chapter 11

Feedstock Supply Chains

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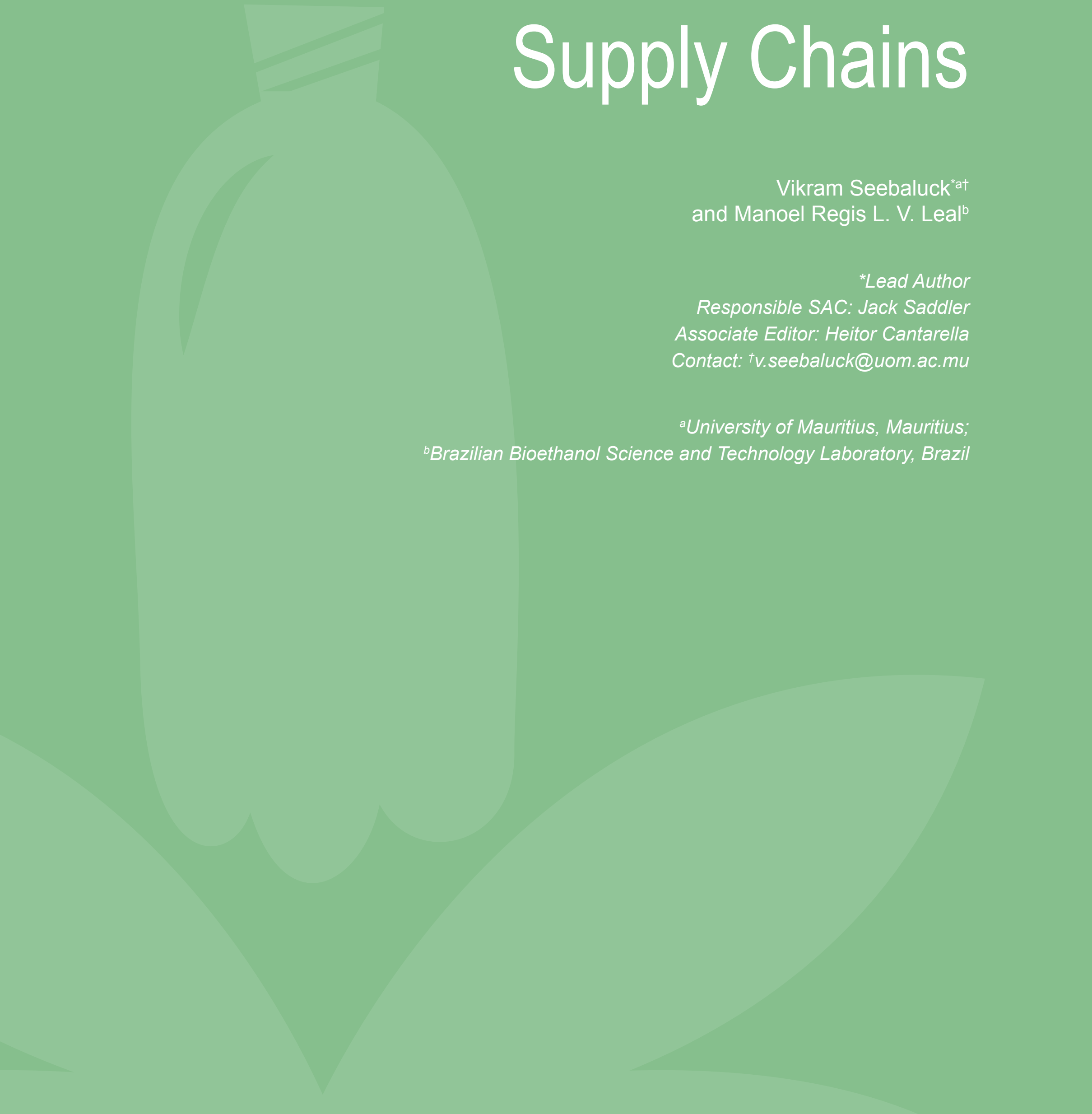

Highlights

- Feedstock supply chains bridge biomass production in fields to industrial processing. Although it will be influenced by the type of crop, the chain will typically include harvesting, collection, baling, transport, drying, storage and pre-treatment, all of which should be efficiently and cost-effectively designed to enhance the overall sustainability of bioenergy projects.
- Except for some large-scale commercial crops such as sugarcane or corn, biomass supply chains for bioenergy production are currently underdeveloped despite the fact that significant improvements could be achieved by modernizing the logistic operations to make them more efficient. Capitalization, replication or adaptation experiences could be derived from the existing commercial biomass supply chains.
- Modern biomass supply chains offer significant possibilities for gathering all types of biomass and synergizing their physico-chemical properties with subsequent energy conversion processes.
- There is good potential to develop alternative options to provide stable and continuous supply of suitable feedstocks to processing plants. Potential improvements include storage, biomass densification, use of complementary fuels available over the year, and multi-fuel processing.
- Scale of bioenergy crops production is crucial in the choice and development of suitable supply chains. Mechanical operations are generally favored by large-scale production, as it is the case with sugarcane or corn. However, given that the availability of bioenergy crops may be scattered in situations like its cultivation in marginal areas, there is the need to determine the minimal or reasonable cultivable area on which mechanization or at least partial mechanization could be efficiently and cost-effectively undertaken. This is vital in tapping the maximum available and suitable land for bioenergy crops production as well as the associated socio-economic benefits.
- Scientific innovations and practical experiences, together with the collaboration of equipment manufacturers would largely contribute in cost-effectively and efficiently transferring different types of biomass from fields to factories.
- Appropriate policies in synergy with those on crop production and conversion processes (the immediate nexus of biomass supply chains) would support the development of region-specific efficient feedstock supply chains; there is a need for technical and financial supports as well as capacity building.

Summary

Bioenergy expansion is nowadays gaining momentum with commercial scale and modern production systems gradually being developed worldwide. One of the key lessons learned in such developments is that the long-term economic success and sustainability of bioenergy projects depend on the proper management of the overall energy system, which includes supply chain operations as a key determinant. Biomass supply chains thus form part of the knowledge-based bio-economy of the future which is needed for replacing traditional fossil resources that are becoming costly and environmentally destructive. This chapter reviews the biomass supply chain operations with case studies of typical commercial energy crops in view to provide an insight of progress achieved so far and future prospects. There exist some large-scale biomass supply chains which could be further optimized to provide key lessons to quickly develop or adapt them to new bioenergy feedstocks having substantive market penetrability. However, given the rather varying context in which bioenergy projects are evolving in different regions, a more coordinated approach for technical and financial supports as well as for capacity building would assist in developing efficient biomass supply chains for bioenergy production. Scientific innovations would contribute in cost-effectively and efficiently transferring different types of biomass from field to factories. These would require the assessment of field experiences to scientifically develop efficient logistics in close collaboration with equipment manufacturers. Thus, appropriate policies in synergy with those on crop production and conversion processes between which supply chains are squeezed in should be promoted to meet the need to increase the share of modern bioenergy in the global energy supply. Such developments would bring benefits for the climate, energy access or security and developmental opportunities.

11.1 Introduction

This chapter focuses on feedstock supply chains that bridge biomass production or availability to its industrial processing into bioenergy. Except for some crops such as sugarcane, corn, soybeans and rapeseed, large scale biomass supply chains for bioenergy production are underdeveloped and are new or emerging for many potential bioenergy feedstocks; this is due to the quite recent rapidly developing market for energy biomass (Vakkilainen et al. 2013) and the growing need to convert waste biomass into useful energy products in the quest for diversifying renewable environment-friendly energy resources. The know-how and expertise in this area thus need to be strengthened while capitalizing on the experience acquired so far with some feedstocks such as sugarcane or corn. Besides reviewing the biomass supply chains for energy production, the key factors influencing the logistic operations as well as the impacts and nexus with the overall biomass to bioenergy cycle are also presented in this chapter. The technology gaps, challenges and opportunities for improving and developing new biomass supply chains for bioenergy production are given together with an overview of the commercial supply chain operations for four different biomass sources, namely sugarcane (a food and fuel crop), eucalyptus (a tree species), miscanthus (a new crop for power generation) and oil palm (an oil crop). These examples provide insight for capitalization, replication and adaptation opportunities for bioenergy production from other types of biomass available or produced in different world regions. Corn is a major feedstock used for ethanol production in the US for use as oxygenate in gasoline. Corn supply chains are modern with long standing experiences while options for harvesting and supply of corn stover are being developed (Klingenfeld 2008; Gonzalez et al. 2011; Darr 2012; Gutesa 2013; Shah 2013) given its significant availability and potential for bioenergy production. However, this feedstock is linked to considerable debate on its sustainability for biofuel production, the land use change impacts and ‘food versus fuel’ issue. Bioenergy from corn is presented in other chapters of this book.

11.2 Key Features of Biomass Supply Chains

Biomass supply chains are mainly characterized by their design, cost and sustainability among other features. The growing portfolio of bioenergy feedstocks differ in their physico-chemical properties and availability, thus requiring specific logistics designs adapted to the characteristics of the materials handled and the scale of production. The need for pre-treatment prior to storage or processing may impose an additional complication on the supply chain. The operations are thus normally designed taking into consideration the quality of the available biomass as well as the subsequent energy conversion processes or storage needs, which usually requires that the biomass is pre-treated to be technically convenient to the processing configurations or for storage and re-transportation purposes. Optimization of the structural flow pattern, including the functioning of the biomass supply chain steps with adjustments to specific conditions of production systems (e.g. climate and topology, feedstock, technologies, infrastructures, energy end uses, etc.), can largely contribute in improving the viability and cost-effectiveness of the bioenergy system. Any incremental improvement at each logistics step should be tapped given that supply logistics have a significant bearing on the total delivered cost of biomass to an energy plant which can go up to around 40% of the cost of the biomass production (Johnson and Seebaluck 2012). From the sustainability perspective, it eventually becomes important to green the supply chains through the use of properly selected approaches and energy efficient logistics steps to improve the energy and environmental balances of the bioenergy system. Additional factors, such as weather conditions, can affect the yield and quality as well as the harvesting and collection time, while real time knowledge can improve communication between the factory and raw biomass suppliers to ensure coordinated and constant supply of quality biomass to the processing plant.

11.3 Biomass Crops and their Supply Chains

Supply chain operations primarily depend on the types of biomass to be harvested or collected which are broadly classified into oil or sugar/starch-bearing crops or lignocellulosic feedstocks. Globally, there are around 350 oil-bearing crops identified as potential feedstocks for biodiesel production (Atabani et al. 2012) out of which crops like oil palm, soybeans and rapeseed have reached commercial processing. Harvesting of oil seeds is undertaken manually or is semi-mechanized with power cutters and picker type lifts, but fully mechanized systems, which exist only for a few crops, still need to be developed or addressed as a technological gap (HREDV 2009). Modified mechanical harvesting equipment for other crops have been proposed for harvesting of crops like jatropha but these still need to be fully developed. On the other hand, lignocellulosic biomass in the form of energy crops, agricultural wastes and forest residues represents the most abundant source of renewable biomass with production of $1x10^{10}$ metric tons annually, which is about half of the biomass produced in the world (Alvira et al. 2010). It is the future feedstock for the biofuel and bio-based industry; it could produce up to 442 billion liters of bioethanol per year due to its high diversity around the world (Darjanaand and Mirjana 2013). However, second generation cellulosic ethanol conversion technologies which has to emerge would be needed to realize this potential. To maintain the viability and sustainability of bioenergy production worldwide, there are growing interests in the production of energy crops such as perennial grasses which are attractive in terms of their high production yield, low input requirements, high content of lignin and cellulose, ability to adapt to marginal land and rain fed conditions, and their generally anticipated positive environmental impacts. Factory biomass wastes produced from traditional food and forage crops are equally increasingly being used for bioenergy production. For instance, sugarcane, a common crop grown in more than 100 countries worldwide, offers both field and factory wastes for energy generation. Lignocellulosic feedstocks supply chains may be manual to semi-mechanized as well as fully mechanized systems. For instance, sugarcane resources offer diverse mature commercial applications of these alternative systems while the supply chain operations of other emerging energy crops like *Arundo Donax* are generally learnt and extrapolated from sugarcane, but need to be adapted and optimized (Seebaluck 2012).

The supply chains are generally less costly for factory derived waste biomass (e.g. sugarcane bagasse), while the cost for collected biomass is higher depending on the complexity of the operations (e.g. sugarcane agricultural residues). On the other hand, dedicated energy crops are generally associated with specifically designed supply chains that usually bear higher cost but which could be reduced depending on the scale of production and technology applications. It must also be highlighted that around three quarters of the biomass used for food, feed, industrial wood and traditional fuel wood is not fully exploited at some point in their harvesting, transport and processing (Nielsen et al. 2007) thus providing opportunities for optimization of these logistic operations.

11.4 Typical Layout of the Biomass Supply Chains

Generally, depending on the biomass and fuel type, the supply chains would include harvesting, collection, baling, transport, drying, storage and pre-treatment prior to conversion to bioenergy products. These steps are interlinked and should be planned from a total chain perspective rather than separately to obtain an efficient and cost-effective biomass supply. The typical general layout of biomass supply chains is given in Figure 11.1. It is therefore natural that many attempts have so far been made to simulate and optimize specific biomass supply chains on the understanding that cost reductions could originate from more efficient logistics operations.

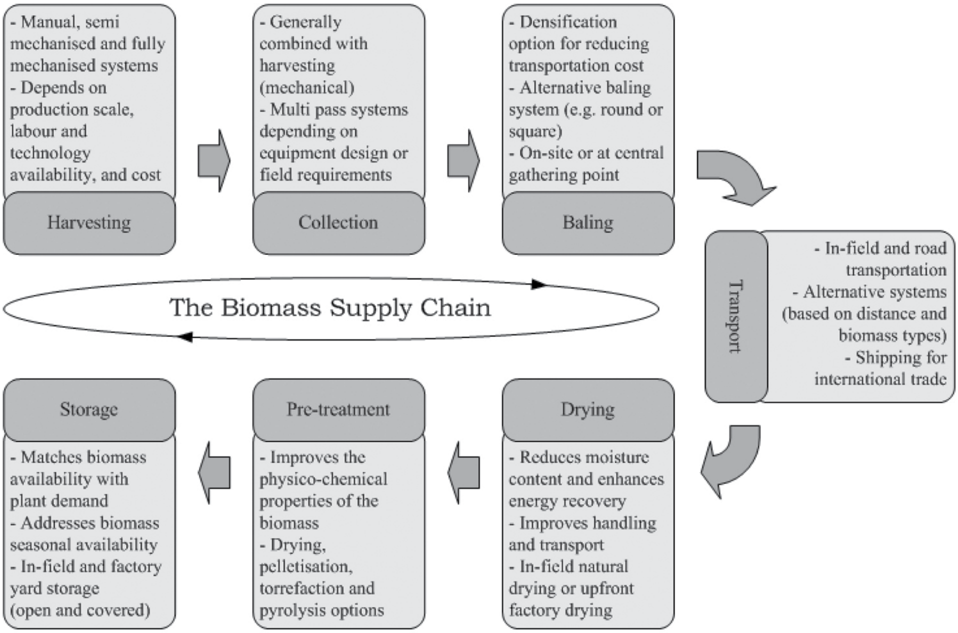

Figure 11.1. Typical layout of biomass supply chains.

11.4.1 Harvesting and Collection

Harvesting and collection depends on the type of biomass (e.g. grass, wood, crop residues or seed crops) and it represents one of the significant cost factors in the production of biomass energy crops (McKendry 2002; Gonzalez et al. 2011). It may be undertaken manually or mechanically depending on production scale, labor and technology availability, and cost. Multi-pass or single pass or whole crop harvesting are generally used for harvesting oil seed crops while lignocellulosic grassy biomass are usually mechanically harvested with equipment like combine, mower, shredder, rake, baler (square or round), windrower, loafer[11] and forage harvester which have different speed of operation and efficiency (ASABE 2006), making the process energy intensive. New harvesting techniques are constantly being developed with single or multi-pass system (Bentini and Martelli 2013). Harvesting and collection generally introduce extraneous matter (e.g. soil), which contaminates the feedstock and leads to process operational problems. The soils are also generally affected with mechanical operations which results in lower yields over the crop cycle.

For crops like sugarcane, a combination of manual, semi-mechanical and full mechanization is practiced in different regions worldwide. For low-density biomass, loafing offers an attractive option since collection, densification and transport can be done with a single piece of equipment. For wet biomass, a field shredder is generally employed to cut the materials into pieces and spread on the field for drying, which is subsequently cut by a mower and placed in swath for immediate bailing. Baling is a conventional key technology used for improving the bulk density of harvested biomass to make handling and storage easier while it simultaneously reduces the risks of deterioration (Forsberg 2000; Gold and Seuring 2011; Stelte 2011; Pirraglia et al. 2012; Lim et al. 2012; Idah and Mopah 2013). Mechanical logging in particular thinning operations are generally opted for harvesting forest biomass (Damen and Faaij 2006; Mabee et al. 2006; Rauch 2007; Gold and Seuring 2011). Cut trees are generally left at harvesting sites for a few months which enables significant reduction in moisture content through natural drying (Yoshioka et al. 2005; Ayoub et al. 2007; Gold and Seuring 2011). Gold and Seuring (2011) reported that baling and chipping can generally be undertaken at harvesting sites or at centralized collection platforms (Thornley et al. 2008) after which the chipped biomass is usually directly processed into bioenergy or converted into pellets for long distance transportation (Hamelinck et al. 2005; Uslu et al. 2008).

11.4.2 Transportation

Transportation (in-field and road) is influenced by many factors including technical, social and environmental impacts as well as the legal and infrastructural framework considered in the management of the supply chain. It is linked to the characteristics of the material, the carrying capacity of the vehicles and the distance to storage areas and the processing plant. Considering the typical locations of biomass fuel sources (farms or forests), the transport infrastructure is mainly road transport which favors short distances and greater flexibility compared with other modes such as train or ship, generally considered for long distance biomass transport.

One of the main economic variables of transport is the travel time which is influenced by distance and speed (Gronalt 2007); distance is related to the routes travelled as well as

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[1] Loafing refers to stack handling which involves collecting residual straw, as an alternative to baling, allowing paddock siding of the material.

the proportion of tilled land and its biomass yield for infield transport (Perpiná et al. 2009; Gold and Seuring 2011) while speed is influenced by road properties and infrastructure, and mode of transportation. Infield transportation moves the biomass to the roadside where it is loaded to road transportation vehicles for conveyance to the factory.

Baling is generally recommended for low-density biomass as a means of reducing costs of transportation, handling and storage (Petrolia 2008). Else, the transportation cost becomes significant in the bio-energy system (Mayfield et al. 2007; Searcy et al. 2007; Gasol et al. 2009; Gold and Seuring, 2011). Gold and Seuring (2011) reported that maximizing truck cycle capacity through increase in biomass bulk density (Hess et al. 2007) and optimizing the utilization of vehicle payload (Möller and Nielsen 2007) are useful options for reducing transport costs.

From an environmental point of view, transportation causes emissions such as particulates matter, nitrous oxide and carbon dioxide which are directly influenced by the distance travelled. The overall legal and infrastructural framework and road properties influence the functioning of a bioenergy supply systems particularly in developing countries where poor road infrastructures may deter investors.

11.4.3 Storage

Storage matches biomass supply with designed plant demand. Thus, the availability of the biomass for year round processing would determine any storage requirement. Most agricultural biomass is available seasonally during the crop harvesting period (Caputo et al. 2005) thus giving a limited time frame for collecting large amount of biomass. This leads to significant seasonal needs of resources, both in equipment and workforce, leading to an increase in the cost of obtaining these resources including their suboptimal utilization, in particular the storage space. For some crops and regions, a single annual harvest may under-utilize the logistics machineries and equipment (Uslu et al. 2008) while requiring more labor compared to perennial harvesting (Thornley et al. 2008; Gold and Seuring 2011).

Biomass storage provides a buffer to the continuous supply of biomass to the processing plant, in particular for feedstock characterized by short harvesting periods. Seeds are typically stored in sealed bins or silos while biomass is transformed into bales or pellets for storage. Gold and Seuring (2011) reported that both open and covered storage may be suitable for baled biomass; round bales can however tolerate only certain levels of exposure to rain and weather compared to square bales which need to be stored in covered areas given that they are more prone to weather damage (Haq and Easterly 2006). Critical choice of the type of storage is needed since storage location and duration of storage are associated with expenses and risks such as biomass quality degradation and dry matter losses (Van Belle et al. 2003; Damen and Faaij 2006; Hess et al.2007; Ayoub et al. 2007; Caniëls and Romijn 2008). This can be done on field, at intermediate storage location or at the processing plant, but the most common type of storage is on-field biomass storage which is usually the cheapest option. On-field storage is however associated with significant biomass losses and uncontrollable moisture leading to technical problems and reduced efficiency in power plants. There are also often health and safety issues, such as danger of spores and fungus formation and self ignition as a result of increased level of moisture in the biomass. Intermediate storage location involves transportation of the biomass twice by road transport vehicles resulting in higher delivered cost. This may add 10–20% to the delivered costs, as a result of the additional transportation and handling costs incurred (Allen et al. 1998). Storage of biomass at factory sites can favor its upfront drying by making use of boiler exhaust heat or flue gas (Rentizelas et al. 2009) prior to their conversion into energy products.

11.4.4 Pretreatment

Pretreatment is generally undertaken to improve the physico-chemical properties of the biomass for enhanced energy productivity and adaptability to the subsequent conversion process, while it also provides a safe option for long-term biomass storage and export. Common pre-treatment techniques are drying and pelletization while torrefaction, pyrolysis and gasification are promising alternatives currently under development.

Drying enables reduction in moisture content of the material, enhances combustion efficiency and improves its resistance to decay and fire risks, while it also reduces handling and transportation costs due to the significant weight reduction that is achieved (Hamelinck et al. 2005; Deswarte et al. 2007; Gold and Seuring 2011). Natural drying such as in-field or ambient drying is less costly compared to upfront factory drying where suitably designed equipment and a source of energy are needed. However, the applicability and effectiveness of natural drying largely depends on climatic conditions (Dunnett et al. 2007). Pelletization results in both moisture reduction and increase in bulk density (Haq and Easterly 2006; Perry and Rosillo-Calle 2008; Uslu et al. 2008; Seebaluck and Thielamay 2010; Gold and Seuring 2011). It also leads to high heating value e.g. wood pellets (Hamelinck et al. 2005; Junginger et al. 2008). Biomass pellets can be kept longer with reduced losses in dry matter (Junginger et al. 2008). However, higher costs are associated with pellets production compared to baled biomass (Haq and Easterly, 2006). Biomass densification technologies are nevertheless receiving considerable attention for their technical refinement and for improving their cost-effectiveness. The quantity of wood pellets traded has significantly increased over the past decade (Vakkilainen et al. 2013) which would most likely intensify in the future to offer possibilities of pellets cost reduction.

The size, moisture content and also the percentage impurities are key factors that determine whether the biomass needs to be pre-processed. Boilers in power plants are often designed for a specific moisture range for optimum efficiency and thus the raw material has to be pre-processed accordingly. Also, whenever co-firing or co-combustion[2] is practiced in the same furnace, a drop in efficiency is usually recorded

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[2] Co-firing or co-combustion is the burning of two different types of materials at the same time. It is generally used to improve the combustion of fuels with low energy content while it provides many other advantages such as reduced emissions, improved efficiency and reduced corrosion, erosion and scaling of boiler equipment.

thus requiring proper design based on the optimum raw material properties. In some emerging processes like the low pressure catalytic depolymerization process for biodiesel production, the biomass moisture needs to be reduced to less than 20% which poses formidable challenges to such projects (Seebaluck 2012). Densification techniques such as briquetting and pelletization thus offer commercial options for increasing the bulk density of the material, as well as for reducing the moisture and size of the materials thereby providing important gains in energy efficiency. However, due to cost constraints, low cost natural field or yard drying options are sometimes practiced. However, they are usually affected by climatic conditions. Emerging techniques such as pyrolysis need further work to define its economic and technical benefits (Jahirul et al. 2012) but carry good prospects for improving biomass energy productivity. There are studies on how to improve the characteristics of specific biomass types for transportation and trade (Sheng Goh et al. 2014) and many others are in progress. On the other hand, impurities such as alkali metals that are normally found in annual and fast-growing crops, can lead to technical problems in power plants. To avoid such situations, the biomass first needs to be pre-treated using a crushing, washing and dewatering process to remove the undesirable impurities to permissible design limits (Seebaluck and Seeruttun 2009).

It has also been shown that biomass moisture varies with the time of harvest and is generally higher for immature crops. Thus, moisture content management can potentially lead to economic and environmental advantages. Models such as the Integrated Biomass Supply Analysis & Logistics model (IBSAL) (Sokhansanj et al. 2006), which uses a dynamic moisture sorption routine, are generally employed to determine daily moisture changes during harvesting operation.

11.5 Challenges, Best Practices and Key Lessons in Biomass Supply Chains

The main challenges in biomass supply chains are the seasonal availability of biomass in varying quantities at rather scattered locations, particularly agro-forestry residues. These make harvest operations costly, for instance biomass characterized by annual single short harvesting periods lead to the utilization of relatively more logistics machineries and equipment over a short period of time thus increasing operational costs, while the material should also be properly stored for year-round processing which again incurs additional cost. These challenges naturally lead to the need for designing cost-effective supply chains operations including proper storage systems in view to ensure continuous supply of suitable feedstock to bioenergy plants.

The topography is an important consideration in supply chains, particularly for modern systems where mechanization is favored. Appropriate available and suitable areas should thus be identified for bioenergy crops cultivation together with suitable machineries developed for the logistic operations. In many cases, the experience acquired from existing crops such as sugarcane can be replicated and adapted to the new bioenergy resources. For marginal areas where bioenergy crops could be potentially grown, appropriate logistic operations should be developed taking into consideration factors such as land slope, soil rock density or types.

Natural drying should be favored as far as possible to reduce the complexity of integrating a front-end drying factory process. This leads to less boiler operational constraints, important gains in energy productivity, improvement in the overall energy balance of the biomass to bioenergy process and reduced production costs. For instance, cut trees are usually left for a few months at harvesting sites for drying while other biomass may be left for around two weeks for natural moisture reduction.

The concept of multi-biomass utilization (biomass co-firing or co-combustion) can offer multiple benefits, leading to total system cost reduction. Biomass co-firing is currently undertaken in many plants globally and its full potential has yet to be fully tapped (Vakkilainen et al. 2013). Significant savings can be realized with respect to storage as the inflow of biomass throughout the year is smoother with multiple biomass thereby putting less pressure on the supply chain, both for equipment and labor. For instance, the simultaneous use of straw and reed canary grass was investigated and a 15–20% cost reduction was obtained simply by using the two biomass sources instead of one (Nilsson 2001). The logistics can however become quite complex, especially when a variety of biomass streams are involved. However, this can be addressed by growing and harvesting selected biomass crops that require similar logistical operations. Crops having almost similar characteristics and fuel properties are also preferred for co-combustion given their adaptability and efficient joint processing in the same energy conversion process. A typical practical example of such application would be the co-combustion of cane bagasse (factory waste) and cane agricultural residues (field waste) in the same furnace (boiler). This would reduce or avoid the use of coal as complementary fuel during sugarcane off-crop season in existing commercial cogeneration power plants, as it currently occurs in Mauritius. It also has a high potential in countries like Brazil where cane agricultural residues are largely available. However, the price of the biomass derived energy has to first be made more attractive.

11.6 Case Studies of Biomass Supply Chains

11.6.1 Sugarcane

Sugarcane is a global commercial agricultural crop that supports the developmental and societal needs of the many tropical and subtropical countries that grow this crop. Traditionally it has been exploited for the production of sugar as a sweetener. However it is now being grown at a large commercial scale to generate multiple products, particularly bioethanol and cogenerated electricity. It has today become the world's most economically valuable bioenergy crop with its potential for producing over 100 metric tons of biomass per hectare annually which is used for the production of food, feed, fuel, fiber and various specialized products (Johnson and Seebaluck 2012).

Harvesting and delivery of sugarcane is a complex and costly operation which requires extensive coordination, especially for large-scale production; it constitutes approximately 40% of the operating cost of cane production with transport accounting for 14% in South Africa (SACA 2010). Sugarcane is unique in that a large amount of fiber is moved to the factory in the course of sugar production, although this fibrous residue is used for power generation. Cane supply management usually involves four types of operators: growers, harvest contractors, hauliers and the mill itself. The logistic operations extend from manual to semi-mechanized as well as fully mechanized options: they generally include burning (for manual harvesting), cutting, loading, in-field transport, trans-loading, road transport, offloading and feeding to the factory. For efficiency improvement, integrated and centrally coordinated processes are favored rather than managing them separately. However, the whole chain can be affected by any change occurring to the individual processes, for instance, harvesting of unburnt cane results in lower cutting rate (in the case of manual harvesting) and higher loading and transport requirements due the additional amount of cane residues, but more fiber is made available in the factory for power generation while the environmental air pollution from cane burning is avoided.

Cane grown in many countries such as in South Africa is burnt prior to harvesting and is generally manually harvested (Purchase et al. 2008). However, environmental regulations together with the increasing importance of cane fiber for electricity generation suggests that reduced burning and increased gathering and use of crop residues will become increasingly common in the coming decades. Such trends are already observed in countries like Brazil, Mauritius and India, where bagasse cogeneration is now viewed as a strategic energy asset. Green cane harvesting with the use of chopper harvesters (full mechanization) favors the availability of sugarcane agricultural residues, but it is generally undertaken in suitable topographies and where upfront appropriate land preparation and cane cultivation have been done. Such an option is possible for large growers or grouped planters. On the other hand, based on figures reported by Meyer and Fenwick (2003), it is found that cutter output is higher for burnt cane by around 25% while it was found that manual harvesting is more expensive than mechanical harvesting (Ahmed and Alam-Eldin 2014). Thus, the use of manual, semi-mechanical or mechanical harvesting would highly depend on cost of labor besides land suitability and the environmental regulatory framework.

Cane supply chains are mainly influenced by the topography: large vehicles enter the fields in flat areas whereas in difficult topographical areas small in-field trailers transfer the biomass to larger road vehicles at loading zones. Tractor-drawn field trailers, rigid chassis and articulated trucks with payloads ranging from 5-30 metric tons are used for cane transport and efforts are geared towards improvements in vehicle utilization through the use of appropriate software. Rationalization of transport equipment and improved coordination can reduce production costs and is a current focus area of industry development efforts. Furthermore, to remain competitive in cane production, its cultivation is being moved from marginal areas to more appropriate land. However, within the production system, the high-cost areas of harvesting and transport could be improved by introducing a logistics benchmarking system and vehicle scheduling software, while emphasis on the design of haulage vehicles is also likely to increase productivity (Johnson and Seebaluck 2012).

Cane residues provide many agronomic benefits (soil protection against erosion, weed control, nutrient recycling and increase in soil carbon) and a few problems (risk of fire, delay in ratoon sprouting and difficulties in some agricultural operations) when left in fields. Burning before harvest may result in long-term decline in productivity, especially for highly erodible and infertile soil. The issues of cane burning, left-over, or collection of the cane residues have received major attention in many cane producing countries and have been assessed with respect to the benefits, soil impacts and economics for energy generation (CTC, 2005; Hassuani et al. 2005; Leal and Hassuani 2006; Purchase et al. 2008; UNDP 2009; Seebaluck and Seeruttun 2009; Johnson and Seebaluck 2012). Harvesting of cane residues requires additional changes to harvesting and transport systems, thus requiring cost assessments that include the economic value of residues and recognize local and regional differences. Assessments based on short-term economics may give different results from those that take long-term crop yield effects into account, but there is normally scope for harvesting of some portion of the non-stalk components of cane without adverse long-term effects.

In an analysis of the electricity generation potential of cane agricultural residues in Mauritius, Seebaluck and Seeruttun (2009) concluded that burning a mixture of 70% bagasse with 30% cane residues is optimum and would involve collecting 35% of the total residues while the rest could be left for preserving the agronomic benefits to the soil. In Brazil, several studies have been conducted on sugarcane straw impacts on soil organic matter (SOM) (Canellas et al. 2003; Razafimbelo et al. 2006; Galdos et al. 2009; Cerri et al. 2013) demonstrating that there is a significant positive impact of the straw on the ground. This was also verified for Australian conditions (Wood 1991). Based on specific field experiments, Braunbeck and Magalhães (2010) showed the importance of straw on soil erosion and soil water retention. Nevertheless, to date, there are no agreed to minimum values of straw biomass to be left in the field as this depends on soil topography and climate.

Straw recovery routes have been evaluated in several field tests and incipient commercial operation in some mills, but the technologies are still in the developing stage and need to be optimized while taking into consideration the local conditions. Three basic systems have been used in these tests: baling, whole cane transport (straw and cane are transported together and separated at the mill in a dry cleaning station) and hay harvester (Hassuani et al. 2005; Leal and Hassuani 2006). The latter approach has been discontinued due to high maintenance costs. Doubts persist about the best system, but there is a tendency to accept that harvester and whole cane system are good systems whereas baling may be better for longer distances (Hassuani 2013). Another advantage of baling is the low straw moisture content of around 10-15% while whole cane system delivers straw with moisture content of the order of 35-40%. The main disadvantages of baling are high ash content (up to 10%), availability of short period for baling after harvest, soil compaction and ratoon damage by the baling machine.

The recovery costs have not yet been consolidated with the literature indicating a wide range of values. Hassuani et al. (2005) indicated costs of US$ 18/t straw (dry basis) for baling and from US$ 14-31/t straw (dry basis) depending on the amount of straw recovered. Perea (2009) gave the recovery cost of straw delivered at the mill gate as R$ 58-63/t (~27.0-29.3 USD/t) for hay harvester, R$ 69/t (~32.1 USD/t) for baling and R$ 31/t (~14.4 USD/t) for whole cane system. However, it was found that sugarcane residues represented a significant amount of biomass that could be made available at the mill at an attractive cost. This material could then be used for surplus power generation, second generation biofuels or other biomaterials production.

11.6.2 Eucalyptus

Eucalyptus is among the fastest growing hardwood plantations widely cultivated for bioenergy in many countries with practical cases in Australia, Brazil, Hawaii, Ireland, South Africa, Uruguay, and Venezuela (Gonzalez 2008). Its conversion technologies are mature and well understood while several others are being developed (Rockwood and Alan 2008). Generally, for wood plant species to be economically viable, it should produce high (or moderate) density wood that easily dries, having suitable chemical characteristics and be easily harvested using appropriate machinery all year round. Eucalyptus largely meets these criteria as it has a high productivity potential over short rotations. It tolerates a wide range of soil types, commonly exhibits straight stem forestry production and, unlike other trees, it does not have a true dormant period and it retains its foliage which enables growth during warm winter periods. However, efficient harvesting of eucalyptus remains a challenge and cost-effective harvesting machinery has yet to be improved in leading eucalyptus producing country such as Brazil (Couto et al. 2011).

Eucalyptus is highly productive in temperate forestry and has yields of 18 m^3/ha/year over 12-year rotation with single species clones (AFOCEL 2003) and up to 35 m^3/ha/year with hybrid clones in France (AFOCEL 2006). Field trials in the US gave rotation length and yields for pulpwood of 5 to 8 years with a mean annual increment of 19.8 to 39.5 green metric tons/ha/year or 10 to 20 dry metric tons/ha/year (Gonzalez et al. 2011). Wood density is important as it largely determines the calorific value per unit volume (Neilan and Thompson 2008) and eucalyptus has denser wood than other species utilized for biomass production over short rotations: Short rotation coppice willow has a wood density of 0.4 Mg/m^3 (Nurmi and Hytönen 1994) whereas Eucalyptus nitens grown on two sites in Australia has a density of 0.471 Mg/m^3 and 0.541 Mg/m^3

respectively (Greaves et al. 1997) while Eucalyptus Gunnii grown in the Midi Pyrenees in France has a density of 0.5 Mg/m^3.

Eucalyptus plantations may yield wood fiber at a competitive cost if the harvesting operations are optimized (Spinelli et al. 2009). Currently motor-manual tree harvesting techniques (using chainsaws) still dominate in eucalypt plantations worldwide. The projected increasing trends and competitiveness in commercial wood supply of eucalyptus create demands for the mechanization of forest harvesting operations as labor becomes increasingly scarce and expensive. Even where motor-manual harvesting techniques are still competitive, there is a general interest to mechanize operations to streamline the timber harvesting process and anticipate future labor shortages.

There are two main options for harvesting and transport of eucalyptus, namely cut-to-length (CTL) and whole-tree (WT) harvesting. The former includes harvester-debarker, CTL timber forwarder and roundwood truck whereas the later is generally comprised of WT feller-buncher, WT forwarder, delimber-debarker-chipper (DDC) and chip lorry. The CTL system is popular in Europe while the WT system is favored in the US (Spinelli et al. 2009). Mechanical felling-processing is the highest cost item in CTL harvesting, representing around 40% of the total delivered cost whereas in WT harvesting, chipping and transportation each account for roughly 36% of the total delivered cost (Spinelli et al. 2009). In Australia, the optimization of the transport scheduling of woodchips for in-field chipping operations was examined and it was found that significant savings could be made in transport and chipping operations (Acuna et al. 2012). Hence, optimization of these process stages could maximize returns.

A WT harvesting system is generally less costly than a CTL harvesting system with the delivered cost being about 20 euro/green metric ton of bark-free pulp chips compared to CTL harvesting which is around 25-30 euro/green metric ton of debarked pulp roundwood (Spinelli et al. 2009). WT harvesting may allow for additional revenues by saving the cost of chipping at the plant and by favoring the cost-effective exploitation of logging residues as a boiler fuel. However, the WT system has its own weaknesses, such as the need for large landing space for parking the DDC unit and the high cost of the equipment.

11.6.3 Elephant Grass/Miscanthus

Miscanthus, a C4 perennial grass, is a promising resource for use as solid combustion fuel given its high yield potential, low requirements for soil tillage, weed control and fertilization as well as the long crop cycle of up to 25 years (Clifton-Brown et al. 2008). It is a fast growing plant with growth rates as high as 40 tons of dry biomass per hectare per annum and can be harvested up to four times a year which makes it a prospective crop for energy use (Strezov 2008). An energy analysis of the crop gave a high energy ratio of 45.3 (Angelini et al. 2009) showing its high bioenergy potential, although the analysis did not take into consideration the conversion of the biomass to energy. *Pennisetumpurpureum*, commonly known as Elephant grass, is equally a potential crop having high biomass productivity that can be used for energy production through combustion (Morais et al. 2009; Morais et al. 2011); it has an average gross calorific value of 18 MJ/kg (Flores et al. 2012). Even if the crop is mainly intended for combustion, there has recently been interest in utilizing it as a feedstock for lignocellulosic biorefining technologies (Haverty et al. 2012; Melligan et al. 2012). However, options for the future use of the crop depend on the economics and environmental performance of its production, supply and processing.

There are two harvesting systems for miscanthus, namely self-propelled forage harvester that harvests and chops the biomass and then blows it into a trailer, and pull-type harvester-baler that delivers large bales. Both harvesting systems are presently used for the collection of miscanthus in Devon (UK), where large-scale commercial production of herbaceous energy crops is undertaken (Smeets et al. 2009). However, the standard method of harvesting involves mowing and baling (Richard et al. 2012). According to OMAFRA (2010) and based on the expected peak yield of miscanthus, the cost of mowing and baling is estimated to be $356/ha.

Storage for an average of six months is required for the continuous availability of miscanthus in power plants. Storage is possible in farm buildings or open air (without covering) or covered with plastic sheets or organic materials. The cheapest and most common option is open air storage with plastic sheeting (Jones and Styles 2008) which is also commonly applied to store silage. Storage in new buildings is expensive, unless existing buildings are used. Open air storage without covering is problematic due to the loss of biomass from decay, whereas open air storage covered with organic material is only attractive when suitable and cheap organic wastes are available, which may not always be the case. According to Lewandowski (2000), covered outdoor storage of chopped or baled miscanthus was adequate to bring moisture content down to less than 20% thereby avoiding costly forced drying of harvested biomass (Gigler et al. 2000) before it could be utilized in small-scale boilers.

Transportation of harvested miscanthus by trucks is the most cost effective option for distances of 100 km or less (Perlack et al. 2002). According to OMAFRA (2010), the costs of hay production, loading, transportation, and unloading of the bales is $61.44/ha whereas the cost of chopping/shredding prior to combustion is estimated based on the use of a hammer mill (Mani et al. 2006).

11.6.4 Palm Oil

Oil palm is an important oil-bearing crop of the tropics with a high outturn of oil per unit area. World palm oil production is on a steep rising path and it is the highest yielding plant among major oil crops producing on average about 4-5 metric tons of oil/ha/year, about 10 times the yield of soybean oil (Choo et al. 2005). In the world market, Malaysia and Indonesia account for 90% of the palm oil export and they will likely remain the key players in the palm oil sector accounting for 28.5 million metric tons or 85% of the world's palm oil production (Sumathi 2008). Besides producing oils and fats, there is increasing interest for oil palm renewable energy namely bio-diesel production.

Crude palm oil is found to be the most attractive feedstock for industrial production of biodiesel (Vanichseni et al. 2002;Sumathi 2008). The attractiveness of palm lies in its high yield of oil which by far exceeds that of other vegetable oils. Moreover, its production cost is lower than other vegetable oils (Tan et al. 2009; Basiron et al. 2004; Boons and Mendoza 2010). Palm oil production is rapidly expanding due to the food sector increasing demand in developing countries mainly India and China while a minor fraction of around 12% is used as biodiesel.

Fresh fruit bunches (FFB) of oil palm can be harvested mechanically but are mostly harvested manually with some machinery and farm equipment while trucks are used for its transport. The first harvest is generally undertaken after five years of the plant cycle which is more than 30 years; however, it is generally replanted after 25 years because it starts getting too tall for convenient harvesting (Thapat 2008). Young palms are harvested with a chisel whereas along-handled sickle is used for tall palms and there is no fossil energy input to harvesting (Shabbir 2009). Workers usually carry the bunches to the road and load them in trucks for transportation to processing units. Pleanjai and Gheewala (2009) estimated the transportation fuel energy to be 7 GJ/ha.

Palm oil mills are generally located close to the planting areas to allow transport of harvested fresh fruit bunches within 24 hours to avoid excess generation of free fatty acid and to have a reasonably high oil extraction percentage (Shabbir 2009). During the process of oil recovery, waste biomass in the form of empty fruit bunches, fibrous fraction and shells can be used as fuel for the boiler house.

11.7 Concluding Remarks

Biomass supply chains involve critical elements that influence the viability of biomass to bioenergy projects. Some crops, such as sugarcane, provide useful experience regarding biomass supply for bioenergy production, although it is likely that further optimization in the logistic operations can bring added improvements. Thus, given the key multiple roles that bioenergy development could play in many world regions and its pressing need, key lessons could be derived from existing commercial biomass supply chains. This would be done to capitalize, replicate or adapt them to new and emerging bioenergy crops or for the desired modernization of the logistic operations of many energy crops that are so far underdeveloped. Generally, the main issue for an optimum biomass supply chain is to ensure a stable and continuous supply of suitable feedstock at competitive prices. This will require correctly designed cost-effective sustainable biomass supply chains. Scales of bioenergy crops production play a crucial role in the development of efficient and cost-effective supply chains as well as the overall bioenergy systems. However, given that bioenergy crops could also be potentially grown in rather smaller land areas, appropriate logistics operations should be developed to tap such potential as well as the associated socio-economic benefits. Therefore, it becomes important to provide technical and financial supports to innovate efficient biomass supply systems that are fully compatible with different production scales, the feedstocks quality and their processing.

11.8 Recommendations

- Existing biomass supply chains for bioenergy production should be modernized and optimized to improve the competitiveness of bioenergy projects.
- Key lessons should be learnt from existing efficient and cost-effective supply chains, and disseminated for application to other energy crops.
- Emerging tools (e.g. Agro-Ecological Zoning (AEZ)) should be used for identifying appropriate land for bioenergy production. Appropriate topographies would facilitate use of mechanized operations, which are appropriate for large-scale production. For marginal areas where bioenergy crops could be potentially grown, appropriate logistic operations should be developed, particularly in areas where the scale of production would be rather smaller but which may be associated with important socio-economic benefits.
- The overall legal and infrastructural framework necessary for the proper functioning of a bioenergy supply systems should be enhanced in particular for developing countries where poor road infrastructures may deter investors.
- The synergies or nexus of supply chains with other steps involved in biomass to bioenergy production (mainly agriculture and industrial processing) should be developed and optimized, for instance by adopting appropriate agricultural practices or by delivering raw materials that could be directly processed without pre-treatments.
- To alleviate the challenges of crops seasonality, adequacy of raw materials and year-round use of equipment and labor, appropriate cost-effective storage systems should be designed while other more practical options like multi-fuel processing (co-combustion or co-firing) in energy plants should be enhanced.
- Natural biomass drying should be favored as far as possible to avoid complex energy-intensive and costly front-end processing in factories which would also affect the overall energy and environmental balance of energy production from biofuel crops.
- Appropriate simulations and software should be used to facilitate the optimization of the structural units in the supply chains and improve the cost-effectiveness of the bioenergy system.
- All fractions of biomass crops (harvested part up to field residues) should be fully utilized as far as possible. The appropriate mass, energy and environmental balances should be undertaken to assess the potential and benefits.
- Technical and strategic options for decentralizing the activities involved in biomass supply chains should be developed to provide small scale entrepreneurship opportunities such as biomass densification (briquetting, pelletization or torrefaction) for sales to power plants.

- Efficient transportation systems that use less fuel, reduced fleet size as well as producing less GHGs emissions through the use of renewable fuels (bioethanol or biodiesel) should be promoted; it would improve the overall energy and environmental balances of the bioenergy project.

11.9 The Much Needed Science

- Specific tools using GIS and AEZ should be developed to identify suitable and available areas for bioenergy crops cultivation including subsequent efficient crop handling.
- Alternative modes of harvesting and transportation should be investigated in terms of energy use, environmental impact and their economics to indicate the best options for different world regions having different economical context. Typical supply chains for bioenergy crops production in marginal areas should be developed taking into consideration the specificity of the lands.
- The socio-economic impacts of scale of bioenergy crops production on the development and design of appropriate supply chains and the overall sustainability of bioenergy systems should be investigated given that small to medium scale bioenergy projects would much likely contribute in tapping the full bioenergy potential in many world regions.
- The internal or captive use of renewable energy, in particular biomass based fuels, as is the case in bioenergy processing plants, should be investigated and promoted in biomass supply chains to make the overall biomass to bioenergy system sustainable.
- Appropriate biomass densification techniques and equipment that can handle multiple types of biomass should be developed and deployed for field operations to improve transportation and storage for upfront processing. Other techniques such as pelletization should be deployed while emerging ones like torrefaction should be investigated with respect to its technical performance and economics.
- The appropriate fraction of biomass residues that should be left in fields for preserving the agronomic benefits should be investigated for specific crops to provide opportunities for collecting part of it for bioenergy production. The nutrients obtained in the form of ash or sludge in processing plants should be investigated for their potential reuse or recycling to fields as good sustainable practices.
- Multi-fuel processing (e.g. co-combustion or co-firing of several biomass types in a single furnace) in flexible plants should be investigated based on the physico-chemical properties of biomass collected, handled and sent to processing plants.

- Low cost in-field biomass drying options should be investigated in an attempt to reduce any equipment and energy-intensive upfront processing in bioenergy processing plants; on the other hand moisture tolerant conversion technologies should be developed.

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