PERSPECTIVE

Smooth Cordgrass (*Spartina alterniflora* Loisel.): The Case for Utilization of a Colonizing Plant Species

Gregory J. Duns [1]

[1] AirChem Consulting and Research, London, Ontario Canada N5X 0E2
E-mail: gjduns@gmail.com

Submitted: 12 June 2020
Accepted: 23 June 2020
Published: 30 June 2020

Abstract

The status of utilization of colonizing plants (weeds) must be regarded as being in infancy. With the increasing need for alternative feedstocks to replace petroleum, which is used to produce energy, chemicals, and other products, attention is now on alternative sources of biomass, such as agricultural and forestry residues. However, weeds represent a considerable amount of biomass which remains a largely untapped resource. Smooth cordgrass (*Spartina alterniflora* Loisel.) is an example of such a species that has yet to be exploited to its full potential. This coastal, salt-tolerant plant has proliferated in many areas, especially in China, forming extensive stands. The species was introduced to China from North America, about 40 years ago, for coastal erosion protection. Since introduction, smooth cordgrass has colonized the coastal areas forming extensive stands along China's eastern seaboard. These infestations have become a severe problem at many locations in the eastern coastal regions.

The present report is a case study and perspective concerning the utilization of smooth cordgrass in China. I describe examples of the economical and efficient utilization of the plant's biomass to form a variety of practical products on a commercial scale. These show that it is possible to find new and effective ways to achieve large-scale usage of otherwise waste biomass from this species and others, which are similar. Further comprehensive research and development towards full valorization of smooth cordgrass with innovative utilization are required. The future will hopefully see increasing utilization of weeds to meet the increasing demand for resources that are sustainable and renewable.

Keywords: *Spartina alterniflora;* cord grass; bioresources; biomass utilization; renewability; sustainability

Introduction

There is globally an increasing interest in the search for renewable, and environmentally-benign resources to replace petroleum as the source to produce energy and raw materials for manufacturing of a wide range of products. The interest is primarily driven by increased energy demands, rising costs and depleting supplies of petroleum, and environmental concerns over the use of petroleum and petroleum-based products. Concurrently, there is an increasing interest in renewable and sustainable biological resources (bioresources) as industrial raw materials. Such bioresources, particularly those based on lignocellulosic biomass from plants, have seen rapidly increased utilization for biomass applications. These sources include waste materials such as agricultural, forestry, and aquatic or fisheries wastes. The large amounts of these materials, generated annually, in almost any country of the world, make them ideal candidates as bioresources. Biological resources meet many criteria of the "Green Movement" i.e. they are, in general, renewable, sustainable, environmentally-safe, non-toxic, and their use contributes to overall greenhouse gas reduction (Walker, 2015).

The main components of lignocellulosic biomass are cellulose, hemicellulose and lignin, together with small amounts of proteins and other compounds. Such material is sometimes referred to as plant biomass as plant cell walls are mainly composed of these compounds. In general, many sources of lignocellulosic bioresources are abundant, sustainable, and renewable, being composed mostly of carbohydrates produced by plants as products of photosynthesis. With adequate sunlight, water, nutrients, and soil, plant-based bioresources are accordingly renewable (Tursi, 2019).

In utilizing plant biomass, the whole biomass may be utilized, such as burning it for heat or fuel in its most simplistic form, or only a few components may be utilized, e.g. carbohydrates for bioethanol. It generally involves converting it to another form (biomass conversion), which involves the conversion of biomass into its various constituent components (e.g. cellulose, hemicellulose, and lignin).

These components can then be further converted into other products by a variety of methods such as chemical, mechanical (pressure, agitation, grinding) and/or biological processes (enzymes, microbes) to produce many possible products. These products include bioenergy/biofuels (bioethanol, biomethanol, biodiesel, biogas), cellulose fibres, lignin, carbohydrates, proteins, phytochemicals, as well as smaller chemical building blocks to synthesize other, larger chemicals that would otherwise be obtained from petroleum refining (Stevens and Verhé, 2004; Tursi, 2019).

In addition to traditional and extraneous sources of lignocellulosic biomass from agriculture, forestry and fisheries and their wastes, another potential source exists in the large numbers of colonizing plants that exist in most parts of the world. Utilization of colonizing plants represents a vast pool of available lignocellulosic biomass, which can be an economically and environmentally advantageous alternative to the use of fossil fuels as a resource.

There are many potential applications for colonizing taxa, although, for the most part, they remain a vast untapped and unrealized pool of available biomass (Burry et al., 2104; Sharma and Pant, 2018). The issue of some of these taxa becoming ‘invasive species’ is a common theme worldwide. There is a general perception that some colonizing taxa can crowd out desirable, native species both on land and in waterways and coastal areas. They may also have detrimental effects on local habitats, environments, and economies. These plants, if dealt with at all, are commonly removed and then buried or burned, creating an additional environmental pollution problem (DiTomaso et al., 2006; Duns and Chen, 2009). Utilization of these otherwise problematic species would accordingly be a way to not only reduce pollution but to help local economies as well by providing raw materials to produce energy or other products (Chandrasena, 2008; 2014; 2019; Duns and Chen, 2009).

Smooth cordgrass (*Spartina alterniflora* Loisel.) is one such example of a colonizer that can produce extensive biomass. The vast growths of smooth cordgrass in some parts of the world, such as the west coast of North America and the eastern coast of China, represent a vast amount of biomass produced every year. The species has proven to be problematic in places where it has established. Despite considerable attention towards its management and control, it remains a problem at many locations. The significance of smooth cordgrass is indicated by the fact that there is an international conference solely dedicated to it, with the first one held in 1990 in Seattle, Washington, U.S.A. (Mumford et al. 1991).

Smooth cordgrass is presented here as an example of a potentially problematic species, but one that can be extremely useful for a variety of uses. The species was selected to illustrate the case for the utilization of colonizing taxa because of many years of personal experience, studying its utilization, primarily in China. Seeing it from all stages to being a locally abundant weed, to being utilized on a commercial scale, has been a rewarding experience, while also teaching some valuable lessons as to how to deal with such plant species more broadly.

Colonizing Species as Bioresources

Colonizing plants (weeds), some of which can become ‘invasive’, generally grow quickly, have high fecundity, and many can tolerate a wide variety of growing conditions. Many are stress-tolerant and can grow where other species may not grow easily in different environments. They often produce large stands, displacing others. However, this same prolific growth also represents the production of large amounts of biomass that may be utilized.

There has been limited interest in the utilization of weeds for beneficial purposes, mainly because the discipline of Weed Science has been so focused on controlling weeds. (It should be clarified that ‘utilization’ here, in general, refers to processing the biomass of the dead plant biomass and not the utilizing of living plants for purposes, such as erosion control or as ornamental purposes. The latter applications are also valid and should be noted, as such). While there has been a considerable increase in the use of biomass from various sources including forestry, agricultural, aquatic and fisheries as raw materials for energy and manufacturing, this interest has not been extended to the utilization of biomass from weeds to nearly the same extent.

Despite the ever-expanding plethora of journals, trade magazines and textbooks dealing with various aspects of biomass and bioresources, only a small percentage of the publications deal with the commercial utilization of weeds in some form or other. This lack of attention indicates the under-appreciation of weeds as a viable source of biomass. The reason could be that weeds are, traditionally, considered a nuisance, and as such to be dealt with by control or eradication, rather than considered as a credible source of utilizable biomass; this theme will be revisited in subsequent sections.

In addition to smooth cordgrass, various aspects of the utilization of other weeds have been undertaken (see Catallo et al., 2008; Liao et al., 2013; Brouwer et al., 2019; Sharma and Pant, 2019) in recent years. Other studies have been more specific, focusing on the utilization of well-known weeds, such as water hyacinth (*Eichhornia crassipes* (Mart.) Solms), reviewed by Malik et al., (2007), Guna et al., 2017, and Yan et a., 2017); common reed (*Phragmites australis* (Cav.) Trin. ex. Steud.) reviewed by Burry et al. (2014, 2017), and parthenium weed (*Parthenium hysterophorus* L.) (Chandrasena and Rao, 2019). A more general account of the utilization potential of colonizing taxa has been provided by Chandrasena (2008) with an appeal to consider a closer integration of beneficial aspects of weeds into human societies (Chandrasena, 2014; 2019).

To date, most of the investigations into the possible utilization of weed biomass have remained at the research study and assessment stage. Only a few have resulted in further development or viable commercialization. The consensus appears to be that weeds will remain a much under-utilized and neglected resource for some time, which is the viewpoint shared by this author. There are, of course, both advantages and disadvantages in the use of weeds as bioresources, and utilization is not the "*be-all and end-all*" for the problems they cause. These advantages and disadvantages, particularly concerning the exemplar I am using, will be further expanded on in the Discussion section.

Spartina alterniflora: General characteristics and habitat

Smooth cordgrass is a rhizomatous perennial herbaceous C4 grass plant that generally ranges from 1-3 m in height, with leaf blades that are around 30 to 50 cm long and are 6 to 15 cm wide. The leaves lack auricles and have ligules that consist of a fringe of hairs. The plant stems are hollow and hairless, while the rhizomes are long and hollow. A dense stand of smooth cordgrass is somewhat like a small forest of dark green plants, with minimal light penetration to the mud or soil beneath the stand. The plant is deciduous; its stems die back at the end of each growing season. These thick, extensive stands represent a large pool of biomass, going to waste when nothing is done with it.

Smooth cordgrass is hexaploid and can undergo both vegetative and sexual reproduction. The latter contributes little to the maintenance of established stands of growth but may play a more critical role in the establishment of large disturbance-generated patches of plant growth. During September and October, seed heads are normally present that are approximately 30 cm in length and can carry spikes containing 12-15 spikelet seeds and have flowers that are generally inconspicuous and are normally 5 to 8 cm long (Landin, 1991; Li et al., 2020). Its seeds are dispersed primarily via water which may facilitate its rapid spread over considerable distances, which plays a significant role in its tendency to be invasive (Thompson, 1991; Chelaifa et al., 2010).

Smooth cordgrass is a typical, strongly salt-tolerant species (halophyte). This physiological adaptation to high salt content allows the species to grow abundantly in coastal or marsh habitats as a warm-season grass. High salt tolerance, prolific reproduction and efficient C4 photosynthesis have combined to give the species the capacity to produce large biomasses in a typical growth cycle.

The species tends to thrive in anoxic, marsh habitats (Figure 1) due to its ability to oxygenate its roots and rhizosphere (Thompson, 1991; Simenstad and Thom, 1995). In its native range, it exhibits varying forms of growth in different salt marsh zones, depending on the local habitat or environment. Plants growing under optimum conditions can reach a maximum height of above 2 m while those growing in highly salt marshes may be stunted to a height under 1.0 m, including inflorescences. Unlike most other marsh plants, the salt-tolerance of smooth cordgrass is directly proportional to water depth, forming dense monospecific stands in salt and brackish marshes with mid to high tide levels (Landin, 1991; Thompson, 1991; Ayres et al., 2004; Chelaifa et al., 2010).

Figure 1. Growth of smooth cordgrass in a coastal salt marsh in eastern China (from Qin, 2013)

Biogeographical Distribution, Native range and Spread

As noted previously, the seeds of smooth cordgrass are dispersed mainly by water, facilitating their spread over considerable distances, playing a major role in its spread. Biogeographical patterns suggest that the genus *Spartina* originates from the Atlantic and Gulf Coasts of North America. The genus *Spartina* contains 14 to 17 species, most of which are native to North America, while only *Spartina maritima* is native to Europe (Landin, 1991; Chelaifa et al., 2010).

Smooth cordgrass made its way across the North American continent to the west coast where it is now found along the Pacific coast in the Washington State, where it has become a significant problem (Simenstad and Thom, 1995). It has also spread to California, especially in the San Francisco Bay area, and north, to British Columbia in Canada.

Smooth cordgrass was introduced to Europe and East Asia for coastal protection, and eventually even spread to the coasts of South Africa, Australia, and New Zealand (Ayres et al., 2004; Grevstad et al., 2007; Patten et al., 2017). The species was also introduced to China in 1979, for coastal protection, erosion control and sediment stabilization. It must be said that the species did play a decisive role in these aspects but also has had a significantly detrimental impact on coastal ecosystems.

Since its introduction, smooth cordgrass has grown out of control to become a problematic species, to the point where, in 2003, it was among the first plants included in the official list of *Invasive Alien Species* (IAS) in China. It has flourished over the past 40 years and rapidly expanded along China's eastern coastline. China now has the world's largest area of this species, which is presently approximately 55,000 ha (Xie, Han et al., 2019).

The area of spread increased by 10,000 ha between 1985 and 2015 with the fastest expansion rate of 463.64 ha occurring between 1995 and 2005. In 2004, smooth cordgrass salt marsh areas in Jiangsu Province alone reached a total of about 150 km^2 (Li et al., 2020). Significantly, from a utilization point of view, it is estimated that the total dry matter production of its above-ground parts ranges from 7.5 x 10^5 to 1.15 x 10^6 tons per year. This represents a considerable, yearly pool of utilizable plant biomass (Xie et al., 2019; Li et al., 2020).

Despite controlling erosion and stabilizing sediments, the adverse effects resulting from smooth cordgrass infestations along the coast are considered to outweigh any positive environmental effects of its intended introduction. Smooth cordgrass, as a typical halophyte, has readily adapted to high salt content in coastal habitats, occupying bare flats as well as often replacing native C3 plants, such as common reed and seepweed (*Suaeda salsa* (L.) Pall.), to become one of the dominant plants in China's coastal wetlands, and the most abundant halophyte in tidal flats in China.

Smooth cordgrass infestations have had significant negative impacts on coastal ecosystems and economies. Many native species have been displaced as smooth cordgrass occupies ecological niches of food molluscs, plants, fish, and endangered birds. In addition, it causes fast sediment deposition blocking harbours to shipping and fishing. Infestations have even invaded fishponds and mangrove swamps (Wang et al., 2008; Li and Qiu, 2011; Li et al., 2020).

The management of Smooth Cordgrass

While smooth cordgrass continues to flourish, considerable effort has been directed at methods to effectively manage these infestations. The traditional, time-honoured way was to mechanically remove and then burn the biomass. In some cases, the residue is added to the soil as a fertilizer or soil amendment. The physical control methods are widely practiced in China, normally after the stems have died (Figure 2). This burning represents a vast amount of potentially useful biomass, and the smoke from the burning of large stands of plants can be a source of air pollution presenting a significant health risk to those with respiratory problems.

Figure 2. Residual smooth cordgrass stalks being collected by hand (upper photo) and burning of gathered stalks (lower photo) in eastern China

Other methods of control for smooth cordgrass include mechanical removal using machinery (mowing/waterlogging and mowing/tilling) (Xie et al., 2019), and effective herbicides, such as Haloxyfop-R-methyl (Xie et al., 2019; Zhao et al., 2020), and Imazapyr (Patten et al., 2017). In addition, biological control has also been attempted with the application of a delphacid plant hopper -*Prokelesia marginiata* (Van Duzee, 1897; Grevstad et al., 2007) and the fungal pathogen *Fusarium subglutinans* (Wollenw. & Reinking, 1983; Gong et al., 2012). Added to the above efforts are ecological manipulations and restoration attempts to substitute and displace smooth cordgrass with common reed (*Phragmites australis*) (Wang et al., 2008) and a fast-growing mangrove pioneer species - *Sonneratia apetala* (Buch. -Ham). (Chen et al., 2014).

Utilization of Smooth Cordgrass

Smooth cordgrass has been utilized for some traditional applications over the years, and other possible utilizations of a more sophisticated technical level have also been investigated. In the sections below, I describe what they are, what has been done, and what could be done in the future.

Ecological roles and environmental benefits

As previously stated, smooth cordgrass was initially introduced from North America to China for erosion control and estuary reclamation. It has certain fisheries and wildlife uses in its native range; in these native habitats, some waterfowl and wetland mammals are known to eat its roots and shoots. The species is also palatable to livestock (Simenstad and Thom, 1995). Stands of smooth cordgrass may also serve as a nursery area for estuarine fishes and shellfishes, and mangroves.

In the Pacific Northwest estuaries in the USA, species that can utilize smooth cordgrass marshes, include juvenile Chinook salmon (*Oncorhynchus tshawytscha* Wlbaum). Such species may benefit from the spread of salt marsh vegetation (Landin, 1991; Simenstad and Thom 1995). In addition, the species has also been recognized as having strong carbon sequestration capabilities and could be significant for the carbon cycle of the coastal and ocean ecosystems (Lu and Zhang, 2013).

Biomass utilization

As smooth cordgrass is deciduous, its stems die back at the end of each growing season. These dead or dying plants represent a tremendous amount of plant biomass that may normally go to waste at the end of each season. In many instances, in China, and elsewhere, it is simply left to decay and disintegrate or burned, as previously noted.

The most common non-food utilization of lignocellulosic plant biomass, by far, is for bioenergy and biofuels (Stevens and Verhé, 2004; Sharma and Pant, 2018). The increasing awareness of climate change and greenhouse gas effects, depleting petroleum resources and the pollution their use creates, together with increasing petroleum prices over the last couple of decades, has led to the search for safer and renewable alternative energy sources. This is where the option of the utilization of smooth cordgrass biomass becomes relevant.

A study by Lu and Zhang (2013) established the potential of this plant as a biofuel source in China. They estimated that the total annual biomass can reach 2.53 Mt, producing 39 PJ of energy. This amount of energy is equivalent to the energy produced by 1.33 Mt of standard coal. The annual biomass of the above-ground parts of the plant alone is 1.12 Mt, producing 18 PJ of energy, equivalent to that produced by 0.61 Mt of standard coal.

These figures represent a potential significant production of energy and substituting smooth cordgrass biomass for just a part of the massive amounts of coal burned in China would reduce air pollution caused by the burning of coal. This usage of smooth cordgrass biomass may occur in different forms, including incineration or pyrolysis, pelletizing, and combusting in electricity-producing facilities in place of coal, or as biogas production from anaerobic digestion of the biomass (Li and Qiu, 2011).

A recent review (Xie et al., 2019) has divided Chinese research on smooth cordgrass into various sectors, as shown in Figure 3. The data confirms that the central area of research for smooth cordgrass utilization is the bioenergy/biofuels sector, with 43% of the total studies, the majority using stems or straw from the plants, aimed at this area. “Traditional” uses of the species, as feed for livestock and other animals and aquatic species, is the second-highest area of research. This is followed by medicinal applications, for extractive medicinal compounds, followed closely by raw materials for paper and other products (15%), with other lesser applications, such as fertilizers and pollution remediation, forming the remainder of the studies. The authors of the study conclude that the medicinal applications are the most likely viable, high-value utilization of the species.

Some additional research for combined ecological control and utilization management of the species has been undertaken in China. One of these is a combined ecological and integral utilization, whereby stands of smooth cordgrass are replaced by common reed (*Phragmites australis*), while also utilizing its biomass from other applications, such as fodder for dairy cattle, and as a source of extractives for feed and nutrient additives (Wang et al., 2008).

Another is a 7-step ecological engineering system for smooth cordgrass utilization, which involves a low waste, clean production process to make use of as much biomass as possible. This process firstly involves using the biomass as feedstock for the extraction of a bio-mineral liquid, which can be encapsulated and used as a health supplement which has various purported uses (Lu et al., 2020). The residues left after extraction are used as a medium for mushroom cultivation, and then for growing earthworms.

As a final part of the process, the remaining residues are the main component of a microbe-enriched organic fertilizer that is returned to the soil. An analytical evaluation of this system indicated that, if fully implemented, it could result in a potential economic output greater than 2% of the national GDP, illustrating the significance of the use of biomass from weeds (Lu et al., 2020).

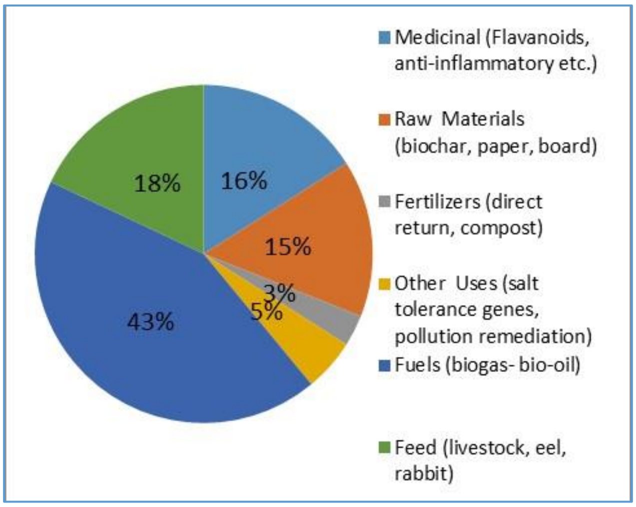

Figure 3. Proportions of studies on different utilization modes of smooth cordgrass in China (Source: Xie et al., 2019)

Commercialization of weed biomass utilization: a success story

An area of potential utilization of materials containing lignocellulosic biomass is as alternatives for wood fibres in the making paper and related products. This type of application has become increasingly important globally due mainly to the need to preserve and maintain the world’s forests for conservation and carbon capture purposes (Stevens and Verhé, 2004; Ayoub and Lucia, 2018). With the advent of the internet and the increasing disappearance of many printed newspapers and other materials, the need for newsprint has decreased, but there are still plenty of applications for pulped materials, including packaging materials (Orts, 2002; Cao and Zhang, 2006).

The vast excesses of smooth cordgrass biomass in China make this plant an obvious candidate as a potential candidate as a source of fibres for such pulping applications. Fibre from straw or stems from various agriculture and forestry wastes, as well as other weeds, have been successfully converted into pulps (Orts, 2002; Ververis and Pereira, 2002; Burry et al., 2017). Accordingly, due attention was directed towards this type of utilization, with which I had personal involvement from 2008 to 2014.

The initial stage of this project, which commenced in 2008, involved a detailed study of smooth cordgrass biomass and its physico-chemical characteristics. Plant samples were harvested in October at the end of the growing season from the upper intertidal area of a muddy salt marsh, located in Dafeng District Port on the eastern coast of Jiangsu Province, China (Lat: 33.217809º; Long: 120.815462º). The dried samples were firstly cut into 1-2 cm pieces, which were then sieved. Samples from the 40–60 mesh fractions were selected to determine their chemical composition and for further use. Based on analysis by scanning electron microscopy, it was observed that smooth cordgrass stems, leaves, leaf sheath xylem and phloem tissue consisted of a considerable amount of fibre.

The fibres were examined microscopically (Figure 4), and their lengths determined biometrically by optical microscope. While the most abundant fibres were in the 0.50-0.60 mm length range, the average fibre were 1.19 mm (Table 1).

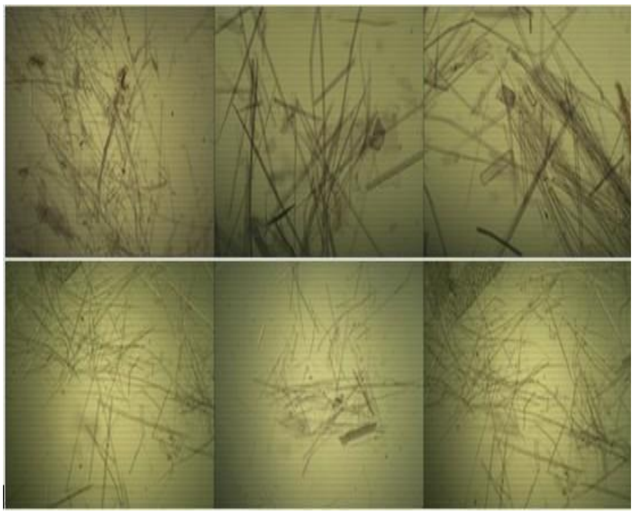

Figure 4. Smooth cordgrass fibres viewed by light microscopy at different magnifications (Source: Wu et al., 2011)

Smooth cordgrass stem samples were characterized chemically using standard methods for lignin, holocellulose, cellulose and hemicellulose contents. The cellulose content of smooth cordgrass is lower than those of the other materials listed, but the lignin content is similar to that of sorghum stalks, and lower than those of common reed, rice straw, and wheat straw (Table 2). A lower lignin content is an advantage for the pulping process (Ververis and Pereira, 2002; Stevens and Verhé, 2004). The analysis of this study suggested that smooth cordgrass straw fibres provide an effective raw material for making pulp, containing on average of 70.1% holocellulose, 35.9% cellulose and 15.9% lignin, and suitable fibre size (Wu et al., 2011).

The results show that the average length of the smooth cordgrass fibres is similar to that of common reed, but greater than that of cotton straw, and lesser than those of wheat and rice straw (Table 1). In general, they are in the range suitable for the preparation of pulps (Ververis and Pereira, 2002; Stevens and Verhé, 2004).

Table 1. Fibre lengths of various lignocellulosic biomass materials (Source: Wu et al., 2011)

Biomass material	Average Fibre Length (mm)
Rice straw	1.29
Wheat straw	1.39
Cotton Straw	1.03
Common reed	1.16
Smooth cordgrass	1.19

Table 2. Chemical characterization of various lignocellulosic biomass based raw materials (Source: Wu et al., 2011)

Material	Holo-cellulose (%)	Cellulose (%)	Hemi-cellulose (%)	Lignin (%)
Smooth cordgrass	70.1	35.9	34.2	15.9
Wheat straw	76.2	39.7	36.5	17.3
Rice straw	60.7	41.2	19.5	21.9
Common reed	64.2	39.8	24.4	23.7
Sorghum stalks	65.9	41.5	24.4	15.6

Further studies indicated that the smooth cordgrass fibre pulp could be mixed with other pulps, such as obtained from bamboo (*Phyllostachys bambusoides* Siebold & Zucc.) pulp, cellulose fibre-residues from paper making, printing factories, corrugated cardboard, and other residues from various paper product manufacturing facilities. Such an approach allows these otherwise waste materials to be recycled. Results indicated that the proportion of smooth cordgrass pulp in these mixtures could reach more than 50% (Chen et al., 2011).

The final step in the utilization process was to produce products from the smooth cordgrass fibre-pulp in a clean pulp production line. Following the process of Cao and Zhang (2006), the fibres were firstly sprayed to soften and swell them, with accompanying tension reduction, to facilitate breakdown and introduction to a pulping machine. Secondly, fibre pulp from the straw bundles was prepared through a straightforward process that saved energy and was environmentally-safe, minimizing pollution. This process can produce tons of fibre with a yield of 80% of 40 mesh fibre pulp. Thirdly, a metal mould for the product to be manufactured was submerged in the pulp slurry, and the slurry pulled into the mould by vacuum to form the shaped product. Finally, the products were ejected out of the mould and deposited on a conveyor, moving through a drying oven.

Using this process with composite fibre bundles and chemical pulps of smooth cordgrass fibres as one of the main components, various moulded products were made (Figure 5). These included industrial packaging products, such as fruit trays, lightweight shipping pallets, environmental protection products, decorative wall panels and automotive wheel containers (Wu et al., 2011; Qin et al., 2014).

A factory was built near the coastal city of Dafeng, Jiangsu Province, on the east coast of China, to establish a production line for the fibre-based packaging materials and other products in 2011. With an annual output of 5,000 tons, this facility realizes the industrial utilization of smooth cordgrass and represents the first of its kind in the moulded pulp industry. Dafeng has long been the site of severe smooth cordgrass infestations and therefore, a sensible location to place such a facility.

Although located in a remote location, this facility employs approximately 50 people including production line workers, engineers, office staff and management in addition to those seasonal workers hired to harvest the plant biomass. Various moulded products are sold nationally, and some, such as egg and fruit trays, sold to buyers in Germany and Switzerland, among other countries.

In a modification to the production, smooth cordgrass fibre bundles were prepared together with various additives and utilized in a hydraulic vulcanizing press moulding machine using flat plate moulds and bowl mould plates to produce ‘green’ dishes and ‘green’ eating bowls (Qin, 2013). Product testing results met the FDA requirements for product quality standards, and the price for these products has reached more than 20,000 RMB (approximately USD 2,800) per ton. Such pulp-based products, which are made from plant fibres, possibly mixed with other organic pulps, as raw materials, are green technologies, which are environmentally superior and safer than those of many other industries. The potential for broader applications and uses are confirmed sales and interest in the products.

Figure 5. Wheel hub packing container (top) and back of fruit tray (bottom) made of mixed pulps containing smooth cordgrass fibres

Our studies indicated that smooth cordgrass biomass has the potential to be used in various other commercial applications as well. These include: (a) preparation of biochar in various forms, as the sole component, or part of a mixture (Liao et al., 2013; Sharma and Pant, 2018), (b) as a filler for improving the properties of concrete (Mello et al., 2014) and (c) fibres to partially or totally replace wood fibres in wood-plastic composites (WPCs), which can be used to produce a variety of building materials, including flooring, wall panels and furniture (Ayoub and Lucia, 2018). The production of WPCs with weed biomass was recently demonstrated using Canadian goldenrod (*Solidago canadensis* L.), another well-known colonizing plant in China (Liu et al., 2017).

Discussion

Based on fundamental chemical and biometric studies of smooth cordgrass and the moulded pulp products produced from it, it is apparent that pulp moulding provides a commercially effective means of utilization of the species, as a source of non-wood fibres. Using this species as an industrial raw material to make packaging products provides a basis for further utilization of other weeds and straw materials in the future. Fibres can be used as raw material to manufacture a variety of products on an industrial scale. These products, such as packaging materials and shipping containers, have been profitable, providing a boon to the local economy.

This type of raw material is mostly free, and the expenses involved in employing local workers to harvest and dry the plant stalks are minimal. From a personal perspective, it is rewarding to see the research and development come to fruition with the commercialization of such ventures. Not only does such an application provide an alternate means of dealing with a problematic plant, but it also doubles its environmental and ecological effectiveness by substituting for another limited resource, namely, wood fibres. Thus, the use of smooth cordgrass biomass serves two purposes: firstly, a free raw material for industrial manufacture, and secondly, a degree of biodegradability and recyclability.

As discussed previously, while several utilization options of smooth cordgrass biomass have been investigated, only a few have been adopted at the industrial scale. Most studies have been confined to research without commercial development. The exception, as presented here, utilizing fibres from the stems as raw material, pulped, and moulded to produce several products, is an example of what can be achieved using weeds as bioresources.

This lack of utilization of weeds may be due to several factors, including a general reluctance to work with weeds as they have associated stigma and negative connotations (Chandrasena, 2008; Sharma and Pant, 2018). Weeds are generally considered “unwanted”. The advantages of using weeds as raw materials are related to their robust and fast growth, tolerating a range of ecological conditions. They are also very tolerant and can be repeatedly harvested, leaving behind sufficient rootstock and plant parts (stems) that may regrow and are amenable for continual, sustainable harvesting.

Many weeds are ideally suited as bioresources, as they are generally not utilized for other purposes. This material can substitute for the biomass of traditional crops, such as corn (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench), wheat (*Triticum aestivum* L.), canola (*Brassica napus* L.) and others, which are used as feedstock for biofuels. Such use can alleviate the tension in the “food vs fuel” arguments, as well as land-use conflict issues (Stevens and Verhé, 2004; Piotrowski et al., 2015; Sharma and Pant, 2018).For coastal species, such as smooth cordgrass, these arguments do not hold, as they do not compete with crops for growing space. Many landowners, where large stands exist, would no doubt gladly let someone harvest them for free, or perhaps, impose a modest licensing fee.

On the negative side, there are certain disadvantages in the use of weeds as bioresources. These include the unpredictability of growth of any plant species and seasonal or yearly variations of growth. The abundance and harvesting can also sometimes be constrained by circumstances. If the raw material for production becomes unpredictable, manufacturers or users of those products may have to adjust production, taking account of these variations. There is also the possibility of seasonal changes, locational variations, or ageing, which may cause changes in biomass quality, energy content or chemical composition of smooth cordgrass, as has been reported in an early paper (Squiers and Good, 1974). Such variations may require obtaining alternative sources of biomass (Nordfjell, 2007), which could affect the corresponding uses of the substitute raw materials in specific applications (Bekele et al., 2017). In such cases, careful quality control and raw material analyses are required to take these possibilities into account.

Another important factor that must be considered with the utilization of weeds is the risk of introducing colonizing taxa into new locations. This concern has been raised for certain well-known bioenergy/biofuel crops. Examples are grasses – Miscanthus (*Miscanthus x giganteus* (Greef & Deuter ex Hodkinson & Renvoize), switchgrass (*Panicum virgatum* L.) and reed canary grass (*Phalaris arundinacea* L.) (Raghu et al., 2006; CAST, 2007). Thus, effective, and efficient utilization of colonizing taxa may require them to be managed appropriately, grown in isolated and controlled areas so that they do not spread to areas where they are undesired.

As an additional factor, there may be difficulties in harvesting stands of specific taxa, simply because of extent and access. Even in the case of smooth cordgrass, harvesting is a constraint as it is mostly done manually from coastal marshy or tidal areas by labourers. Such areas are not easily accessed mechanical harvesters. In my view, these problems are, for the most part, not insurmountable and can be overcome to promote the utilization of colonizing taxa for profitable, commercially viable industries.

Despite the common problem created by weeds, there are differences in the way they are treated or dealt with according to countries or continents. Some jurisdictions, such as the Dafeng District in Jiangsu Province, China, have had local and provincial government support and successfully taken advantage of their smooth cordgrass infestations and are utilizing this source of biomass for profit. However, this is a clear exception to the norm. Most other areas that also have large-scale infestations have tended to either neglect them, ignore them, or attempt to eradicate them.

A tendency to utilize such sources of biomass depends mostly on the available local resources and whether possible alternatives exist. For a vast country like China, which still lacks many natural resources, there is an incentive to look for such alternatives. This may explain the more positive attitude toward their use compared to other places where there are plentiful resources, overall. In North America, for example, there are sufficient forests to sustainably provide for wood fibres to produce paper pulp and associated products.

The general attitude towards weeds, over many decades, has been a negative mindset. Some countries or societies have long made use of certain weeds and come to terms with them as useful resources. Under such circumstances, they generally are not considered as undesirable species and therefore not considered “weeds” as such (Chandrasena, 2008; Duns and Chen, 2009).

Conclusions and Outlook

Smooth cordgrass biomass is an example of what can be done in terms of the utilization of weeds. They can be turned into useful products that help the environment and be profitable at the same time. The ever-increasing need for environmentally safe, and renewable resources to replace petroleum-based materials for energy and manufacturing has led to the continual search for such materials and will undoubtedly continue in the future.

While there are certain disadvantages to utilizing colonizing plants as bioresources for industrial scale applications, as noted above, their advantages, especially for the environment and socio-economic reasons, outweigh these disadvantages. When considering the vast yearly amounts of biomass produced by smooth cordgrass, combined with those of just a few of the other prolific pioneering plants, such as water hyacinth and common reed, the opportunity to do something constructive with it, while at the same time, reducing associated environmental problems, is an opportunity that should not be missed. Thus, there should be a common consensus, if not a strategy, towards utilization of colonizing taxa (weeds) on a global basis, if possible, and not just left for local jurisdictions to deal with as they see fit.

With the world’s population estimated to reach 9.6 billion people by 2050 (Piotrowski et al., 2015) there will be increasing demands for food, and the diversion of agricultural resources for non-food uses. Thus, there will increasingly be a need for alternative sources of raw materials for energy and manufacturing, and weeds can certainly play a role in this regard, as an environmentally sound option in this supply versus demand issue. While the focus herein has been smooth cordgrass, similar approaches towards utilization should readily apply to other colonizing taxa, whether terrestrial or aquatic. If there is sufficient available biomass that can be readily harvested and reasonable logistics available for storage, shipping and processing, there are many possibilities to exploit these plants.

Suffice to say that not all weeds are suitable for industrial-scale applications. Their inherent physico-chemical properties, as well as fecundity and aggressive growth at specific locations, has caused apprehension as to the potential harmful effects they may have. Such misconceptions continue to inhibit or prevent their use. However, there is no shortage of weeds, and the opportunities to investigate those suitable for utilization seem endless.

For the effective use of a bioresource, whether it is a weed, crop plant, residues from agriculture or forestry, we need to understand the characteristics of the biomass through comprehensive physico-chemical analyses of its properties. (Vaz Jr., 2014; Tursi, 2019). This knowledge of the material is vitally important to develop suitable technology for processing, and then, move to develop commercial applications (Raguskas et al., 2006; Walker, 2015).

The best possible scenario from my perspective is to establish biorefineries for proper integral valorization of biomass from taxa, such as smooth cordgrass. In this way, several products could be made at the same location from local feedstock consisting of the weed’s biomass, analogous to the different products resulting from the various fractions produced by a petroleum refinery (MacLachlan and Pye, 2007; Vaz Jr., 2015; Walker, 2015).

The utilization of an aggressive species, such as smooth cordgrass, is of course not the complete solution to the problems caused by it or other similar colonizing plants. There may be plenty of situations where utilization is not possible, or the population of such plants has grown out of control on a scale that solutions to control them may be required. In these instances, the most ecologically safe control solutions need to be applied, and utilization can be a part of an integrated approach in such solutions. An integrated management strategy would be ideal if it consists of a combination of judicious control and utilization methods that are environmentally responsible. If the approach provides some local economic benefit at the same time, it may prove most useful in dealing with species, such as smooth cordgrass (Wang et al., 2008).

I personally find that the quest for new, utilizable sources of biomass represents exciting times and limitless opportunities, bringing together scientists, engineers and entrepreneurs from various disciplines and backgrounds. I am optimistic that in the future, the utilization of weeds will become more common. To achieve this goal, further research, development and, importantly, education, are required regarding the useful properties of weeds.

Acknowledgements

The author acknowledges the continuing assistance and support of Professor Jishuang Chen and Professor Zuodong Qin. The author gratefully appreciates the immensely helpful comments and assistance of Dr. Nimal Chandrasena, Editor-in-Chief of *Weeds*, and the suggestions and changes of an anonymous referee, which greatly improved the MS. The author also declares no conflict of interest or commercial interest in the subject discussed.

Literature Cited

Ayoub, A.S. and Lucia, Lucian A. (Eds.) (2018). *Introduction to Renewable Biomaterials: First Principles and Concepts.* First Edition. John Wiley and Sons Ltd., Hoboken, New Jersey, U.S.A. pp. 239-264.

Ayres, D. R., Smith, D. L., Zaremba. K., Klohr, S., Strong, D. R. (2004). Exotic cordgrass and hybrids (*Spartina* sp.) in the tidal marshes of San Francisco Bay. *Biological Invasions*. 6: 221-231.

Bekele, L. D., Zhang, W., Liu, Y., Duns, G. J., Yu, C. et al. (2017). Impact of cotton stalk biomass weathering on the mechanical and thermal properties of cotton stalk flour/linear low density polyethylene (LLDPE) composites. *Journal of Biobased Materials and Bioenergy.* 11: 27–33.

Brouwer, P., Nierop, K. G. J., Huijgen, W. J. J. and Schluepmann, H. (2019). Aquatic weeds as novel protein sources: alkaline extraction of tannin-Rich *Azolla*, *Biotechnology Reports,* (Available at: https://doi.org/10.1016/j.btre.2019.e00368).

Burry, W., Doelle, K. and Liu, S. (2014). Common reed (*Phragmites australis*), eradicate or utilize? Part 1: Potential use as a biochemical feedstock. *Journal of Bioprocess Engineering and Biorefinery*, 3 (4): 285-295.

Burry, W., Doelle, K., Liu, S. and Appleby, R. (2017). Common reed (*Phragmites australis*), eradicate or utilize? Part II: Potential use as an industrial fiber source after hot water extraction. *BioResources,*12 (3): 5697-5714.

Cao, G and Zhang Y (2006). Progress in the development of moulded pulp products, *Packaging Engineering*, 27: 21-23.

Catallo, W. J., Shupe, T. F. and Eberhardt, T. L. (2008). Hydrothermal processing of biomass from invasive aquatic plants. *Biomass and Bioenergy,* 32: 140-145.

Chandrasena, N. R. (2008). Liabilities or assets? Some Australian perspectives on weeds, *In:* Kim, K. U., Shin, D. H. and Lee, I. J. (Eds.) *Utility of Weeds and their Relatives as Resources*, Kyungpook National University, Daegu, S. Korea. pp. 9-56.

Chandrasena, N. R. (2014). Living with weeds: a new paradigm. *Indian Journal of Weed Science*, 46 (1): 96-11013.

Chandrasena, N. (2019). Seeing 'weeds' with new eyes. *Weeds*, 1 (2): 1-12.

Chandrasena, N. and Rao, A. N. (2019). Parthenium weed: uses and abuses. Chapter 10: *In*: Adkins, S. Adkins,. Shabbir, A. and Dhileepan, K. (Eds.). *Parthenium Weed: Biology, Ecology and Management.* CABI Invasives Series. CABI International, UK. pp. 190-211.

Chelaifa, H., Mahé, F. and Ainouche, M. (2010). Transcriptome divergence between the hexaploid salt-marsh sister species *Spartina maritima* and *Spartina alterniflora* (Poaceae). *Molecular Ecology,* 10: 2050-2063.

Chen, H., et al. (2014). Eradicating invasive *Spartina alterniflora* with alien *Sonneratia apetala* and its implications for invasion controls. *Ecological Engineering,* 73: 367-372.

Chen, J.S., Qin, Z. D., Xu, Z., Wu, L., Wei, Y.Q., Wang, X. and Duns, G. J. (2011). Utilization of an invasive species (*Spartina alterniflora*) in the molded pulp industry. *Pakistan Journal of Weed Science Research*, 2012 (Special Issue) 18: 137-146.

Council for Agricultural Science and Technology (CAST). 2007. Biofuel feedstocks: The risk of future invasions. *CAST Commentary QTA,* 2007-1, CAST, Ames, Iowa, 1-8.

DiTomaso, J. M., Brooks, M. L., Allen, E. B., Minnich, R., Rice, P. M. and Keyser, G. B. (2006). Control of invasive weeds with prescribed burning. *Weed Technology,* (20): 535-548.

Duns, G. J. and Chen, J. S. (2009). Use of invasive plant species as bioresources. Abstracts, International Congress on Biological Invasions, Fuzhou, China. 2-6 November, 183, (http://www.icbi2009.org).

Gong, L. B., Wang, Y. P., Ling, X. and Yuan, J. (2012). Biological control of *Spartina alterniflora* by a fungal-*Fusarium subglutinans*. *Proceedings of the International Conference on Biomedical Engineering and Biotechnology*, Macao, 2012, 97-100.

Grevstad, F. S., Wecker, M. S. and Strong, D. R. (2007). Biological control of *Spartina. In*: Ayres, D. R., et al. (Eds.) *Proceedings of the Third International Conference on Invasive Spartina,* 2004 Nov 8-10, San Francisco, CA, USA. San Francisco Estuary Invasive Spartina Project of the California State Coastal Conservancy: Oakland, CA. 267-272.

Guna, V. K., Llangovan, M., Gangadharaiah, A. M. and Reddy, N. (2017) Water hyacinth: a unique source for sustainable materials and products. *ACS Sustainable Chemistry & Engineering,* 5 (6): 4478-4490.

Landin, M. C. (1991). Growth habits and other considerations of smooth cordgrass, *Spartina alterniflora Loisel*. *In:* Mumford, T. F., Jr., Peyton, P., Sayce, J.R. and Harbell, S. (Eds). *Spartina Workshop Record.* pp. 15-20. Washington Sea Grant Program, University of Washington, Seattle, 15-20.

Liao, R., Gao, B. and Fang, J. (2013). Invasive plants as feedstock for biochar and bioenergy production. *Bioresource Technology*, (140): 439-442.

Li, N., Li, L. W., Zhang, Y. L. and Wu, M. (2020). Monitoring of the invasion of *Spartina alterniflora. BMC Ecology*, (20):7 (Available at: https://doi.org/10.1186/s12898-020-00277-8).

Li, R. L. and Qiu, G.Y. (2011). *Spartina alterniflora:* potential bio-energy source for biofuel production in China. *Applied Mechanics and Materials* (142): 247–251. (Available at: https://doi.org/10.4028/www.scientific.net/amm.142.247).

Liu, Y. L., Bekele, L. D., Lu, X., Zhang, W., Yu, C. H., Duns, G. J. et al. (2017). The effect of lignocellulose filler on mechanical properties of filled high density polyethylene composites loaded with biomass of an invasive plant *Solidago canadensis. Journal of Biobased Materials and Bioenergy,* 11: 34–39.

Lu, H. F., Zhang, H.S., Qin, P., Li, X. Z. and Campbell, D. E. (2020). Integrated energy and economic evaluation of an ecological engineering system for the utilization of *Spartina alterniflora. Journal of Cleaner Production,* (247): 119592 (Available at: https://doi.org/10.1016/j.clepro.2019.119592).

Lu, J. B. and Zhang, Y. (2013). Spatial distribution of an invasive plant *Spartina alternifora* and its potential as biofuels in China. *Ecological Engineering,* 52(2):175–81. (Available at: https://doi.org/10.1016/j.ecoleng.2012.12.107).

MacLachlan, R. and Pye, E.K. (2007). Biorefining the future. *Canadian Chemical News*, 59(8):12-15.

Malik, A. (2007). Environmental challenge *vis a vis o*pportunity: The case of water hyacinth. *Environment International,* 33: 122-138.

Mello, E., Ribellato, C. and Mohamedelhassan, E. (2014). Improving concrete properties with fibers addition. *International Journal of Civil, Architectural, Structural and Construction Engineering,* 8 (3): 245-250.

Mumford, T.F, P. Peyton., J.R. Sayce. and S. Fiarbell, (Eds). (1991). *Spartina Workshop Record*. Washington Sea Grant Program, University of Washington, Seattle.

Nordfjell, T. (2007). Fuel quality changes during seasonal storage of compacted logging residues and young trees. *Biomass and Bioenergy,* 31: 782-792.

Orts, W. J. (2002). Molded packaging materials from straw pulp. *Industrial Bioprocessing*, 24(6): 7.

Patten, K., O'Casey, C. and Metzger, C. (2017). Large scale chemical control of smooth cordgrass *(Spartina alterniflora)* in Willapa Bay, WA: towards eradication and ecological restoration. *Invasive Plant Science and Management,* 10 (3): 284-292.

Piotrowski, S., Carus, M. and Essel, R. (2015). Global bioeconomy in the conflict between biomass supply and demand. *Industrial Biotechnology*,11 (6): 308-315. (Available at: http://doi.org/10.1089/ind.2015.29021.stp).

Qin, Z. D. (2013). *Molecular basis and technology research for the industrialization of the Spartina alterniflora biomass.* Ph.D. Thesis, Nanjing University of Technology.

Qin, Z. D., Jin, L. L., Wang, J. H. and Chen, J. S. (2014). Development of novel sludge fiberboard combined with fibers of *Spartina alterniflora. Chinese Journal of Process Engineering,* 12: 65-68. (in Chinese)

Raghu, S., Anderson, R. C., Daehler, C.C., Davis, A. S., Wiedenmann, R.N., et al. (2006). Adding biofuels to the invasive species fire? *Science,* 313: 1742.

Raguskas, A. J., Williams, C. K., Davison, B. H., Britovesk, G., Cairney, J., Eckert, C. A. et al. (2006). The path forward for biofuels and biomaterials. *Science,* 311: 484-489.

Sharma, V. and Pant, S. (2018). Weed as underutilized bio-resource and management tool: a comprehensive review. *Waste and Biomass Valorization,* 10 (7): 1795-1810.

Simenstad C. A. and Thom, R. M. (1995). *Spartina alterniflora* (smooth cordgrass) as an invasive halophyte in Pacific Northwest estuaries. *Hortus Northwest*, 6: 9-40.

Squiers, E.R., Good, R.E. (1974). Seasonal changes in the productivity, caloric content, and chemical composition of a population of salt-marsh cord-grass (*Spartina alterniflora*). *Chesapeake Science,* 15: 63–71.

Stevens, C. V. and Verhé, R. (Eds.) (2004). *Renewable Resources: Scope and Modifications for Non-food Applications*, John Wiley & Sons Ltd, West Sussex, England.

Thompson, John D. (1991). The biology of an invasive plant: *what makes Spartina anglica so successful? Bioscience,* 41(6): 393-401.

Tursi, A. (2019). A review on biomass: importance, chemistry, classification, and conversion. *Biofuel Research Journal,* 22, 962-979.

Vaz Jr., S. (2014). Analytical techniques for the chemical analysis of plant biomass and biomass products. *Analytical Methods,* 6: 8094-8105.

Vaz Jr., S. (2015). Lignocellulosic residues for biorefineries. *Advances in Recycling and Waste Management,* 1:1. (Available at: https://www.hilarispublisher.com/open-access/lignocellulosic-residues-for-biorefineries-arwm-1000e101.pdf).

Ververis, C, and Pereira, H. (2002).. Influence of stem morphology on pulp and paper properties of *Arundo donax L.* reed. *Industrial Crops and Products*, 15 (1): 77-83.

Walker, L. (2015). Sustainable development and utilization of plant-based resources for the future. *Industrial Biotechnology,* 11 (6): 293-294.

Wang, G., Qin, P., Wan, S., Zhou, W., et al. (2008). Ecological control and integral utilization of *Spartina alterniflora*. *Ecological. Engineering,* (32): 249-255.

Wu, L. F., Xu, Z. J., Qin, Z. D., Duns, G. and Chen, J. S. (2011). Pulping utilization of *Spartina alterniflora* (common cordgrass) based on fiber characteristics. *Applied Mechanics and Materials,*130-134:833-837.

Xie, B.H., Han, G. X., Qiao, P. Y., Mei, B. L., Wang, Q., et al. (2019). Effects of mechanical and chemical control on invasive *Spartina alterniflora* in the Yellow River Delta, China. *Peer J7*, e7655 (Available at: https://doi.org/10.7717/peerj.7655).

Xie, B.H., Lu, F. and Han, G. X. (2019). Resource utilization of invasive *Spartina alterniflora:* A Review. *Chinese Journal of Eco-Agriculture,* 27(12): 1870-1879. (in Chinese).

Yan, S.H., Song, W., and Guo, J.Y. (2017). Advances in management and utilization of invasive water hyacinth (*Eichhornia crassipes*) in aquatic ecosystems – A review. *Critical Reviews in Biotechnology*, 37 (2): 218-228.

Zhao, Zhi-Yuan; et al. (2020). Emergency control of *Spartina alterniflora re*-invasion with a chemical method in Dongtan, China. *Water Science and Engineering.* 13 (1): 24-33. (Available at: https://doi.org/10.1016/j.wse.2020.03.001).