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Sustainability of Sisal Cultivation in Brazil Using Co-Products and Wastes

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Abstract

This work evaluates the potential of co-products from sisal fiber extraction and of plant residues at the end of the productive life cycle and their upgrading into bioproducts and biofuels, focus on Brazil, and, specifically on the Sisal Identity Territory in the state of Bahia. Sisal co-products and residues are identified and quantified; Environmental and socio-economic indicators are applied. Energy potential and bioproducts from sisal in Brazil have been studied in universities and research centers, but not sufficiently quantified, so the scientific bases for this purpose are still limited. Considering an annual sisal fiber production in Brazil at 100,000 MT, and a 4% yield from the fiber extraction process, an estimated 2.4 million metric tons of products are thus generated by the defibering process, consisting of pulp, sisal tow, and juice. Furthermore, an estimated 900,000 metric tons per year of residual biomass from the stems at the end of the 10-year productive cycle is produced and presently left to rot in the field.

Keywords: sisal, *Agave sisalana*, sustainability, co-products, residues, biofuels, bioproducts

1. Introduction

Brazil is the largest producer and exporter of sisal fiber. Sisal provides a livelihood for approximately 700,000 people in 38 municipalities in the State of Bahia, where about 95% of Brazilian sisal is produced (CONAB, 2012). Sisal may be grown on marginally productive lands in semiarid regions not suitable for other crops. Its cultivation and processing are labor intensive (Dellaert, 2014) and provide a livelihood for the population of one of the poorest regions in the country. The sisal-producing region has hydric deficit all year round, with constant drought risk. Raw sisal fiber in Bahia is obtained through dry decortication, using traveling diesel-operated decorticators. Co-products from this operation can be separated into pulp (made up of the cuticle and parenchymal tissue), sisal tow (short fibers), and juice (chlorophyllous sap). The long sisal fiber obtained by decortication represents only 4% of the weight of the leaves processed; therefore 96% of the leaves is left on the ground. Life cycle is 8 to 10 years, after which the plant flowers and dies. Productivity in the Brazilian sisal-producing region is low: less than a metric ton of dry fiber yearly per hectare. About two-thirds of sisal farms have less than 10 hectares, and only 4% cover more than 100 hectares (IBAM, 2007). Considering an average annual production in the past six years of 100,000 metric tons of sisal fiber (FAO, 2013) and a 4% fiber yield, 2.5 million tons of sisal leaves were processed, and 2.4 million tons of decortication residues produced and wasted. Furthermore, at the end of the plant life cycle, 10% of the area under cultivation is replanted. Taking 120,000 hectares planted with sisal in Brazil, a density of 5,000 plants per hectare (Silva, 1999) and a weight of 15 kg per residual stem, a total of 900,000 metric tons of residual biomass will be produced annually.

The present study evaluates the theoretical and technical potential for the production of bioproducts and biofuels from the agricultural residues of sisal fiber production. Estimates of the amount of co-products and bioproducts, and the application of sustainability criteria are based on interviews with stakeholders in the sisal sector. A detailed study of available scientific literature and technical and scientific reports published by institutions involved with sisal was also carried out. For the evaluation of the potential for sustainability, indicators were chosen based on criteria developed by the *Roundtable on Sustainable Biofuels* program (RSB, 2011). This study analyzes the production of animal feed, fuel briquettes, fungicide/bioinsecticide and agave nectar and/or inulin.

The use of these co-products and residues represents an opportunity to ensure additional income to the sisal farmer, employment and income generation and a guarantee of sustainability for the sisal productive chain, which is not attainable with the present scheme of just producing long sisal fiber for use in conventional applications.

This study focuses on the study of the potential for sustainability of sisal cultivation through the upgrading of co-products of fiber extraction as well as of residual biomass at the end of the productive cycle, and in the application of sustainability indicators based on a selection of criteria proposed by the *Roundtable on Sustainable Biofuels* program (RSB, 2011).

2. Methodology

Qualitative and quantitative data were collected *in situ* through a survey of information in the sisal region, in interviews with the main stakeholders, through consultation with government agencies and the private sector and through research in the scientific literature and technical reports by organizations working with sisal. The study focuses on the Sisal Identity Territory where the commercial center of sisal in the state of Bahia is located and where the main processing enterprises are located, as well as organizations with an interest in the development of the sisal productive chain. The interviews included a sisal company exporter, sisal producers, Sustainable Development Association and Solidarity of the Sisal Region - APAEB, Natural Fiber Association (Sindifibras), consultants and academia. Documents were consulted produced by government agencies such as Secretariat of Science, Technology and Innovation of the state of Bahia - SECTI, Brazilian Agricultural Research Corporation (Embrapa), Agricultural Research Corporation of the state of Rio Grande do Norte - EMPARN and Food and Agriculture Organization - FAO, and research reports in the scientific literature. The amounts of co-products from the defibering of sisal leaves were estimated from the average productivity of sisal fiber per hectare, the sisal total area cultivated in Brazil and personal communications obtained in pilot plant studies for recovery of sisal juice (Campbell, 2014). The amount of residual biomass obtained from the plant stem was estimated assuming the planting density practiced in Brazil and the stem average weight at the end of the productive life cycle of the plant. Assessment of environmental risks, social and rural development and food safety are based on the selection of sustainability criteria of the *Roundtable on Sustainable Biofuels* [RSB] that defines twelve principles based on aspects of social and environmental sustainability (RSB, 2011). It was selected six principles: greenhouse gas emissions, water use and quality, biodiversity, soil health, social and rural development and food security, as used by Terrapon-Pfaff et al. (2012).

3. Sisal Growing in the World and Brazil

3.1 Sisal Growing in the World

In countries such as China, Tanzania and Kenya, the productive system is more advanced than in Brazil, and is characterized by large estates with a greater degree of mechanization and more advanced agricultural techniques. Decortication is done in large continuous feed machines using a large amount of water injected in the rotors, about 100 m³ per metric ton of dry fiber (Terrapon-Pfaff et al., 2012; Medina, 1954). This facilitates the removal of traces of parenchymal tissue, and improves the quality of the sisal fiber produced. However, this technique generates a large amount of residual water which is kept in lagoons or discarded in rivers. This mode of operation has caused environmental problems due to generation of greenhouse gases, such as methane, brought on by anaerobic digestion, as well as the consumption of large amounts of water, not always plentiful at the processing site. Discarding wstewater from decortication has caused pollution of waterways as well as noxious effects on the aquatic fauna (Terrapon-Pfaff, 2012). In China, where sisal cultivation is mechanized and technically advanced, decorticators are similar to those in Tanzania, but their design is more modern, the units being more compact and efficient. Decortication also uses water, but in smaller quantities compared to Tanzania. World sisal production is shown in Figure 1.

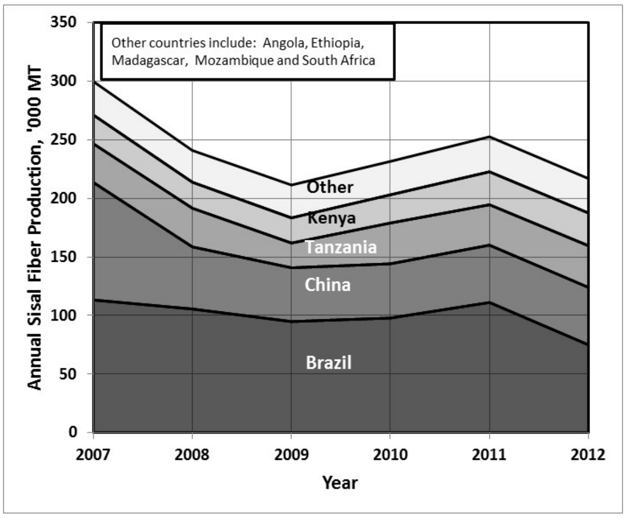

Figure 1. Sisal fiber production

Source: FAO (2013).

3.2 Sisal Growing in Brazil

Brazil is the largest producer and exporter of sisal fiber. Production occurs in the Northeast region of the country and provides a livelihood for about 700,000 people (CONAB, 2012). The state of Bahia is responsible for 95% of Brazilian sisal production which is carried out in 38 municipalities located in three Identity Territories, (an official denomination for regional identification). These territories are semiarid regions, poorly suited for other crops. Sisal growing and processing are labor intensive activities (Dellaert, 2014) and provide a livelihood for the population of one of the poorest regions in the country. These regions present high insolation rates and hydric deficit all year round, with constant drought risk (Silva, 1999). Sisal grown in Brazil is of the *Agave sisalana* Perrine species, originally from the Yucatan peninsula in Mexico. The productive system is based on small plots, in a family farming environment. Nearly two-thirds of the sisal farms in the region have less than 10 hectares, and only 4% are estates larger than 100 ha (IBAM, 2007). The decortication process is carried out using traveling diesel-operated decorticators, of unsophisticated design and using diesel motors. Leaves are fed manually and no water is utilized. Processing capacity is low, about 15 to 20 kg/h dry sisal fiber (Silva, 1999). Decorticators used in Tanzania and China have a production capacity of 400 to 800 kg/h (Lock, 1969).

In present practice the sisal grower and farm owner, contracts decortication services with the owner of a decorticator, locally known as "motor", whose working team consists of 5 persons, each entrusted with a specific task in the decortication process. The raw fiber produced is dried and a middleman typically transports it to brusher installations where residues adhering to the fiber are removed. The owner of the brusher then sells the fiber to the final transformer or exporter (Boaventura, 2015). Figure 1 shows the Brazilian sisal fiber production in the last six years. The reduction in Brazilian production may be attributed to prolonged drought, as well as reduced profits for the farmers, which have reduced any incentive for starting new sisal planting.

4. Quantitative Estimates of Co-Products and of Residual Plant Biomass at the End of the Productive Cycle

4.1 Products and Co-Produts from Sisal Fiber Extraction

Estimates of the amount of co-products from decortication and of residual biomass at the end of the plant's productive cycle will be based on 100,000 metric tons, the average annual sisal fiber production in Brazil over the last six years (FAO, 2013). According to the material balance provided by Campbell (2014), the amounts of co-products are shown in Table 1, which covers the production of long fiber, dry pulp, juice, and sisal tow.

Table 1. Average product and co-products (last six years)

Product/co-product	MT	%
Long fibre	100,000	4
Dry Pulp (*)	150,000	6
Juice	1,500,000	60
Tow	20,000	0.8
Water (difference)	730,000	29.2
Total	2,500,000	100.0

Note. (*) 15% humidity.

Source: Campbell (2014).

4.2 Residual Biomass and Sap at the End of the Plant's Productive Cycle

As there is no precise information of the productivity of sisal fiber in Brazil, we shall adopt an estimate of 1 metric ton/hectare/year. According to Silva (1999), planting density used in Brazil is 5,000 plants per hectare. Plant cycle considered is 10 years. The average weight of a fresh stem before floral stem growth is estimated at 15 kg. It is estimated that 10% of the planted area is renovated annually, which means replanting of 12,000 hectares/yr. Therefore the total weight of the fresh stems left to rot in the fields annually amounts to 900,000 metric tons.

According to Mapinda (2015), every 5 kg of fresh stem can yield 1 kg of syrup. Therefore syrup production potential is 180,000 MT/yr. According to estimates (Miranda-Ham et al., 2008) the inulin content in Agave fourcroydes syrup is 26 mg/g (D.W.) which translates to a potential inulin production of 4,680 MT/yr, besides other sugars present, assuming these numbers apply to *Agave sisalana*.

5. Bioproduct and Biofuel Generation Potential

Proven and potential uses exist for the use of co-products from decortication and residual biomass. Tested applications include the production of animal feed from leaf pulp and sisal tow, and the production of briquettes from plant stems. Laboratory results for other potential applications have to be confirmed in a larger production scale in order to determine their feasibility. They include the production of fungicide and bioinsecticide from sisal juice and the production of agave nectar and/or inulin from the fresh stem at the end of the plant's productive cycle.

5.1 Production of Animal Feed from Sisal Pulp and Tow

A potential application of sisal pulp is its use in animal feed formulation, considering that one of the most important limitations to animal husbandry in semiarid regions is the scarcity of fodder. As shown in "Products and co-products from sisal fiber", the yield of dry pulp after juice removal by pressing and sisal tow separation is 6% of leaf weight. The use of fresh sisal bagasse as animal feed has been attempted, without success (Herrera et al., 1980), partly because of its oxalic acid content. The soluble carbohydrates in the pulp also ferment rapidly and produce lactic acid, increasing acidity and reducing palatability and nutritional value (Preston & Leng, 1987). Gebremariam (2008) carried out a study on sun-dried sisal pulp as feed for ruminants in Eritrea. A base diet of barley straw was provided *ad libitum* and further enriched with several levels of sisal pulp and cottonseed cake. This study concluded that sisal pulp was effective as a supplement in sheep feed, that live weight increased with increasing amounts of dry sisal pulp, and that the best results was obtained with the addition of a small amount of cottonseed cake. According to Holanda et al. (2009), during dry spells in northeastern Brazil, goat daily live weight loss is estimated at 25 grams. These authors also evaluated the enrichment of sisal pulp on goats. Sisal pulp is poor in phosphorus, but rich in iron and calcium. It also contains zinc, copper and manganese levels adequate for goat feed. Final feed formulation included 5% urea and 3% MAP (monoammonium phosphate). Enriched feed thus achieved 19.8% raw protein. Average feed consumption was 1,326 g/day/nanny goat and 600 g/day/kid goat. Average milk production was 623 ml/day and average live weight gain, 175 g/day/kid. Sisal tow may be used for geo-blankets or in plasterboard manufacture, but these applications require washing and further tow processing. A more immediate use, which is recommend in this work, is as feed bulk, which may be added to sisal pulp after comminution in a hammer mill. Table 2 shows dry sisal pulp availability and its enrichment with urea and MAP used in the production of animal feed.

Table 2. Production of animal feed from sisal pulp

Description	Value	Units
Dry pulp (15% humidity)	150,000	MT/yr
(Urea + MAP) (*)	12,000	MT/yr
Enriched Pulp	162,000	MT/yr
Price of enriched feed	233.30	US$/MT
Cost% of additives (Urea & MAP)	13	%

Note. (*) Monoammonium phosphate.

5.2 Briquette Production from Sisal Stems

As shown in "Quantitative estimates of co-products and of residual plant biomass at the end of the productive cycle", 900,000 metric tons of fresh sisal stems are produced yearly at the end of the 10-year productive cycle. These stems consist of cellulosic material and a sap which contains considerable amounts of complex sugars (Miranda-Ham et al., 2008). The cellulose portion can be used for the production of briquettes which can be burned in boilers and industrial furnaces substituting firewood as a fuel. In northeastern Brazil firewood is typically produced clandestinely from scarce natural vegetation. Such deforestation constitutes an environmental problem and contributes to ecological unbalance in the region. In Mexico, briquettes are presently produced in an industrial unit from the stems of *Agave tequilana*, after sugar extraction for tequila production (Lippel, 2014). The stem, after sap extraction, must be comminuted and dried to 10-12% humidity. The dry material is processed in compactors to produce briquettes having a heating value of 4,600 to 5,100 kcal/kg (Patrik, 2015). Table 3 shows the potential production of briquettes from sisal stems, the heating value of the briquette, and energy generation potential per hectare.

Table 3. Briquette production from sisal stems

Description	Value
Available Biomass (70% humidity, MT/yr)	900,000
Raw material for briquette production (12% humidity, MT/yr)	306,818
Briquette production (2% humidity, MT/yr)	275,000
Heating Value, kcal/kg	4,600
Energy potential for briquette production in Brazil, Gcal/yr	1.27×10^9
Energy potential for briquette production in Brazil, Gcal/ha	1.06×10^5
Ash production (1.5% of briquette weight) (MT/yr)	4,125

5.3 Other Applications ― Fungicide and Bioinsecticide from Sisal Juice

According to the calculations shown under item "Quantitative estimates of co-products and of residual plant biomass at the end of the productive cycle", the amount of sisal juice produced in the state of Bahia, considering an average yearly production of sisal fiber of 100,000 MT (FAO, 2013), is about 1.5 million metric tons. Technical reports (SECTI, 2009) on sisal co-product utilization describe research showing the potential for the production of fungicide and bioinsecticide from sisal juice. Two different products were obtained, one from juice centrifugate, the other from an aqueous extract of dried decortication residue. Laboratory experiments indicated a yield of 13 kg of active substance per metric ton of juice, 98.7% of the material processed being returned to the soil as nutrient replenishment. *In vitro* tests with this material at São Paulo State University - UNESP, described in SECTI (2009) showed its effectiveness as fungicide against Candida albicans (an infection-causing fungus) and against Malassezia pachydermatis (a yeast causing dandruff and other skin ailments). The bioactive agent presently used against Malassezia pachydermatis is ketoconazole, 146,589 kg of which were imported by Brazil from January 2010 to December 2014 at a FOB cost of US$ 9,368,433 (MDIC, 2015).

The aqueous extract of the dried decortication residue was effective against Brevipalpus phoenicis – red and black mite, producing 100% mortality in 12 hours. This mite is vector of the citrus leprosis virus, a major disease in citrus orchards. The remaining solid residue can be used as animal feed. Complementary testing, however, is required to confirm this application. The sisal raw materials for these applications can be obtained at the decortication site using simple techniques, preserving scarce resources (water, firewood, soil nutrients); solar energy may be used for the drying steps. These initial laboratory results require further experimentation in a pilot plant scale, as well as *in vivo* testing.

5.4 Other Applications − Sisal Nectar/Inulin from Fresh Sisal Stems

The sap in the sisal stems at the end of the productive cycle is rich in sugars, especially fructans, fructose polymers whose general chemical structure is a glucose molecule attached to multiple fructose residues (Miranda-Ham et al., 2008). They are not hydrolyzed in the stomach or the small intestine. This fosters low sugar blood levels and allows their use in diets for diabetics and in low-calorie diet foods. Preliminary studies with *Agave fourcroydes*, a species similar to Agave sisalana (sisal) indicated the presence of fructans with varying degrees of polymerization (Miranda-Ham et al., 208), with contents of 26 mg/g (D.W.) in some periods of the year. Presently the main commercial sources for fructan production of the inulin type are chicory roots (Cichorium intybus), dahlia (Dahlia pinuata), as well as Jerusalem artichoke (Helianthus tuberosus) (Miranda-Ham et al., 2008). Inulin is presently produced commercially in Mexico from *Agave tequilana* and production results have been obtained with *Agave americana* in South Africa (Boguslavsky et al., 2007). Brazil imported, from 2010 through 2014, 2.6 MT of inulin at a FOB cost of US$ 8,293,777 (MDIC, 2015).

6. Environmental Risk Evaluation

6.1 Greenhouse Gas Emissions

The process for sisal fiber extraction used in Brazil does not consume water; the co-products are left at the decortication site to dry and rot in the sun. Generally the raw pulp left on the ground serves as cover and nutrient for the surrounding soil, but there is no uniform distribution of this material in the sisal field. Studies by Holanda et al. (2009) show the presence of nutrients in the juice that act as fertilizers. Juice separation from the raw pulp is carried out using manual presses. Processing of the plant stem at the end of the productive cycle does not contemplate sap separation, due to lack of detailed information that would allow building of commercial units. As mentioned before this sap is a potential raw material for the production of agave nectar and/or inulin.

CO_2 emissions were calculated based on a production module consisting in two traveling decorticators, as described earlier. Production capacity considered was 20 kg/h dry fiber, operating 8 hours/day and 250 days/yr. Considering a 4% dry fiber yield with some losses and juice removed by pressing, a total of 850 MT/yr of pressed mucilage are to be transported from the field to the final processing site, a distance estimated at 10 km. The pressed mucilage, along with the sisal fiber, are transported in a dumpster truck consuming 0.25 liter of diesel/km. CO_2 emissions were taken as 2.64 kg CO_2/liter of diesel, which corresponds to 41.3 kg CO_2/MT of dry fiber.

CO_2 emissions during decortication were calculating with a 7.3 kw diesel motor, consuming 0.31 l/kw-h (stationary diesel motor 10,5 HP, 2300 RPM). Under these conditions CO_2 emissions amounted to 149 kg CO_2/MT fiber.

Production of the briquette press was 1.5 MT/h at 2% humidity. Considering a planting density of 5,000 plants/hectare and 15 kg as the average weight of a sisal stem, the weight of stems to be transported a distance of 10 km by dumpster truck was calculated and the CO_2 emissions were calculated. CO_2 emissions were calculated at 8.8 kg CO_2/MT briquettes.

For CO_2 emissions during briquette burning, information for wood burning was used (109.6 kg CO_2/GJ) along with the heating value of the briquette (4,600 kcal/kg). The final value was 2.11 MT CO_2/MT briquette. The results of these calculations are shown in Table 4.

Table 4. CO_2 Emissions per processing step

Step	Value
Decortication, Kg CO_2/MT fiber	149.0
Pulp and fiber transportation, Kg CO_2/MT fiber	41.3
Stem transportation, Kg CO_2/MT stems	8.8
Briquette burning, MT CO_2/MT briquettes	2.1

6.2 Water Use and Quality

Sisal is a drought-resistant plant, not requiring irrigation and surviving prolonged dry spells. As was previously described, the leaf decortication process does not employ water and uses a traveling decorticator powered with a diesel engine. Therefore water consumption for decortication is negligible. In the semiarid region where sisal is grown, annual rainfall is 800-1000 mm, with long dry spells. Local rural population uses water from tube wells (Carmo, 2015). A program of the state of Bahia government, called Agua para Todos (Water for All) contemplates water supply for the population not yet served by tube wells, who presently use intermittent rainwater collected in tanks. Therefore, given the nature of the species and the dry decortication process used, water is not a problem for environmental sustainability in this case.

6.3 Biodiversity

According to RSB (2011) norms, operations with biofuels should avoid negative impacts to biodiversity, to ecosystems and conservation values in the environment. Some of the main causes for biodiversity loss are: destruction and reduction of natural habitats, introduction of exotic and invasive species, excessive exploitation of animal and plant species, soil, water, and atmospheric pollution. Even though sisal is not a native plant (it originates from Yucatan, in Mexico) it adapted well to the soil and climate of northeastern Brasil. Its commercial cultivation has been carried out in a monoculture regime for decades. It does substitute natural vegetation but has the advantage of leaving the residues of fiber processing and other plant residues on the ground. In addition to sisal cultivation small landowners generally keep part of their land for food crops, such as beans, manioc, and maize. Although Brazilian conservation legislation mandates that landowners in the caatinga region (where sisal is cultivated) preserve 20% of the native vegetation, compliance is not adhered to by all farmers, due to lack of knowledge, lack of enforcement (Cunha, 2010), or because they reason that in the small plots they generally work, such preservation would deprive them of additional gains obtained with subsistence food crops. Growing sisal for fiber is not an economically viable operation (Dellaert, 2014; Silva, 2003). For this reason some farmers are converting to goat farming as an additional source of revenue. Accordingly, (Cunha, 2010), deforesting has been observed in the Sisal Identity Territory, where 52% of the land is planted with sisal (IBGE, 2013). Table 5 shows some biodiversity indicators relating to sisal growing and the sisal ecosystem.

Table 5. Biodiversity indicators

Indicator	**Value**
Land used for sisal cultivation in the Sisal I. T. (*), ha	118,310
Land used for other crops in the Sisal I. T., ha	111,117
Land with sisal harvest in the Sisal I. T., ha	68,820
Land with other crops harvested in the Sisal I. T., ha	102,133
Number of sisal plants per hectare	5,000
Fertilizer use	none
Pesticide use	none

Note. (*) I. T.: Identity Territory (region characterized by sisal cultivation).

Source: IBGE (2013).

6.4 Soil Health

Operations involving biomass should adopt practices to reverse soil degradation and/or maintain its health (RSB, 2011). Soil quality has deep effects on the health and on the productivity of a given ecosystem and related environments. Agricultural wastes make an important contribution in supplying nutrients for carbon preservation and soil fertility. It is important that a balance be kept between the amount of residue that should be removed and that which should be kept on the field to maintain nutrient equilibrium (Terrapon-Pfaff et al., 2012). Sisal is a crop cultivated in Brazil for decades in monoculture, with no added fertilizer or pesticides, given the absence of diseases that may affect its production. Not only are all the decortication residues left on the sisal fields, but the plant stem at the end of the productive cycle is also left there, along with invading plants, which also serve as soil fertilizers. According to Cunha (2010) deforestation of native vegetation has been practiced and justified by the expansion of grasslands and food crops, as well as goat raising, that, along with sisal growing, tend to increase the consumption of soil nutrients. The separation of pulp for animal feed production will produce a large amount of juice, which can serve as a fertilizer through fertirrigation, as it contains substances that will help restore soil nutrients (Holanda et al., 2009).

7. Social and Rural Development

Studies by Silva (2003) already indicated the economic unfeasibility of sisal growing for farmers with less than 14 hectares, which, at the time, represented 71% of the total area planted with sisal. According to the same author, the economic gain for the sisal farmer amounted to only 65% of the minimum wage. Lack of effective public policies and frequent prolonged droughts have contributed to a decrease of interest in sisal growing. Some companies that manufactured sisal products in the region have closed, causing unemployment. There are, however, positive social aspects, as workers can organize in rural unions and government Social Security can offer benefits in case of sickness, as well as disablement and retirement pensions. A more recent study (Dellaert, 2014), on the sustainability of sisal cultivation in Brazil used the life cycle evaluation technique involving the three pillars of sustainability: social, environmental and economic. The study considered only the production of long sisal fiber and its utilization by the auto industry; it did not consider the use of decortication co-products or residual biomass. It concluded that most salaries lie below the minimum wage practiced in Brazil. It also pointed out that the largest environmental impact (55%) was caused by the inefficient use of decortication equipment, and, that there is ample space for improvement, when compared with the process used in Tanzania. It also determined that labor accounts for 82% of fiber production costs.

Under the present Brazilian mode of operation, the farmer hires the services of the owner of a decorticator and receives from 25 to 30% of the price paid for the raw sisal fiber (Boaventura, 2015). According to Silva (2003) this payment is not sufficient to cover the farmer's expenses, which may make the operation economically unfeasible.

If pulp is sold to animal feed producers, the farmer will have additional gains. At the end of the productive cycle, the farmer may also sell the sisal stem for briquette production, after sap removal. Additional revenue may be garnered in the future by selling the decortication juice for fungicide and by the sale of sap from the stem for the production of agave nectar and/or inulin. This additional gain may be shared with the owner of the decorticator and all his team. These activities will bring economic benefits to the farmer who will now have an additional gain from the sale of the sisal pulp and plant stems for the fabrication of briquettes. In the medium term revenue may be also earned through the use of the leave juice and stem sap, which will create additional jobs, and help prevent rural exodus to the cities due to lack of employment. Information in Table 6 was calculated using a decorticator producing 40 MT of dry sisal fiber per year. Total labor involved in this operation is 11 people: 5 operate the decorticator (leaf cutting, transportation, decortication, residue disposal, fiber drying); 4 are needed for mucilage pressing and enriched mucilage processing (1 in the field and 3 in the mucilage enriching unit), 1 driver and 1 helper. Considering a yearly production of one metric ton of dry fiber per hectare, the production of 40 MT/yr of fiber requires 40 hectares of planted area. For an area of 1,000 hectares, therefore, 275 people will be required for the decortication and mucilage enriching operation.

The briquetting production will be 1.5 MT/h of briquette. The amount of stems required will therefore be 8.000 MT/yr. Labor required to uproot and fill 8 4-MT dumpsters was estimated at 32 people, plus a driver and a helper. For briquette production four people were considered, making a grand total of 38 people. The planted sisal area required to provide feed for the briquette machine is 107 hectares/yr. By extrapolation, we arrive at a total labor requirement of 356 people for 1,000 hectares planted with sisal.

Table 6. Income and Employment Generation Indicators by productive activity

Indicator		
Employment – enriched pulp		275 persons
(decortication, transportation, processing — per 1,000 ha)	Operating mode	8-hour shift/day
Employment – briquette		356 persons
(uprooting, transportation, processing — per 1,000 ha)	Operating mode	8-hour shift/day
Fungicide from sisal leaf juice		Still undefined
Agave nectar and/or inulin		Still undefined

8. Food Security

Sisal farmers, mostly small (less than 10 ha) landowners usually reserve part of their plots for subsistence agriculture and for goat rearing for their own consumption and sale in the local market. Due to soil and weather conditions in the sisal region, to the scarcity of rain and long dry spells as well as low soil fertility, these lands are not suitable for commercial exploitation of food crops. There are no forecasts for an increase in the area planted with sisal. It is highly unlikely that the marginally fertile areas used for sisal would be used for commercial food crops. A large amount of people (around 700,000) are involved, directly and indirectly, with sisal growing and transformation, (CONAB, 2012) and depend on this crop for their livelihood.

Subsistence agriculture of crops such as beans, maize, and manioc (Cunha, 2010), as well as goat rearing should guarantee the sisal farmers' food supply, aided by the state government Water for All program. The production of animal feed from sisal pulp may foster goat rearing in the region, both for family consumption and sale, considering that food shortage for animals is one of the main obstacles for this activity, particularly during droughts.

9. Impacts of the Environmental and Socioeconomic Sustainability Potential

Table 7 presents a summary of environmental and socioeconomic aspects discussed in this work.

Table 7. Environmental, socio-economic effects and environmental sustainability

Sustainability Principle		Sisal Agricultural Residue Uses
Environment	Greenhouse gases	CO_2 emission by briquette burning replaces CO_2 emission by firewood burning and avoid environmental problem
	Water use and quality	Minimum use, scarcity, non-irrigated crop
	Biodiversity	No significant changes
	Soil health	Nutrient replenishment with juice
Socio-economic Aspects	Social and rural development	Employment and income generation for the farmer and dinamization of the productive chain
	Food security	Sisal cultivation does not compete with food

10. Results and Conclusions

CO_2 emissions are not significantly affected by production of sisal co-products and use of the residual biomass given the nature of the processing steps to obtain such products. Decortication does not use water and proposed processes for the production of animal feed and briquettes may be practiced in locations with a minimum supply of water and electric energy. As to soil health, all the agricultural waste from sisal growing are presently returned to the soil, where they act as fertilizers, avoiding or reducing synthetic fertilizer use. The valorization of co-products and residues, returning the decortication liquid to the soil using fertirrigation will help maintin soil nutrient equilibrium. As to biodiversity, there is a legal mandate to keep 20% of the land with native vegetation. This would contribute to reduce any negative effects caused by sisal monoculture. Subsistence farming as practiced today, along with the practice of planting sisal in conjunction with food crops, and the government's Water for All program should assure food for sisal farmers. From the socioeconomic viewpoint there is a possibility of increased earnings for the sisal farmer from the sale of pulp and stems, as well as future possibilities involving further processing of leaf juice and stem nectar. It is expected that job generation in the field and in processing centers will contribute to avoid labor exodus from the field to nearby urban centers.

Recent studies have concluded that growing sisal solely for fiber production is an economically unfeasible proposition for the small farmer (Dellaert, 2014; Silva, 2003). This study points out to the possibility of increased earnings from sisal farming through the appreciation of its co-products and residues, by the private sector or the government.

11. Recommendations

i) Invest in research and development for the production of presently imported agave nectar and/or inulin from sisal stems and of fungicide from the decortication juice, in order to increase sisal farmer earnings;

ii) Research processing schemes for sisal tow (short fibers) for the production of composites and/or plasterboard;

iii) Invest in the productive chain through private sector or government agencies to improve farming practices and mechanization.

iv) Carry out feasibility and commercialization studies for projects involving the production of sisal briquettes as a substitute for firewood or fossil fuels; and of animal feed for supplementing goat feed, particularly during long droughts.

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References

Boaventura, E. M. (2015). *Personal Communication on fibre commercialization*.

Boguslavsky, A., Barkhuysen, F., Timme, E., & Matsane, R. N. (2007). Establishing of Agave Americana Industry in South Africa. *CSIR Materials Science and Manufacturing*. Port Elizabeth, South Africa. Retrieved August 18, 2014, from http://researchspace.csir.co.za/dspace/bitstream/10204/1371/1/Boguslavsky_2007.pdf

Campbell, A. (2014). *Personal communication on sisal production system in Brazil*.

Carmo, J. C. C. (2015). *Personal communication on water supply*.

Cunha, T. S. (2010). *A Atividade Sisaleira e a sua Interferência Sobre o Bioma da Caatinga no Município de Valente - BA*. Serrinha: UNEB, 2010. Monografia (conclusão de curso Licenciatura em Geografia). Departamento de Educação. Universidade Estadual da Bahia.

CONAB (Companhia Nacional de Abastecimento). (2012). *Sisal*. Outubro 2012. Brasília. Retrieved from http://www.conab.gov.br/OlalaCMS/uploads/arquivos/12_10_29_11_45_31_sisal2012.pdf

Dellaert, S. N. C. (2014). *Sustainability Assessment of the Production of Sisal fiber in Brazil*. Utrecht, 2014. Dissertation (Sustainable Development: Energy and Resources). Faculty of Geosciences, Utrecht University.

FAO (Food and Agriculture Organization). (2013). Jute, Kenaf, Sisal, Coir and Allied Fibres. *Statistical Bulletin*. Rome. Retrieved October, 2014, from http://www.fao.org/fileadmin/templates/est/COMM_MARKETS_MONITORING/Jute_Hard_Fibres/Documents/JUTE_Statistical_bulletin_2013.pdf

Gebremariam, D. Y., & Machin, D. H. (2014). Evaluation of sun dried sisal pulp (Agave sisalana Perrine) as feed for sheep in Eritrea. *Livestock Research for Rural Development, 20*(11). Retrieved from http://www.lrrd.org/lrrd20/11/gebr20183.htm

Herrera, F., Wyllie, D., & Preston, T. R. (1980). Fattening steers on a diet of ensiled sisal pulp and molasses/urea supplemented with sunflower meal and leucaena forage. *Tropical Animal Production, 5*(1), 18-23. Retrieved July, 2014, from http://www.utafoundation.org/TAP/TAP51/5_1_4.pdf

Holanda, J. S., Torres, J. F., Santos, Z. L., Lima, G. F. C., & Carvalho Filho, J. V. (2009). *Processamento de resíduos de sisal e avaliação nutricional na alimentação de caprinos*. Congresso Internacional de Fibras Naturais, 2009, Salvador.

IBAM (Instituto Brasileiro de Administração Municipal). (2007). *Desenvolvimento Sustentável da Região Sisaleira: Valente – Bahia*. Estudo de Caso. Rio de Janeiro.

IBGE (Instituto Brasileiro de Geografia e Estatística). (2014). Retrivied January, 2014, from http://cidades.ibge.gov.br/download/mapa_e_municipios.php?lang=&uf=ba

LIPPEL. (2014). *Lippel exporta fábrica de briquetes ao México*. Retrieved from http://www.lippel.com.br/br/blog/lippel-exporta-fabrica-de-briquetes-ao-mexico.html#.VOJOFPnF9KJ

Lock, G. W. (1969). *Sisal* (p. 365). London: Longman.

Mapinda, H. (2015). *Personal communication on Agave nectar/inulin*.

Medina, J. C. (1954). *O sisal* (p. 285). São Paulo: Secretaria da Agricultura do Estado de São Paulo/Diretoria de Publicidade Agrícola.

MDIC (Ministério do Desenvolvimento, Indústria e Comércio Exterior). (n.d.). *AliceWeb* Retrieved from http://aliceweb.mdic.gov.br//consulta-ncm/consultar

Miranda-Ham, M. L., Herrera Alamillo, M. A., Castro Concha, L. A., Herrera Herrrera, J. L., Balam, M. C. E., & Robert Diaz, M. (2008). *Evaluación Del contenido de azúcares en líneas clonales de Agave fourcroydes seleccionadas por su alto contenido de fibra*. Mérida, Centro de Investigación Científica de Yucatan (CICY), agosto, Relatório de pesquisa.

Patrik, R. (2015). *Personal communication on briquette production*.

Preston, T. R., & Leng, R. A. (1987). *Matching Ruminant Production Systems with Available Resources in the Tropics and Sub-Tropics*. Penambul Books, Armadale, New South Wales, Australia.

RSB. (2011). *Principles & criteria for sustainable biofuel production*. Lausanne: Roundtable on Sustainable Biofuels.

SECTI (Secretaria de Ciência, Tecnologia e Inovação da Bahia). (2009). *Sisal Liquid Waste Use in Pesticides and Veterinary Drugs*. Preliminary Technical Feasibility Based on Research by Unesp-Assis and Embrapa-Algodão. Salvador, Brazil.

Silva, F. S. M. (2003). *Sustentabilidade agroecológica da cultura de sisal*. Salvador, 2003, 90. Il. Dissertação (Mestrado) em Gestão Integrada das Organizações. Unidade Baiana de Ensino Pesquisa e Extensão (UNIBAHIA).

Silva, O. R. R., & Beltrão, N. E. M. (Orgs.). (1999). *O agronegócio do sisal no Brasil* (p. 205). Brasília: Embrapa-SPI; Campina Grande: Embrapa-CNPA.

Terrapon-Pfaff, J., Fischedick, M., & Monheim, H. (2012). Energy potentials and sustainability−the case of sisal residues in Tanzania. *Energy for Sustainable Development, 16*(3), 312-319. http://dx.doi.org/10.1016/j.esd.2012.06.001