested mowing the weeds between the rows, close to the soil surface, as an effective practice for the management of *Setaria* spp. and *Amaranthus* spp.

3.2. Kenaf (Hibiscus cannabinus L.)

Kenaf (diploid ($2n = 2x = 36$)) is a warm-season, *C* 3, annual, spring crop. Originated in Africa, kenaf is favored for cultivation in tropical, subtropical, and temperate areas and is targeted for the fields of southern Europe [108]. In Northern Italy, Amaducci et al. [12] recorded a mean biomass yield value of 15.7 t DM ha^{-1} y^{-1} in their three-year field trials. It should be noted that kenaf is not primarily grown for energy purposes. However, it has been included because the potential of this multipurpose crop for bioethanol production has recently been highlighted [3,109,110]. To achieve high biomass yields in the Mediterranean origin, the crop is established by seed from mid-April to early May [111]. According to Alexopoulou et al. [112], a preventative step to achieve successful establishment is to avoid planting in fields with high infestation levels of velvetleaf (*Abutilon theophrasti* Medic.). This broadleaf weed is very similar to kenaf in the early growth stages and is a difficult-to-control species. No trials have evaluated the effects of its interference on kenaf growth and yield. However, the presence of 2 plants m^{-1} in a row was reported to reduce the stem diameter and plant height of another fibrous crop [113]. Fields infested with perennial grasses such as *S. halepense*, *Panicum maximum* Jacq., and sedges (*Cyperus* spp.) are also inappropriate [29,114].

The crop has wide adaptability in different soil types, but optimal development occurs in well-drained, deep, fertile soils [115]. Sowing is performed from mid-spring to May. The sowing date is very important, as the soil temperature should be above 15 °C to allow seedlings to emerge about five days after seeding [112]. The soil should be plowed (25–30 cm) and disk harrowed to ensure that a fine textured seedbed is prepared [21]. The use of a cultipacker before and after sowing is also beneficial for seedbed preparation [116]. A well-prepared seedbed is essential to achieve good seed–soil contact and maximum emergence [117]. The seeds should have a high germination rate. Sowing depth should be 1.25–2.50 cm [117]. It is very important to follow these agronomic practices so that the crop can show its optimum growth rates and outcompete weeds. Recommended seeding rates are 8–12 kg ha^{-1} and 10–15 kg ha^{-1} to achieve plant populations of 185,000–370,000 and 300,000–500,000 plants ha^{-1}, respectively. Common row spacing ranges from 35 to 50 cm [112].

Increased seeding rates and narrow row spacing are common cultural practices to suppress weeds. However, in two case studies conducted to evaluate the effects of such practices on kenaf growth, no weed data were recorded [118,119]. Research is required to investigate the role of row spacing and plant population for weed management in this multipurpose crop. However, the selection of competitive cultivars is a useful weed management option (Table 6).

Table 6. General agronomic practices and recommendations for kenaf establishment, cultural practices to suppress weeds and direct weed control methods.

General Agronomic Practices/Recommendations for Establishment	Cultural Practices to Suppress Weeds	Direct Weed Control Methods
Avoiding fields infested with *A. theophrasti*	Competitive cultivars	Interrow cultivation between 3 and 6 WAS (plant height: 15 cm)
Well-drained soils	Fertilization	Pre-emergence herbicides
Soil T ≥ 15 °C		Post-emergence herbicides (plant height GS: 35 cm)
Ploughing (25–30 cm) fb harrowing Seeding rates: 8–15 kg ha^{-1} Row spacing: 45–75 cm 20–40 plants m^{-2} Sowing depth: 1.25–2.50 cm Row spacing: 35–105 cm		

In a study by Ajibola and Modupeola [120], total weed density was 17% lower in plots of the cultivar "*Tangum 1*" as compared to the values recorded in plots of the cultivar "*Cuba 108a*". Aluko and Anjorin [121] observed that the presence of "*Ifeken* 100" cultivar reduced weed biomass by 53% compared to that of "*V1 400–2*", indicating that tall genotypes are very competitive against weeds. The same can be noted for fertilization. Nitrogen fertilization at the rates of 60 and 80 kg ha^{-1} was reported to promote kenaf growth and result in lower values of weed biomass [122]. In a study by Kuchinda et al. [21], kenaf exploited the nitrogen inputs (90 kg N ha^{-1}) added at crop thinning more effectively than *Euphorbia heterophylla* L., *Crotolaria retusa* L., and *Ageratum ciliare L.* Less. [120].

As for direct methods of weed control after the emergence of the crop, it should be noted that the critical period for weed control lasts between three and six weeks after sowing [21,120]. Five weeks after sowing, kenaf shades the ground and outcompetes weeds [123]. Alexopoulou et al. [112] recommend interrow hoeing when the kenaf plant height is 15 cm and the weeds are on the two-leaf growth stage. Another supplementary operation may be needed. Hoeing at three and six weeks after sowing can create weed-free conditions [21]. In addition, mechanical weed control can be integrated with the use of cover crops. Aluko et al. [29] observed increased weed control levels when they applied hoeing operations combined with the use of cover crops such as sweet potato (*Ipomoea batatas* (L.) Lam.) or egusi melon (*Citrullus lanatus* (Thunb.) Matsum. and Nakai.). The use of cover crops before sowing the main crop is a recommended practice for weed suppression in industrial and bioenergy crops [55,124].

There are also safe herbicides available for weed control during kenaf establishment. Pre-emergence application of *S*–metolachlor at 1440 g ai ha^{-1} was proven an effective weed control option in kenaf, and no phytotoxicity symptoms were detected in crop plants [29]. Pre-emergence application of pendimethalin at 1000.5 g ai ha^{-1} has also been reported to be applied successfully for weed control in kenaf [125]. Post-emergence herbicides that control broadleaf weeds may be phytotoxic for the crop. However, research has shown that post-emergence herbicides are also available to control grass weeds. The application of ACCase-inhibiting herbicides is safe when kenaf plants are 35 cm high [126,127]. Weed control efficacy was observed to be over 80% for post-emergence application of fluazifop–*p*–butyl at the rate of 300 g ai ha^{-1} without causing herbicide injury symptoms to the crop [29]. Fluazifop–*p*–butyl, quizalofop–*p*–ethyl, clethodim, and sethoxydim at various rates did not cause injury to kenaf plants in a study by Webber [126].

4. Conclusions

This study reveals that weed management is essential for the successful establishment of the selected lignocellulosic crops. Safe herbicides are limited, and most of them cannot control a broad spectrum of weeds. However, several cultural practices can be adopted to suppress weeds in these crops. Mulching techniques, increased seeding rates or planting densities, and delayed sowing or planting are valuable in giant miscanthus and switchgrass. Increased seeding rates and competitive cultivars are effective for cardoon and sweet sorghum. Kenaf can exploit added fertilization and smother weeds. Mechanical weed control is also useful, especially when applied during critical crop growth stages. Moreover, it can be integrated with the appropriate cultural practices to create effective weed management strategies. Utilizing crop competition to suppress weeds is a very promising option that can result in even lower inputs for the cultivation of these lignocellulosic crops. Further research is required to develop effective weed management strategies in bioenergy crops, with emphasis on cultural practices and different soil and climatic conditions than those in Europe.

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