

Review Article

Establishment and Production of Switchgrass Grown for Combustion: A Review

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Abstract

Switchgrass (*Panicum virgatum* L.) is a C₄-grass with deep fibrous root systems indigenous to North America. In recent years switchgrass has been considered to be a “model” energy crop due to its high productivity, perenniality, and adaptability to various sites and soils. This paper specifically reviews published works on the effect of cultural management practices on switchgrass establishment, biomass production and composition, dynamic of nutrient and non-structural carbohydrates (NSC) translocation from above-ground to roots and nitrogen-use efficiency (NUE).

INTRODUCTION

In recent years, notable interest has been paid to biomass-based energy production due to economic and environmental issues related to fossil fuel [1]. Use of grain corn (*Zea mays* L.) as the common feedstock for ethanol production has raised serious concerns about its sustainability. These concerns are mainly related to environmental pollution due to increased soil erosion and high agricultural inputs including chemical fertilizers and herbicides. Therefore use of perennial plant species (grasses and woods) which are more environmentally friendly sources of bioenergy production has gained more and more attention [2]. A ten-year study that began in the 1980's at Oakland Ridge National Laboratory identified switchgrass as an ideal species for bioenergy production due to variety of its desirable characteristics [3]. Consequently, dedicated research effort over the last thirty years, has led to significant progress in developing switchgrass as a biofuel crop [4]. The ultimate use of switchgrass is commonly either ethanol or heat [5]; however, when cultivation land is limited, energy production through combustion seems more feasible [6]. In this article the challenges associated with establishment, survival, and production of switchgrass grown for combustion are discussed.

SWITCHGRASS PLANT OVERVIEW

Switchgrass is a warm-season (C₄), sod-forming perennial tall grass native to North America [7] with deep fibrous roots which can reach up to 3 m deep [8]. The species has been evolving since approximately two million years ago and its dispersal from tropical regions to Central and North America created an extensive genotypic variation among the crop species leading to high adaptation of switchgrass to a wide range of growing conditions [9]. Latitudinal differences are most responsible for

variation among switchgrass populations. Latitude of origin has been reported to have a significant impact on productivity, survival, and adaptation traits of switchgrass [10,11]. In 1966, Porter [12] categorized switchgrass populations between two distinct ecotypes; “upland” and “lowland.” Lowland ecotypes occur in lower hydric conditions in lower latitudes, whereas upland varieties occur in drier, elevated conditions and are more common at higher latitudes [13]. Lowland ecotypes are more tolerant of wet conditions than upland types and grow taller and faster, but are more sensitive to drier conditions [14]. The leaves of lowland switchgrass are bluish-green and coarser and thicker than upland varieties. Additionally, the ligules are longer and the panicles are larger than upland types [15]. Upland ecotypes have thin stems, are generally less productive than the lowland varieties, often grow in a bunch form and are adapted to dry conditions [16]. Although lowland ecotype is less tolerant to dry conditions, the extensive root systems of switchgrass allow for both ecotypes to be more drought tolerant than other herbaceous crops such as *Miscanthus* (*Miscanthus giganteum* L.). Elberson et al. [17] determined that latitudinal differences were the main factor influencing adaptability, when southern varieties had higher yields in the north than northern varieties. When grown too far north however, southern varieties could be winter-killed [3]. In general, northern ecotypes have a longer winter dormant period with better winter survival than southern ecotypes when grown at the same latitude [18]. Conversely, planting northern varieties in southern locations does not necessarily maximize the yield because these varieties cease growth sooner in the fall due to their adaption to shorter growing season [19]. Figure 1 illustrates biomass yield differences between upland and lowland cultivars [20]. Among lowland ecotypes, the most productive cultivars were Alamo, SL941, SL931, Kanlow, NL942 and SL932 with average biomass production of 12.2 to 14.8 Mg

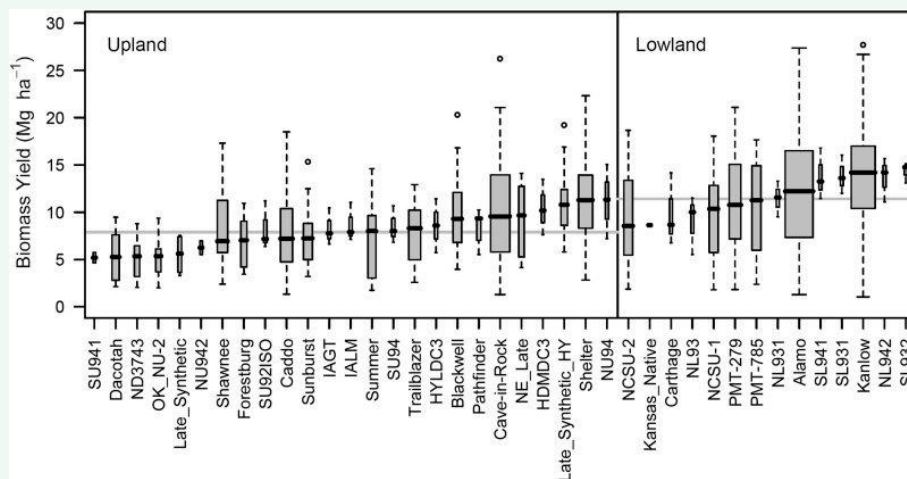


Figure 1 Biomass yield comparison between upland and lowland switchgrass cultivars at several locations in the USA (adopted from Wullschlegel et al. [20], with permission, copyright American Society of Agronomy).

ha⁻¹. Within upland ecotypes, Cave-in-Rock, NE Late, HDMDC3, Late-Synthetic-HY, Shelter, and NU94 were the highest yielding cultivars with median yield of annual biomass production ranged from 9.6 to 11.4 Mg ha⁻¹.

High adaptation to various sites and soils [21] plus high productivity with low chemical input (i.e. nitrogen fertilizer, herbicides and pesticides, etc.) [22], perenniality [23] as well as feasibility of harvest with conventional hay-making equipment [24] have been general criteria for the selection of switchgrass as a promising dedicated energy crop [21]. The ability of switchgrass to positively influence the environment by sequestering carbon (C), reducing soil and wind erosions, and increasing wildlife habitat has also been considered and well documented [5,25,3].

ESTABLISHMENT MANAGEMENT

One of the important challenges in switchgrass production is seedling establishment [23,4]. Similar to many warm-season perennial grasses, switchgrass has been known to be difficult or slow to establish [23,26,27]. Poor establishment in the planting year directly relates to reduced stand vigor and yield in succeeding years and limits large scale crop adoption [10,28,29]. It is estimated that a stand failure costs growers over \$300 ha⁻¹[30].

Switchgrass initially allocates energy to establishing an extensive root system in the first and second year and will consequently only reach 33 and 66% of its maximum production capacity, respectively [31]. Due to the allocation of energy to the development of root structures, switchgrass will not reach its full yield potential until the third year [32]. This extended establishment time has dissuaded many growers and entrepreneurs from planting switchgrass given the lack of financial return in the first two years; however with proper planning, switchgrass can be profitable endeavor for growers.

Establishment of switchgrass specifically in the establishing year can be influenced by several factors including high seed dormancy and weed pressure, improper planting technique or seedbed preparation, and adverse environmental conditions

[3,23,33].

Seed dormancy

Seed dormancy is one of the major challenges in establishment of switchgrass [28]. Switchgrass seed has been proven to be highly dormant at seed dispersal [34,35,36]. Innate seed dormancy can be caused by many chemical or physical inhibition mechanisms; however, it is most often due to the immaturity of the seed embryo at dispersal [37,38]. Chemical inhibition is caused by hormones that restrict germination [38] whereas; physical inhibition is caused by seed coat barrier [39]. One strategy to increase germination rates for maximum stand establishment is to reduce seed dormancy [40]. Dormancy reduction can be achieved through various methods. Two common approaches are stratification and after-ripening [41]. Studies concluded that stratification or a wet pre-chilling treatment at 5°C for two or more weeks reduced dormancy rates [42,43]. Averaged over two Cave-In-Rock seedlots, Shen et al. [41] found that stratification at 5°C for 14 days increased germination from 7% to 75%. Zhang and Maun [38] also found that germination rates could be increased from 3% to anywhere from 88-98% by scarification of the seed coat. Although this method was successful, in a review article, Parrish and Fike [3] stated that seed priming, scarification and hormonal treatments may not be applicable strategies on large-scale switchgrass production. One seed dormancy-breaking technique that is more feasible for large-scale production is after-ripening, storage of seeds for one or more years in a warm environment, which has shown positive practical effects on the reduction of dormancy in switchgrass [44].

Sowing rate

Variable germination rates of switchgrass due to seed dormancy can confound determination of sowing rate [14]. Several studies have developed, various planting rate recommendations have been made based on different calculation methods. Whether based on mass per area or number of "pure live seeds" per area, there have been many points of confusion regarding this matter [3]. Pure live seed (PLS) refers to seed that

is viable, including both dormant and non-dormant seeds [10]. In a standard germination test [45], results would be lower than in a viability test for PLS because dormant seeds will not necessarily germinate [46]. Seed distributors often test their seeds for viability (PLS), germination rate, weed seed contaminations and inert matter and include the test results on the seed packaging. Using the distributor's test results for PLS (%) or germination (%) to calculate planting rates will lead to an inaccurate planting rate [47]. Due to reduction in dormancy rates over time, current germination percentages do not necessarily correspond with supplied information. Conversely, seed testing laboratories will present inflated test data collected from controlled environment that do not accurately represent the stressed conditions that might occur in the field. In summary, the use of seed distributors' test results for determination of sowing rate should be avoided. Forberg et al. [48] concluded that it is more practical to implement a vigor test and then compensate for restricted germination by adjusting sowing rates.

Precise planting rates are crucial for a successful and economical planting of switchgrass as a bioenergy crop [29]. A low stand frequency will limit yield and too high of a stand frequency will waste seed [49]. The average recommended planting rate is 4 to 10 kg ha⁻¹ PLS [33,36,50]. Alternatively, recommendations have been made based on number of established plants per m². Teel et al. [36] recommended 20 plants per m² as an adequate established stand for bioenergy usage; however, it is difficult to plant at a rate targeted for number of established plants per area. Forberg [14] found 30-50% seedling mortality after emergence across four varieties (Blackwell, Carthage, Cave-in-Rock, and Dacotah) grown in Massachusetts. He also observed higher seedling mortality with higher seeding rates. Stand densities of 278 plants m⁻² from 600 PLS m⁻² could be achieved [3]. Ultimately, desired stand frequency or density is the principle consideration for the determination of planting rates. Vogel and Masters [49] designed a frequency grid with which stand density of switchgrass could be determined. In their previous switchgrass establishment research, frequency-grid-measured switchgrass stands of 40 to 50% or greater indicated a successful stand, frequencies between 25 to 50% were marginal to adequate, and frequencies <25% indicated partial stands that need replanting [47,51]. Mitchell and Schmer [47] reported that in most cases, poor seed quality resulted in poor stand establishment that required re-planting.

Other factors that affect the establishment of switchgrass include soil preparation and seeding methods, seed placement, planting date, weed control, and environmental conditions [23,52].

Seeding methods

Methods of seedbed preparation for planting switchgrass typically include: conventional and no-till planting into killed sods or bare soil [3]. Although several reports have indicated the preference of conventionally tilled seedbeds over no-till planting [36,53,54], no-till planting of switchgrass has also been proven to be useful in some circumstances [55]. There is limited information regarding the suitability of various seedbed preparations for switchgrass cultivation in different conditions [3]. McKenna et al. [56] and Teel et al. [36] suggested that planting into an

herbicide-killed sod is possible with proper equipment, but they also stated that switchgrass stands planted using this method may be reduced compared with switchgrass stands planted into conventionally tilled seedbeds. Similarly, several researchers [26,53,54] suggested that switchgrass planted through direct drilling into killed sod was a less reliable method when compared with conventional tillage. In another approach, Monti et al. [23] showed that establishment of switchgrass was enhanced when conventionally prepared seedbeds were rolled or compacted after seeds were broadcasted. It is now well documented that switchgrass emergence increases greatly in a firm seedbed bed [23,26,57,58]. Venturi et al. [58] showed greatest germination in two varieties of switchgrass in well-tilled soil that was compacted before and after planting. They found lowest germination in tilled treatments without any compaction. Sadeghpour et al. [57], similarly reported that greatest germination rate, stand density, and biomass production was found when switchgrass was compacted two times after planting either with a roller or a cultipacker. In dry conditions, increasing seed-soil contact could also enhance germination through higher available moisture to the seeds. In contrast, other reports indicated no yield advantage from conventional tillage over no-till planting. For example, Rehm [59] found no switchgrass yield difference between no-till and conventional planting methods. King et al. [60] compared no-till with conventional planting of switchgrass at two locations in Nebraska and found that the yield advantage of one tillage system over the other was dependant on season and location. In a series of studies in Tennessee a 50 to 150% increase in switchgrass seedlings in a no-till system compared with a conventional seedbed preparation was found [61]. Sadeghpour et al. [27] found significant advantage of no-till planting over conventional tillage when precipitation was low during the growing season. In the same study, they used cereal cover crops, which are known to be fast growing and able to suppress weeds and provide N for the subsequent crop [62,63] to control weeds and enhance switchgrass establishment and found oat as the most effective cover crop for switchgrass establishment [27]. It could be concluded that the advantage of no-till planting of switchgrass over conventional tillage was partly due to soil and water conservation and also to the potential for earlier planting [3,55]. It is yet to be determined which planting method should be preferred due to various results in different locations.

Depth of Planting

Depth of seed placement is critical in emergence and the establishment of switchgrass [3]. In general, planting depths of 1 to 2 cm have been recommended to growers based on several studies [10,26,33,36]. Newman and Moser [64] found no significant difference between switchgrass emergence in plantings depths at 1.5 and 3 cm. However, they observed a 40% emergence reduction when they increased the sowing depth to 4.5 cm. It has also been suggested the emergence can be affected by soil texture in conjunction with planting depth and moisture level. Aiken and Springer [65] found that soil texture and seed size among switchgrass cultivars had a greater effect on emergence than differences in planting depths within < 2 cm. Planting depths < 1 cm in sandy soils may result in low seedling survival under drought stress condition. Conversely, seedlings established in a clay soil at the same depths showed high survival

at the same level of water stress [66]. In a recent greenhouse study, Berti and Johnson [10] observed significant differences on switchgrass emergence between surface planting (0 cm) and planting at the depth of 1.3 cm; however, did not find any significant differences in planting depths of 1.3 to 6.4 cm. In a field study the same authors found silty-clay soil as a more suitable media for switchgrass emergence compared with fine-silty and coarse-loamy soils in North Dakota, USA. In a greenhouse study, we also found a shallow planting < 3 cm could be suitable for switchgrass planting.

Seed size is also a factor in seedling emergence and vigor [3]. In several studies, larger seeds produced more vigorous seedlings in a shorter duration than smaller seeds [65,66]. In contrasts, Zhang and Maun [38] found no difference after eight weeks between seedlings from small or large seeds.

Date of Planting

Successful establishment of switchgrass acquires a sufficient stand that will maximize yield in subsequent years [67]. Planting dates can vary from November to July depending on several factors including geographical region; weed control methods; soil temperature; and rainfall patterns [3,23,58,68]. In warmer climates with longer growing seasons, switchgrass can be planted earlier than in cooler climates. However, planting early in the spring in most climates will cause slower seedling emergence than later plantings due to extreme temperature fluctuation and weed competition [14]. Optimal soil temperature for germination of a wide range of switchgrass cultivars have been suggested to be between 27-30°C. However, according to Hsu et al. [68], a soil temperature of 20°C is sufficient for switchgrass emergence and growth. In a field study in Missouri, researchers found emergence to be more rapid at later planting dates in a set of treatments from April to June [68,69]. Similarly, in Massachusetts, we found faster emergence in June and July plantings compared with November and May. However, earlier-planted switchgrass was taller, and had more advanced root systems. In agreement with our findings, in Nebraska, Smart and Moser [42] found much larger seedlings and more vigorous stands in the earlier planting treatments spanning from March to late May. When comparing fall and spring plantings in a Mediterranean climate, Monti et al. [23] found slightly more emergence in spring plantings. Planting in a cool season could benefit seedling establishment by breaking dormancy in seeds by stratification. Hsu et al. [70] found that germination of dormant seeds increases in cool planting conditions. In several other studies, spring plantings of highly dormant seed yielded greater germination than later plantings; [36,71] however, this directly depends on the weather conditions. We found that in a mild winter with low amount of precipitation, emergence did not increase whereas; a cold and wet winter resulted in significant increase in switchgrass germination [Sadeghpour, unpublished data]. When rainfall proliferates in the spring, early plantings of switchgrass could be successful with proper weed control. But in many climates, weed pressure is high in early spring given warm temperature and increased rainfall [26,33]. Weed pressure in the establishment year can be reduced by avoiding planting at a time when weed emergence is high. Many annual weed species have a short period of emergence in the spring; therefore, delaying planting

by two weeks could have positive effects on establishment [72]. In northern climates weed pressure is highest in the spring and thus planting should be delayed until early summer. There must be a balance between a delayed planting date for weed pressure avoidance while still allowing for enough growing season for adequate stand establishment [72].

Weed Control

A relatively small seed size, high dormancy rate, and slow germination often makes switchgrass a weak competitor with many summer annual grass and broadleaf weeds [73,74]. As a result, crop establishment and early growth is often delayed [29]. A poor switchgrass stand during the seeding year can limit yield and large scale crop adoption [10,28,29]. Weeds reduce yields of switchgrass by competing for nutrients, water, light, and space [75,76,77]. Additionally, some weed species produce toxins and growth inhibitors that can cause negative effects on switchgrass [78]. Switchgrass seedlings grow slowly in the first several months and can be out-competed by fast growing annual weeds [27]. Additionally, a major obstacle in weed management in perennial grasses is the lack of registered herbicides approved for this use [3]. In order to avoid stand failure, weed management must be a primary consideration in the establishment year of switchgrass [67]. Cool-season grassy weeds that germinate in cooler temperatures are most threatening to newly emerging switchgrass seedlings. Hsu and Nelson [68] found that crabgrass (*Digitaria sanguinalis* L.), a very problematic weed species, can grow more rapidly than switchgrass at equal temperature. Crabgrass produced up to 20 times more biomass per seedling than switchgrass when grown side by side. In our field trials in Massachusetts, crabgrass was also the most problematic weed in establishment of switchgrass which resulted in a significant reduction in stand density and yield [27].

The most effective weed management strategy in the establishment year could be herbicide application [29]. Efficacy of weed pressure reduction through herbicide application has been documented by several researchers [27,29,73,79]. For conventionally-tilled plantings, many studies have shown success with pre-emergent triazine herbicides, notably atrazine [6-chloro-N-ethyl-N'-(1-methylethyl)-1,3,5-triazine-2,4-dimine] [79,29,27]. Switchgrass is one of the most tolerant grass species to atrazine [72]. Atrazine effectively controls many annual weed species when grown with perennial warm-season grasses [80,81,56]. Problematic weeds such as crabgrass, fall panicum (*Panicum dichotmiflorum* L.), foxtail species (*Setaria* spp.), and barnyardgrass (*Echinochloa crus-galli* L.) are less susceptible to atrazine treatments and require additional herbicide treatments for effective control. With similar growth habits to switchgrass, the control of these grassy weeds is crucial to avoid detriment to switchgrass stands [82]. Sadeghpour et al. [27] found sufficient weed control by using a combination of 1.1kg a.i. ha⁻¹ atrazine and 0.37 kg a.i. ha⁻¹ quinclorac (3, 7-dichloro-8-quinolinecarboxylic acid). Quinclorac (Paramount) is highly effective at controlling annual warm-season grassy weeds as well as some broad leaf weeds and has recently been registered for use in switchgrass production [73,74]. Mitchell et al. [29] reported that a combination of quinclorac and atrazine provided satisfactory weed control for establishing both lowland and

upland switchgrass cultivars in the Central and Northern Great Plains. Boydston et al. [73] reported switchgrass yield and stand loss as a result of post-emergent application of quinclorac however, application of this herbicide in controlling grasses has been found to be very effective [27,73,79]. In a study at Wisconsin, Miesel et al. [83] reported that a mixed application of imazapic (\pm)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-methyl-3-pyridinecarboxylic acid and glyphosate [N-(phosphonomethyl) glycine] at 0.07 kg a.i. ha⁻¹ provided the best grassy weed suppression and resulted in the highest yield compared with different rates of glyphosate alone (1.12 kg a.i. ha⁻¹) or in combination with 2,4-D [(2,4-dichlorophenoxy)acetic acid] at 1.06 kg a.i. ha⁻¹. Kering et al. [84] studied the effect of various herbicides on switchgrass establishment and reported that when quinclorac was mixed with foramsulfuron [1-(4,6-dimethoxypyrimidin-2-yl)-3-(2-dimethylcarbamoyl-5-formamidophenyl-sulfonyl)urea] and pendimethalin(3,4-Dimethyl-2,6-dinitro-N-pentan-3-yl-aniline) efficacy of weed control was more than 70% and switchgrass establishment was improved 13 to 26% compared to untreated control, however, their findings suggest that establishment was marginal and should be improved.

Broadleaf weeds in switchgrass can be controlled by an application of dicamba (3,6-dichloro-o-anisic acid) and 2,4-D [85]. In a recent study, Curran et al. [79] reported that a broad-spectrum post-emergence application of atrazine, quinclorac, dicamba and 2,4-D significantly reduced the weed pressure in the establishment year of switchgrass. Findings of Sadeghpour et al. [27] are in line with earlier reports by Curran et al. [74,79] showing the effectiveness of a broad-spectrum application of atrazine, quinclorac, dicamba and 2,4-D. Further research is needed on herbicide application rates and their effect on switchgrass varieties.

One of the modern approaches to increase the success of herbicide application, reduce herbicide injury and enhance switchgrass establishment is seed safening [86]. Herbicide safeners can prevent herbicide damage of specific crops by reducing the binding abilities of molecules to affect target sites of plants [86]. This can be accomplished through safener-induced stimulation of herbicide catabolizing enzymes, or by safener-enhanced metabolism of herbicides to immobile metabolites [87,86]. Previously, seed safeners were proven to be effective in protecting several forage plants including sorghum (*Sorghum bicolor* L. Moench), perennial ryegrass (*Lolium perenne* L.), and sand bluestem (*Andropogon hallii* Hack) from herbicide injury. To reduce the injury of switchgrass from pre-emergence application of metolachlor[2-chloro-N-(2-ethyl-6-methylphenyl)-N-(methoxy-1-methylethyl) acetamide], Rushing et al. [86] used two methods of seed-safening with fluxofenim (coating vs. controlled hydration). They reported that the controlled hydration (combination of 25, 50, or 100% fluxofenim) resulted in greater yields compared with the coating technique. Before this attempt, Butler et al. [88] was failed to safen switchgrass seeds in greenhouse experiments using fluxofenim.

In no-till plantings of switchgrass, weeds can be controlled effectively with a non-selective herbicide most notably glyphosate before the emergence of switchgrass [67].

As discussed earlier, planting date has a significant effect on weed pressure. Delaying seeding to allow weed emergence before final seed bed preparation will reduce weed pressure [77]. Curran et al. [79] found that delaying the planting until late June, resulted in weed pressure reduction.

PRODUCTION MANAGEMENT

Harvest

Harvesting strategy is dependent upon expected yield, quality and stand maintenance [89]. Frequency and time of harvest are the most important harvest management practices followed by cutting height [90].

Switchgrass harvesting frequency ranges from single-cut to multiple cuttings. Multiple harvests have been a viable strategy for forage agronomists to increase annual yield [3]. Commonly, after plants reach their maximum biomass, they can be harvested before the end of a growing season to allow for re-growth and increase total yield; however, many studies on switchgrass have shown multiple harvests results in yield reduction in succeeding years [3,11,91,92,93]. Madakadze et al. [91] found that a single end-of-season harvest was a more sustainable management practice compared with two or three cuttings. In the south-central USA, Sanderson et al. [11] reported that a single harvest at approximately 260 days of year provided the maximum biomass yield. They also concluded that multiple harvests (three or more) reduced yields over a 4-yr study. Generally, mid-summer harvests remove N and other nutrients from the shoots which would otherwise be translocated into the roots and crowns for successful re-growth in the following year. In a 5-yr study in Tennessee, Reynolds et al. [92] found no yield advantage of two-harvesting system (mid-summer and late-October) over a single-cut in late-October. Similarly, in a trial comparing numbers of harvests, Smart et al. [93] reported the benefits of a single harvest with respect to yield production. They found higher yields in one-cut compared with total biomass produced by a three cutting system. An additional reason for yield reduction in long term studies is tiller density reduction [93,94]. Researchers in Virginia concluded that only a single or at most two-cut management could be appropriate to maximize biomass output [3,95,96].

In addition to harvest frequency time of harvest also influences switchgrass production [22,97] and perhaps is the most important harvest management practice [47]. Recommendations for the ideal time to harvest switchgrass to produce consistent maximum yield varies from site-to-site. A Mid-September harvest was reported as suitable harvest for maximum biomass yield [11,98]. Adler et al. [97] found 40% reduction in switchgrass biomass production when the harvest was delayed until spring. Other reports [24,99] were in line with findings of Adler et al. [97] where they found a 30% yield reduction from spring harvest. In contrast, Parrish and Fike [3] found no yield differences between November and February harvests in Virginia. Generally, biomass yield was reduced when harvest was delayed until after killing frost [24,47]; however, later harvest may ensure stand productivity and persistence of switchgrass. In north-central USA, harvesting after killing frost produced the highest yields [100]. In the same location,

Casler and Boe [101] found that a mid-August harvest reduced switchgrass stand density over time. In general, it is believed that switchgrass should not be harvested within 6 weeks of the first killing frost to ensure NSC translocation to the plant crowns for setting new tiller buds and maintaining stand productivity [47].

Cutting height is another important harvesting management practice that may influence final biomass yield [102]. Limited data is available on the influence of cutting height on the biomass production of switchgrass in the Northeast region of the United States. Existing reports suggest cutting heights between 15 to 25 cm will ensure switchgrass re-growth in the following year [103]. According to Henry et al. [104], the best switchgrass stand could be obtained from a cutting height of 23 cm in a single-cut system whereas in a two-harvest system, 8 cm would be the ideal harvesting height to gain maximum biomass yield. Several reports indicated that although cutting switchgrass low as 5-8 cm compared with 20-25 cm may result in higher biomass yield in the short term, biomass will be lowered in the following years due to intensified weed infestation [102,103,105]. Mitchell and Schmer [47] reported that cutting heights lower than 10 cm resulted in yield reduction due to stand vigor loss. In a three year period Sadeghpour et al. [90] reported that cutting height of 7.5 cm out yielded cutting at 15 cm by 1 Mg ha⁻¹ without increasing weed pressure.

Quality parameters of switchgrass as biofuel feedstock include energy content of grass, moisture, nutrients, and ash. Higher moisture and ash both reduce energy content, since higher moisture requires excess energy input to burn, and ash creates fouling in combustion equipment [106]. The presence of alkali metals and silicates in ash are major contributors to the production of slag, a thick black liquid material that forms when feedstock is burned at high temperatures. Slag coats the surfaces of machinery (furnaces, boilers, fluidized beds, etc.), causes fouling and prevents heat from being recovered [106,31], therefore making the burning process costly. Part of the appeal of switchgrass is that it can be used with existing technologies to supplement current energy production. It is imperative that the end product be used without causing high external costs to existing systems.

Harvesting management of switchgrass such as time of harvest may alter the concentration of unwanted nutrients present in the grass and therefore influence feedstock quality for combustion purpose. There is a general conformity in the literature that delaying the harvest of switchgrass until killing frost (after senescence), reduces N, phosphorus (P), potassium (K), ash, and other nutrients in the grass [91,107,108]. Lower ash content is associated with translocation of mobile nutrients from the above-ground tissue to the root structure [24]. It is reported that every 1% increase in ash concentration decreases the heating value by as much as 0.2 MJ kg ha⁻¹ [109]. Nitrogen cycles down into the below-ground tissues at the end of the growing season [110]. This is due to the fact that switchgrass has evolved to go dormant at the onset of winter, translocates nutrients, including N, from above-ground tissues to the below-ground for re-growth in the succeeding season [3]. Adler et al. [97] found that delaying the harvest until spring resulted in higher energy content of the biomass because of moisture and ash content reduction. Direct

baling of switchgrass requires moisture content of 15% or below [106]. In a multi-harvest study, Gorlitsky et al. [111] found 30% moisture reduction when harvest was delayed from mid-September to mid-November; however, the moisture content from the delayed harvest was still high (29%) which makes it unsuitable for direct baling. In another study, Sadeghpour et al. [90] concluded that delaying harvest until spring (mid-April) can reduce moisture content to an acceptable level of 11 - 15%; however, this comes at the cost of a yield loss of about 25 to 30% which questions the suitability of harvesting in spring. A significant disparity of ash content of switchgrass across multiple locations ranging from 2.8 to 7.6% has been reported [106]. Adler et al. [97] showed that ash content reduced from 3.4 to 2.3% when the harvest was delayed until spring. Researchers [35,107] concluded that reduction in ash concentration from time of anthesis to killing frost harvest was related mainly due to greater proportion of grass stems at late season which contains less silica, a major component of ash, compared to leaves.

FERTILITY MANAGEMENT

Fertilization is perhaps the most unsettled aspect of switchgrass establishment and production [3]. Nitrogen fertilization is not recommended in the establishment year as it would encourage weed pressure and therefore not only increases establishment costs but also causes the economic risk associated with stand failure [67]. Sanderson and Reed [112] reported no biomass yield response to N application (22 and 112 kg ha⁻¹) during the establishment year of "Alamo" switchgrass. They concluded that lack of switchgrass response to N fertilization was due to the ability of switchgrass to use available N in the soil. Reports have also indicated no significant response of switchgrass to P and K [67,113]. This is mainly due to the adequate levels of these elements in most agricultural soils. However, P and K fertilizers and lime are recommended to maintain soil nutrient balance during establishment and throughout production years [89].

Nitrogen

Nitrogen is a critical nutrient for production of biomass and typically the most limiting factor to plants productivity [114]. Managing N fertilizer application is important not only for optimum biomass production but also to maximize the NUE as well as feedstock quality. Excess N concentration in harvested switchgrass can be a liability by increasing the release of N oxide (NO and NO₂) compounds into the atmosphere when combusted [3,114]. Most of studies on N management have been conducted on lowland switchgrass varieties in the Midwest, southern, and upper southeastern U.S.A. Nitrogen fertilizer recommendation are site specific and depend on weather, soil fertility level and management practices [67]. In a multi-location study throughout the upper southeastern USA, Lemus et al. [7] found that in a single-cut system, 50 kg N ha⁻¹ would be sufficient for biomass production of switchgrass; however, a split application of N (100 kg N ha⁻¹) is required in a 2-cut system to maintain grass productivity. It is reported that Alamo switchgrass yielded highest at N rate up to 224 kg ha⁻¹. In a season of higher-than-normal rainfall, production was maximized at 168 kg N ha⁻¹ [3]. Thomason et al. [94] found 448 kg N ha⁻¹ application in a 3-cut

system as the most suitable for maximum biomass production of Kanlow variety. However, multiple harvests each year resulted in a significant yield reduction in the succeeding years and they reported that a single harvest system over a four-year period at one of the locations of their study produced higher biomass compared with the 3-cut system with 448 kg N ha⁻¹ fertilization. While yields were highest (18.0 Mg ha⁻¹) with 448 kg N ha⁻¹ applied all in April and three harvests, no N application and harvesting three times produced almost as much total biomass (16.9 Mg ha⁻¹). This limited response to N is possibly explained by the evolution of switchgrass under low N conditions.

At the same location, Aravindhakshan et al. [115] reported that a single-cut system with only 69 kg N ha⁻¹ was the most economical management practice for producing the greatest biomass production. Vogel et al. [98] tested N application rates up to 300 kg ha⁻¹ for the Cave-in-Rock (a southern upland cultivar). They reported maximum yields at 120 kg N ha⁻¹. Guertsyket al. [22] tested N up to 225 kg ha⁻¹ at three harvest times (July, October, and December) and reported positive response of switchgrass biomass production to N fertilization. They found a 2-cut (July plus frost) harvest system the most productive however, higher N input was needed for this harvest system. In a recent multi-year-location study, Anderson et al. [116] recommended 56 kg N ha⁻¹ in late fall to 112 kg N ha⁻¹ in early spring to optimize switchgrass production. Harvesting switchgrass once a year after frost (December) has been suggested by several researchers [98,107,117]. In a study in Massachusetts on a 3-year old Cave-in-rock switchgrass Sadeghpour et al. [90] found that for a late-summer harvest (September) only a 67 kg N ha⁻¹ was required to maintain stand productivity. No significant response of switchgrass yield to N fertilization in late-fall (November) and spring (April) harvests was detected. They concluded that perhaps less than 67 kg N ha⁻¹ would be sufficient for growing high-yielding switchgrass in the state of Massachusetts. In another recent study, Pedroso et al. [118] found a linear response of switchgrass to N application where the greatest yields (9.7 and 13 Mg ha⁻¹ yr⁻¹) were obtained from the highest N fertilization rates (300 kg ha⁻¹). They reported that the average NUE was between 30 to 44 kg biomass kg⁻¹ N during 2009 and 2010 growing season. Sadeghpour et al. [90] found the average NUE to be from 14 up to 33% which was much lower than the averages reported by Bransby et al. [119]. Nitrogen-use efficiency can also be soil/site specific [3]. Lemus et al. [114] calculated different NUE for two different locations in Virginia. They reported that increasing the N rate at both sites could result in decreasing NUE at one site with no significant response in the other site. In a five-year experiment, Lemus et al. [120] in Iowa found 56 kg ha⁻¹ an ideal N rate in terms of NUE. Overall, based on findings of Pedroso et al. [118], greater N fertilization would be required to sustain biomass production in warm ecoregions with greater yield potential.

Phosphorus, Potassium and pH

Limited research has been conducted on response of switchgrass to P and K fertilization [67]. Reports often suggested little [121] significant effect of these nutrients on switchgrass production which could be due to the inherent ability of switchgrass to use P that is available in the soil mainly through

mycorrhizae symbiosis [122]. Mycorrhizae, by supplying the host plant with essential elements from the soil, can significantly increase plant growth [124]. Mycorrhizae increase a plant's ability to absorb water and growth limiting nutrients (notably P and N) through enhancing the root surface area in contact with the soil [124,125]. According to Brejda et al. [126] response of switchgrass to P and N was reduced when rhizospheremicroflora was back to stem-sterilized soils. In a recent study, Haque et al. [127] found no influence of P on switchgrass productivity and suggested a 135/0 kg N-P ha⁻¹ application as the most economically viable fertilization system for switchgrass production. McKenna and Wolf [56] found small response of switchgrass to P fertilization when P levels in their soil test were low but only in the first year of their study.

Similar to P, switchgrass plants are efficient in their use of K [96]. Frequently little or no response of switchgrass to addition of K is reported [121,128]. In a greenhouse study, Friedrich et al. [129] found no yield improvement with applying K at rates up to 896 kg ha⁻¹. In contrast, Kering et al. [84] reported that a combination application of 135 kg N and 68 kg K ha⁻¹ produced the highest switchgrass biomass in Oklahoma. They however, found no significant differences in biomass yield when comparing application of 68 kg K ha⁻¹ alone with no fertilizer application.

There is a general conformity on tolerance of well-established switchgrass stands to many adverse environmental conditions including extreme pH. Reports on the influence of low pH on newly-established switchgrass seedlings are controversial. According to McLaughlin and Kszos [31] greenhouse studies in North Dakota showed a significant reduction in seedling survival in soil pH < 4.0 or > 8.0. Jung et al. [122] also reported 50% yield reduction on strong acidic (pH 4.3-4.9) soils compared with lime-treated soils. In contrast to these findings, in other studies [130-132] no limiting effect of soil acidity on switchgrass establishment has been found.

CONCLUSION

In the last 30 years, significant progress through dedicated research efforts has been made in developing switchgrass as a bioenergy crop. Although there is an improved understanding of the biology and agronomy of switchgrass, a few aspects of switchgrass establishment and production need further investigation. Reliable establishment methods and effective weed management practices to produce a harvestable biomass in the establishment year, appropriate nutrient management to enhance fertilizer efficiency, and biomass conversion methods are yet not fully determined. Best agronomic management practices coupled with genetics will result in high-yielding quality switchgrass for more efficient conversion.

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