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Wild and cultivated biomass supply chain for biofuel production. A comparative study in West Africa

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Abstract

Limited access to energy has led to interest in biofuels in most West African countries where *Jatropha curcas* (jatropha) has been the most widely studied energy crop. However, due to difficulties in obtaining enough jatropha seed at acceptable costs, *Balanites aegyptiaca* (*B. aegyptiaca*) could be an alternative feedstock for biofuel production at lower costs.

We report the results of a comparative study of the optimal supply cost and supply network configuration of a cultivated and a wild energy crop. These optimal items were determined using a mixed integer linear programming model designed to help decision making concerning biomass supply chains for biofuel production. The model was applied to a case study on jatropha and *B. aegyptiaca* seed supply chains in Burkina Faso. By considering different options for location and technologies used for pre-processing as well as different cropping systems for jatropha cultivation, the case study showed that in contexts like those found in Burkina Faso, a wild energy crop like *B.*

aegyptiaca cannot be competitive compared to cultivated energy crops like jatropha because of its costly logistic operations.

Keywords: Biofuel; energy crops; biomass supply chain; pre-processing; optimization

1. Introduction

Biofuel is defined as fuel produced directly or indirectly from biomass. The main biofuel sources used in developing countries are fuelwood charcoal agricultural by products and dung which are converted into heat and power (FAO, 2004). Energy security and economic development have been among the main reasons for the interest in biofuels in sub-Saharan Africa (Amigun, Musango, & Stafford, 2011; Alexandros Gasparatos et al., 2012). This is particularly true in landlocked Sahelian countries with no petroleum resources like Burkina Faso and Mali, where energy consumption and electrification rates are low. According to the International Energy Agency (IEA, 2016), in 2014, national electrification rates in Mali and Burkina Faso were less than 30 %. Also, in 2014, rural electrification rates in the two countries were less than 10 %. These rates are well below the average electrification rate in sub-Saharan Africa, which was 35 % in 2014 (IEA, 2016). What is more, as they have no oil resources, Burkina Faso and Mali depend heavily on imports of petroleum products to meet the energy needs of key economic sectors such as transport, power generation and industry (Burnod, Gautier, & Gazull, 2010). Imports of petroleum products worsen the two countries' trade balance deficit.

This energy context explains the interest of these two sub-Saharan countries in biofuels (Amigun et al., 2011; Alexandros Gasparatos et al., 2012) and particularly in straight vegetable oil (SVO). SVO extracted from oilseed crops can be blended with diesel or be used directly as a fuel in diesel engines, if the quality standards of the oil are respected (Blin et al., 2013). SVO can also be used in hybrid energy systems combining solar photovoltaic systems and diesel generators like those described by (Adaramola, Quansah, Agelin-Chaab, & Paul, 2017; Franco, Shaker, Kalubi, & Hostettler, 2017). They can be used for electrification at the village or country level (A Gasparatos et al., 2015).

Since the 2000s, *Jatropha curcas* (jatropha) has been the most widely used energy crop for the production of biofuel in Burkina Faso and Mali (Bambara, Sawadogo, Blin, Roy, & Anciaux, 2017). *Jatropha* is a tree or shrub belonging to the Euphorbiaceae family. It grows in tropical and subtropical regions between 30° N and 35°S at altitudes below 500 m above sea level (Brittaine & Lualadio, 2010) and with total rainfall between 300 mm/year and 1500 mm/year (Brittaine & Lualadio, 2010; Domergue & Pirot, 2008; Heller, 1996; Jongh & Van der Putten, 2010). The trees produce yellow fruits, which turn

dark brown when dry. The fruits contain 1, 2 or 3 oil-rich seeds. The dry seeds contain between 32 and 40% of oil (Jongh & Van der Putten, 2010).

The focus on jatropha was stimulated by energy policies such as those of ECOWAS (Economic Community of West African States) (CEDEAO, 2013) that stipulate (as a precautionary principle) that biofuel production shall not compete with food production. As jatropha is not edible, the plant is a good candidate for biofuel production in West Africa. However, to date, jatropha plantations have failed to provide the required amounts of feedstock for biofuel production (Castro Gonzáles, 2016) especially in arid and semi-arid areas where the soil and climatic conditions are not suitable for its growth. This failure is due to the fact that the focus on jatropha as feedstock for biofuel production in Burkina Faso and Mali was based on assumptions about its seed yields even though no reliable experiments had been conducted on its cultivation and on its seed supply chain. This lack of reliable research on jatropha as an energy crop has resulted in the failure of several biofuel projects in West Africa (Castro Gonzáles, 2016). Accordingly, many biofuel production projects based on jatropha were stopped because the expected quantities of seeds were not obtained due to the low yields and the lack of cash to continue biofuel production (e-sud, 2014).

Following these failures, to enhance the profitability of jatropha plantations, most of the biofuel projects promoters focused on improving agriculture practices, varieties, and the control of pests and diseases of jatropha, while seed processing and, above all, logistics were rather neglected (Bambara et al., 2017).

Given the fact that *Balanites aegyptiaca* (B. aegyptiaca) and jatropha has similar gross calorific value (39-40 MJ/kg (Jain, 2019;Deshmukh & Bhuyar, 2009)), some biofuel project promoters have switched to other oleaginous biomasses such as *Balanites aegyptiaca* (B. aegyptiaca). Their main objective was to recover the investments already made (Rérolle, 2014) and also to respect their commitment to biofuel production. B. aegyptiaca is an evergreen tree that is very resistant to drought and can grow under a variety of ecological conditions (e.g. 100 mm to 1,000 mm of rain per year) (Ndoye, Diallo, & Gassama/Dia, 2004). The tree produces fruits each of which weighs from 5 to 8 g. The fruit consists of an epicarp (5 to 9 % of its weight), an edible mesocarp or pulp (28 to 33 % of its weight), an endocarp (49 to 54 % of its weight). The endocarp or hull surrounds the seed (8 to 12 % of the weight of the fruit) (B. P. Chapagain, 2006; B. Chapagain & Wiesman, 2005; C A Okia et al., 2013). The seed contains between 46 % and 55 % of its weight in vegetable oil (Varshney & Anis, 2014). B. aegyptiaca is particularly

abundant in arid and semi-arid regions, mainly in sub-Saharan and Sahelian regions in Africa, the Middle East, and South Asia (B. Chapagain & Wiesman, 2005). In these regions, the plant is one of the main species (Boffa, 2000) and the trees grow wild with no irrigation, fertilization, or care. This implies that no investment is required to grow the oilseeds and that there is also no competition for the occupation of land dedicated to food crops. However, because the seed oil is edible and is useful for various non-fuel uses (Mariod et al., 2017), a competition could exist for the oil end uses. But to date, and to the best of our knowledge, there is no *B. aegyptiaca* fruit or oil processing unit for food uses in West Africa. There is in contrast, a local valorization of oil for soap production. There are also some units that try to produce *B. aegyptiaca* oil for the cosmetics market. But it is a very limited market and often the oil produced does not have the quality required by this cosmetics market.

In any case, whatever the final uses of the seed oil, and especially for biofuel production, the operations necessitated by *B. aegyptiaca* fruits such as collection, pre-processing, storage and transport can be complex and expensive due to the scattered and irregular distribution of the trees (as *B. aegyptiaca* is a wild plant). This is a common feature of all bioenergy production systems to such an extent that in recent years, it is widely accepted that the complex and multi-faceted supply chains of bioenergy production systems call for careful consideration (Kumar & Singh, 2017; Rentizelas, 2013). Unlike its petroleum counterpart - a high-energy density liquid, - biomass feedstock is a low-energy density solid with scattered geographical distribution. Good design and management of the supply chain makes it possible to ensure the availability of the quantity of feedstock of the required quality and its delivery to the conversion unit at acceptable costs, within appropriate time periods. This is why (Eskandarpour, Dejax, Miemczyk, & Péton, 2015) state that “Supply chain management has become a strategic issue for any company looking to meet targets in terms of economic competitiveness, time and quality of service especially in an economic environment characterized by the globalization of trade and the acceleration of industrial cycles”.

This paper aims to compare the supply chains of two kind of biomass; wild biomass (*balanites aegyptiaca*) and cultivated biomass (*Jatropha curcas*) considering the preprocessing options, the yields in seed of each biomass, while optimizing the network design and the sourcing options. The aim is to propose the optimal supply chain in terms of low factory gate cost.

2. Review of literature on modeling and optimization of biomass-to-biofuel supply chains

Numerous studies have been carried out on biomass-to-bioenergy systems in recent years. These studies have covered subjects including biomass to biofuel feedstock and conversion technologies, biomass supply chain design and management including modeling and optimization approaches. The scientific publications listed in Table 1 are well-documented literature review papers on biomass-to-bioenergy systems.

Table 1. Review papers on biomass-to-bioenergy systems

Publications	Topics covered				
	Feedstock	Conversion technologies	Biomass supply chain design	Biomass supply chain management	Modeling and optimization
(Gold & Seuring, 2011)			x	x	
(Yue, You, & Snyder, 2014)	x	x	x	x	
(De Meyer, Cattrysse, Rasinmäki, & Van Orshoven, 2014)			x	x	x
(Mafakheri & Nasiri, 2014)			x	x	
(Sharma, Ingalls, Jones, & Khanchi, 2013)	x	x	x	x	x
(Ba, Prins, & Prodhon, 2016)			x	x	x
(Atashbar, Labadie, & Prins, 2016)			x	x	x
(Ghaderi, Pishvae, & Moini, 2016)	x		x	x	x

A typology of quantitative approaches for the modeling and optimization of the supply chain exists in the literature. Beamon (Beamon, 1998) classified quantitative models in four groups according to the nature of the input data. The first group comprises deterministic models in which all the variables are specified and known. The second group comprises stochastic models in which at least one variable is uncertain and unknown. The third group comprises economic models, and the fourth group simulation models. (Ba et al., 2016) proposed an interesting more generic, more recent classification, and applied it to the biomass supply chains. This classification contains two groups. The first comprises the performance evaluation models that include cost-based models, geographic information systems (GIS)-based models, and simulation models. The second group comprises optimization models including

deterministic models (mathematical programming models), stochastic models, and multi-objective models. These models can be mono or multi product (s) and mono or multi period (s) models. In addition to this classification, (Ba et al., 2016) presented the advantages and disadvantages of each group of models. Mathematical programming models are the most widely used for biomass supply chains. Indeed, according to (D'Amours et al., 2010), mixed integer programming (MIP) methods are the best for tactical and strategic planning problems that can be solved over a longer period of time. A mixed-integer programming (MIP) problem is one where some of the decision variables are constrained to be integer values, if its objective function and all its constraints are linear, it is a MILP (Mixed Integer Linear Programming) problem. Researchers have also addressed the modeling and optimization of the biomass-to-biofuel supply chain from the point of view of decision levels in the supply chain. Literature reviews by (Barbosa-Póvoa, da Silva, & Carvalho, 2017; Ghaderi et al., 2016) classify recent publications on biomass-to-bioenergy supply chains according to the level of decisions, the objective to be optimized, and the type of mathematical model used.

The most common types of biomass used as feedstock in the bioenergy production systems studied are lignocellulosic biomass, sugar and starchy biomass, and oil crops. (Eksioglu, Acharya, Leightley, & Arora, 2009) developed a mixed integer linear programming (MILP) model that determines the number, size and location of units needed to produce biofuels from lignocellulosic biomass. The model also makes it possible to assess the amount of biomass to be transported and processed in a given time period. Based on the cost minimization of both feedstock production and energy conversion, (Gan & Smith, 2011) developed a generic model to define the optimal size of a bioenergy conversion plant. The model also assesses the bioenergy production costs and the biomass supply radius corresponding to the size of the conversion unit. (Marvin, Schmidt, & Daoutidis, 2013) proposed a MILP to determine the location of a processing facility, the capacity and technology required for biomass-to-biofuel supply chains in the Midwestern United States. (Duarte, Sarache, & Costa, 2014) proposed a MILP that has been applied in Colombia to locate a biofuel production unit. (Sosa, Acuna, McDonnell, & Devlin, 2015) developed an optimization model of two supply chains in Ireland (one exploiting trees cut into short pieces, and the other exploiting whole trees). The model analyzes the impact of moisture content and truck characteristics on the supply chain costs. These costs include harvesting, chipping, storage and transport. (Leão, Hamacher, & Oliveira, 2011) proposed a mathematical optimization model to design and plan an optimized biodiesel supply chain for oil crop biomass. These authors studied the production of biodiesel

from castor oil, and their model accounts for the production, transport, and crushing of oilseeds as well as the transport of vegetable oils to the biodiesel production units. (Andersen, Iturmendi, Espinosa, & Diaz, 2012) proposed a MILP for the optimal design and planning of a biodiesel supply chain in Argentina. Their multi-period model takes into account competition for the use of agricultural land, the production, storage and transport of seeds, oil, flour, biodiesel, glycerol and biodiesel. (Ng, Lam, & Yusup, 2013) developed a MILP for the design of an optimal network for the supply of rubber seeds in Malaysia. Their model makes it possible to choose the location of seed collection sites and biodiesel production units. (Babazadeh, Razmi, Rabbani, & Pishvae, 2017) developed a model for the strategic design of a biodiesel supply chain in Iran. The proposed MILP optimizes the number, location and capacity of jatropha cultivation, collection of the seeds and of waste cooking oil, bio-refineries, and distribution facilities. The review by (Ghaderi et al., 2016) classifies recent publications according to the nature of the biomass used as feedstock.

Still concerning oil crops, some studies (B. P. Chapagain, Yehoshua, & Wiesman, 2009; Deshmukh & Bhuyar, 2009; Naik & Balakrishna, 2017) assessed the production of biofuels from *B. aegyptiaca*. They concluded that the important properties of *B. aegyptiaca* biodiesel are quite similar to those of diesel and that *B. aegyptiaca* is a promising feedstock for the production of oilseed-based biofuel. However, to the best of our knowledge, our study (Sawadogo, Bambara, Blin, Anciaux, & Roy, 2017) is one of the first to assess the costs of supplying *B. aegyptiaca* seeds despite the fact that it is known that one of the main obstacles to the commercial exploitation of *B. aegyptiaca* fruits or nuts (the endocarp containing the seed) is the difficulty involved in obtaining adequate and regular supplies of the fruits (Council, 2008). In this paper (Sawadogo et al., 2017), a MILP for strategic and tactical decisions related to the configuration of the upstream supply chain for SVO production systems in West Africa has been developed. The model has been applied to a case of study on *B. aegyptiaca* seed supply chain in the sub Sahelian region of the Burkina Faso. And, considering different location of the pre-processing, different transportation means, different feedstock growing areas with different territorial yield, the model allows to determine the optimal configuration of the supply network that minimizes feedstock harvesting and transportation costs. The same model has been applied to a case of study on jatropha seeds supply chain in West Africa (Bambara et al., 2017). In this second paper, the model has been used to determine the optimal configuration of the supply network that minimizes feedstock cultivation, harvesting and transportation costs, considering different farming systems, different location of the pre-processing, and different

transportation mode. The optimization problem in these two papers was to determine how to produce and collect the biomass and how to deliver it to a biofuel production unit in such a way as to minimize biomass production costs (cultivation and/or harvesting costs) as well as its transport costs.

The above review of the literature identified several papers that modeled and optimized biomass-to-biofuel production systems. But lignocellulosic biomass has been much more widely studied than oil crop biomass. This is clear from review by (Ghaderi et al., 2016) in which among the 146 papers on biomass-to-bioenergy supply chain they analyzed, less than 10 dealt with oil crops. An analysis of papers on modeling and optimization of the lignocellulosic biomass supply chain also showed that these studies almost always include biomass pre-processing in the design of the supply chain. That is not the case for the studies on oilseed-based biomass.

In addition, despite the enthusiasm for biofuels (produced mainly from jatropha seeds) observed in Africa in the 2000s, very few studies on the modeling and optimization of biomass-to-biofuel supply chain have been conducted in African contexts. This can be also seen in the literature review by (Ghaderi et al., 2016). One of the conclusions of this paper is that conducting case studies of biomass supply network design in various countries with different climates is a future research opportunity. Another research opportunity is costs analysis in systems using biomass grown for biofuel production. Indeed, according to (Soto et al., 2018) “the success of the promotion of a new crop depends on its profitability” and, “performing accurate cost-benefit analyses would prevent farmers from taking unnecessary risks of cultivating a non-profitable crop”.

The contribution of the present paper is thus to compare a wild and a cultivated energy crop supply chain costs and network configuration in a West African environment. The purpose of this comparative study is to provide results, that will be an information base, and that could guide farmers and decision-makers in the field of biofuel production for the choice of optimal biomass, in terms of minimizing biofuel production costs in West Africa. Optimal costs and optimal supply network configuration are determined through an improved version of the MILP described in (Bambara et al., 2017; Sawadogo et al., 2017). Improvements to the model are described in the next section. One important aspect of the present work is the integrated approach we used that takes into account in the same framework the agricultural aspects of the energy crop and its supply to the biofuel production unit with respect to regional limitations. This integrated approach allows the model to identify optimal conditions for the cultivation and collection of the energy crop in the soil and climatic and cropping context of the study

region. It then defines the optimal conditions for the supply of feedstock supply the biofuel production unit. Although the model was developed considering West Africa rural environments, its structure was designed to be applied to any other region, regardless of its geographic size. The rural environment in West Africa is characterized by cropping systems used for subsistence family farming and by the weak development of the infrastructure required for the transport, storage, loading, unloading and pre-processing of the feedstock.

3. Methodology

3.1. Description of the problem and assumptions

The system to be optimized is the feedstock supply chain of two oilseed-based biofuel production unit, the first one exploiting a cultivated biomass and the second one, a wild biomass. The supply network of each biofuel production unit (see Figure 1) comprises biomass production sites, biomass collection points, a biofuel production unit, and the infrastructure needed to grow, harvest, transport, store and pre-process biomass. The above-mentioned sites are linked by a road network. As the road is not usually a straight line, tortuosity factor must be defined. Tortuosity factor is defined as the ratio of actual travel distance via the roads to the shortest straight line distance (or the line of sight distance). This factor is applied to approximate the transporting distance via the road network between the biomass collection points and the plant where biomass is used (Sultana & Kumar, 2014).

Each biofuel production unit is in a region where there is a periodic demand for oilseed biofuel. This periodic demand defines the minimum required processing capacity of the biofuel production unit.

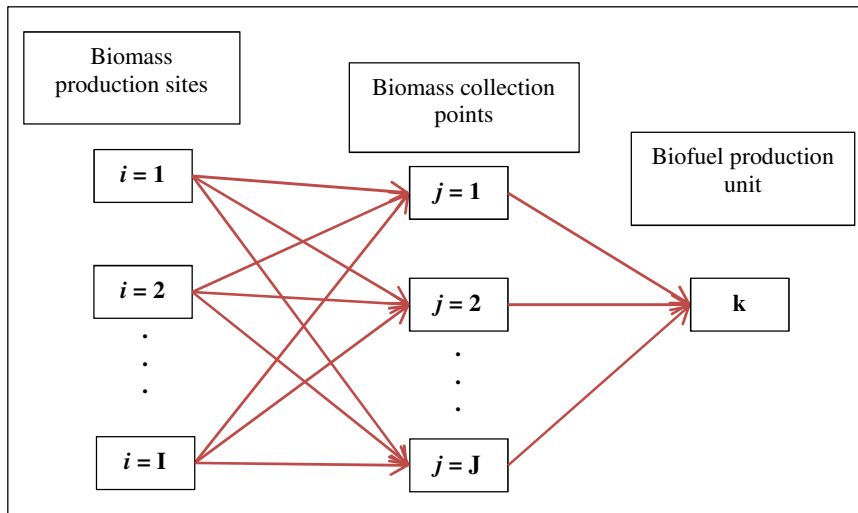


Figure 1. Structure of the supply network

A finite number of biomass production sites are scattered throughout the regions of interest and it is assumed that these biomass production sites are able to fill the biofuel production unit's need for feedstock. It is also assumed that this biomass taken for biofuel production does not affect biomass requirements for the non-fuel uses in the regions of interest.

As stated above, for one of biofuel production unit, the energy crop has to be planted to produce the biomass that will then be harvested. For the other biofuel production unit, the energy crop already exists, and the fruits only have to be harvested. When the energy crop has to be planted, several cropping systems each generating a specific crop yields can be considered. Each biomass production site is characterized by an area available for cultivation or harvesting, a set of means of transport of the biomass and a set of cropping systems.

All the harvested biomass must pass through collection points, and, due to geographical constraints, several collection points are selected in advance. Each collection point is characterized by a set of means of transport of the biomass, a maximum capacity, and a minimum demand for feedstock. The harvested biomass must also be pre-processed. Biomass pre-processing is a set of post-harvest operations such as de-hulling, depulping, cleaning, and drying. It can be performed to reduce the quantity (volume or weight) of the biomass to be transported, to prevent degradation of the quality of the biomass during transport and storage, to ease and improve vegetable oil extraction. Different pre-processing technologies can be used and there are three possible locations for the pre-processing: on the biomass production sites, at the biomass collection points or at the biofuel production unit (see Figure 2). Depending on the location of the pre-processing operations, the biomass to be transported and stored can be the non-pretreated

biomass (fruits) or the pretreated biomass (seeds). Table 2 describes the nature of the biomass, depending on the location of pre-processing.

The optimization problem is the same as in (Bambara et al., 2017; Sawadogo et al., 2017) except that here, not only transport costs are considered but, supply logistics costs (pre-processing, storage, loading, unloading and transport costs).

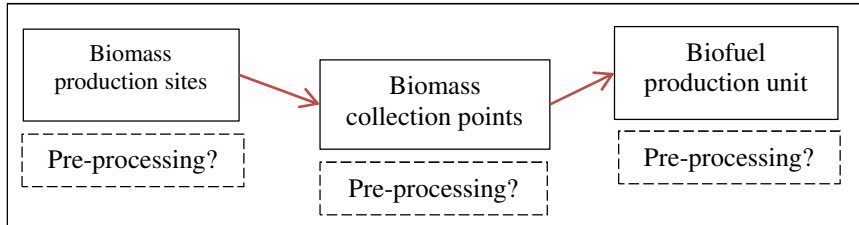


Figure 2. the three possible locations for the pre-processing

Table 2. Nature of the feedstock flow depending on the pre-processing location

Nature of the biomass:	Pre-processing location		
	at the biomass production sites	at the collection points	at the biofuel production unit
required at the biofuel production unit	Seeds	Seeds	Seeds
transported between the biomass production sites and the collection points	Seeds	Fruits	Fruits
transported between the collection points and the biofuel production unit	Seeds	Seeds	Fruits
stored at the biofuel production unit	Seeds	Seeds	Fruits
handled (loaded and unloaded)	Seeds	Seeds	Fruits

3.2. Optimization procedure

Part of the model used for the problem optimization is described in one of our previous papers (Bambara et al., 2017). However, its formulation is improved in the present paper. First, pre-processing, storage, loading and unloading costs and pre-processing technology were included in the model. Second, the formulation of the model has been improved to better account for the location and the number of trees per surface unit for harvesting wild biomass such as *B. aegyptiaca* and also to integrate pre-processing technology. *Jatropha* fruits pre-processing generates husks which, when not treated, are waste. The same is true for the pulp and hull of *B. aegyptiaca* obtained after depulping and dehulling of the fruits. All of these by-products, in addition to occupying space, can contribute to environmental pollution, particularly through greenhouse gas (GHG) emissions such as methane produced by fermentation. This is why pre-processing technology and by-products have been better stated in the model by introducing three decision variables ($ZT_{i,p}$; $ZT_{j,p}^t$; $ZT_{k,p}^t$ see section 3.3.2.). This makes it possible to better account the mass balance, and to facilitate later the integration of the valuation of the by-products in the same model.

All these improvements have introduced nonlinear variables in the model that were linearized using standard linearization techniques involving binary variables. As a result, the mathematical formulation of the problem is still a MILP where an objective function has to be minimized under a set of constraints.

3.3. Mathematical formulation

The objective function is made up of the following costs: cultivation, harvest, transport, pre-processing, loading, unloading, and storage. All these costs account for the variable costs and fixed costs of the operation under consideration. For the sake of clarity, the elements of the mathematical model are described below.

3.3.1. Parameters

$Q_{k,p}^t$ is the total demand for seeds by the biofuel production unit at period t

ST_i is total available surface area of a biomass production site i .

$Prod_b$ is the seed productivity of a tree if cropping system b is considered.

$Nabr_i$ is the number of tree per surface unit.

$\eta_{i,b} = Prod_b \cdot Nabr_i$ is the seed yield of a biomass production site i if the cropping system b is considered.

$Ccult_{i,b}$ and $Fcult_{i,b}$ are respectively the cultivation unit operating cost and fixed cost of a biomass production site if the cropping system b is considered.

$Crec_{i,b}$ and $Frec_{i,b}$ are respectively the harvesting unit operating cost and fixed cost on a biomass production site if the cropping system b is considered.

τ is the tortuosity factor.

Cap_j^t is the maximum capacity of a biomass collection point.

$d_{i,j}$, $d_{j,i}$ are the distance between a biomass production site and a biomass collection point, respectively.

$d_{j,k}$, $d_{k,j}$ are the distance between a biomass collection point and the biofuel production unit, respectively.

$a_{i,j}$ is a parameter that defines the potential allocation of a biomass production site to a biomass collection point $a_{i,j} = \begin{cases} 1 & \text{if } d_{i,j} \leq d_m \cdot x_{m,i} \\ 0 & \text{if ni} \end{cases} \forall i, j, m$

d_m is the maximum travel distance per day for a means of transport m .

$x_{m,i}$ is a binary parameter that determines if transportation means m is available at a biomass production site i .

$x_{m,j}$ is a binary parameter that defines if transport means m is available at collection point j .

C_m is the unit transportation cost using the means of transport.

Q_m is the load capacity of a means of transport m .

Pr_m is the purchasing price of the means of transport m .

$CSto_p$ is the unit cost of storage depending on the pre-processing location.

$CMen_p$ is the unit cost loading and unloading depending on the pre-processing location.

$x_{u,p}$ is a binary parameter that determines the choice of a pre-processing technology depending on the pre-processing location.

CV_u is the operating cost of a pre-processing technology u .

CF_u is the fixed cost of a pre-processing technology u .

δ_e is the removed fraction of biomass (by-product) when pre-processing is performed.

Table 3. Sets

Sets	Index
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Biomass production site	i
Biomass collection point	j
Cropping system	b
Biofuel production unit	k
Means of biomass transportation	m
Time period	t
Pre-processing location	p
Pre-processing technology	u

3.3.2. Decision variables

$y_b \in \{0,1\}$ = binary variable that determines the choice of cropping system b .

$y_i \in \{0,1\}$ = binary variable that determines the choice of a biomass production site i .

$y_j \in \{0,1\}$ = binary variable that determines the choice of a biomass collection point j .

$y_p \in \{0,1\}$ = binary variable that determines the location of the pre-processing.

$N_p \in \mathbb{N}$ = number of selected sites depending on the pre-processing location.

$$N_p = \begin{cases} \sum_i y_i, & \text{if } p = \text{on biomass production sites} \\ \sum_j y_j, & \text{if } p = \text{at collection points} \\ 1, & \text{if } p = \text{at the biofuel production unit} \end{cases}$$

$S_i \in \mathbb{R}_+$ = cultivated surface area of a biomass production site i .

$S_{i,b} \in \mathbb{R}_+ = S_i \cdot y_b$ is the cultivated surface area of a biomass production site i if the cropping system b is selected.

$Q_i \in \mathbb{R}_+ = \sum_b S_{i,b} \cdot \eta_{i,b} \quad \forall i$ is the quantity of fruits, cultivated and harvested on a biomass production site i .

$Q_{i,p} \in \mathbb{R}_+ = Q_i \cdot y_p$ quantity of feedstock available on a biomass production site i if pre-processing location p is selected.

$Q_{i,j,p}^t \in \mathbb{R}_+ =$ quantity of feedstock to be transported from a biomass production site i to a collection point j at period t if pre-processing location p is chosen.

$Q_{j,k,p}^t \in \mathbb{R}_+ =$ quantity of feedstock to be transported from a collection point j to the biofuel production unit at period t if pre-processing location p is chosen.

$ZT_{i,p} \in \mathbb{R}_+ =$ quantity of by-product produced on a biomass production site i if pre-processing location p is chosen.

$ZT_{j,p}^t \in \mathbb{R}_+$ = quantity of by-product produced at a collection point j if pre-processing location p is chosen.

$ZT_{k,p}^t \in \mathbb{R}_+$ = quantity of by-product produced at the biofuel production unit if pre-processing location p is chosen.

3.3.3. Objective function

Minimize $\sum_{n=1}^{12} C_n$

$C_1 = \sum_{i,b} C_{cult_{i,b}} \cdot S_{i,b}$: Total operating cost of cultivation

$C_2 = \sum_{i,b} F_{cult_{i,b}} \cdot y_{i,b}$: Fixed cost of cultivation

$C_3 = \sum_{i,b} C_{rec_{i,b}} \cdot S_{i,b}$: Total operating cost of harvesting

$C_4 = \sum_{i,b} F_{rec_{i,b}} \cdot y_{i,b}$: Fixed cost of harvesting

$C_5 = \sum_{i,j,p,m,t} C_m \cdot x_{m,i} \cdot Q_{i,j,p}^t \cdot d_{i,j} \cdot \tau$: Total operating cost of transporting feedstock between biomass production sites and collection points

$C_6 = \sum_{i,m} Pr_m \cdot x_{m,i} \cdot y_i$: Fixed cost of transporting feedstock between biomass production sites and collection points

$C_7 = \sum_{j,k,p,m,t} C_m \cdot x_{m,j} \cdot Q_{j,k,p}^t \cdot d_{j,k} \cdot \tau$: Total operating cost of transporting feedstock between collection points and biofuel production unit

$C_8 = \sum_{j,m} Pr_m \cdot x_{m,j} \cdot y_j$: Fixed cost of transporting feedstock between collection points and biofuel production unit

$C_9 = \sum_{j,k,p,t} Q_{j,k,p}^t \cdot C_{Sto_p}$: Storage total cost

$C_{10} = \sum_{j,k,p,t} Q_{j,k,p}^t \cdot C_{Men_p}$: Loading and unloading total cost

$C_{11} = \sum_{i,p,u} CV_u \cdot x_{u,p} \cdot Q_{i,p}$: Total cost of pre-processing .

$C_{12} = \sum_{i,p,u} CF_u \cdot x_{u,p} \cdot N_p$: Fixed cost of pre-processing

Constraints

$$S_i \leq ST_i \cdot y_i, \forall i \quad (1)$$

$$0 \leq S_i \leq ST_i, \forall i \quad (2)$$

$$0 \leq \sum_b S_{i,b} \leq S_i \cdot \sum_b y_b \quad \forall i \quad (3)$$

$$0 \leq S_i - \sum_b S_{i,b} \leq S_i \cdot (1 - \sum_b y_b) \quad \forall i \quad (4)$$

$$\sum_b y_b = 1 \quad (5)$$

$$0 \leq Q_i \leq ST_i \cdot \sum_b \eta_{i,b} \quad \forall i \quad (6)$$

$$0 \leq Q_{i,p} \leq ST_i \cdot \sum_b \eta_{i,b} \cdot y_p \quad \forall i, p \quad (7)$$

$$0 \leq Q_i - Q_{i,p} \leq ST_i \cdot \sum_b \eta_{i,b} \cdot (1 - y_p) \quad \forall i, p \quad (8)$$

$$ZT_{i,p} = \begin{cases} Q_{ip} \cdot \delta_e, & \forall i, p | p = \text{on biomass production sites} \\ 0, & \forall i, p | p = \text{at collection points} \\ 0, & \forall i, p | p = \text{at the biofuel production unit} \end{cases} \quad (9)$$

$$ZT_{j,p}^t = \begin{cases} 0, & \forall j, t, p | p = \text{on biomass production sites} \\ \sum_i Q_{i,j,p}^t \cdot \delta_e, & \forall j, t, p | p = \text{at collection points} \\ 0, & \forall j, t, p | p = \text{at the biofuel production unit} \end{cases} \quad (10)$$

$$ZT_{k,p}^t = \begin{cases} 0, & \forall k, t, p | p = \text{on biomass production sites} \\ 0, & \forall k, t, p | p = \text{at collection points} \\ \sum_j Q_{j,k,p}^t \cdot \delta_e, & \forall k, t, p | p = \text{at the biofuel production unit} \end{cases} \quad (11)$$

$$\sum_p y_p = 1 \quad (12)$$

$$\sum_{j,t} Q_{i,j,p}^t \leq Q_{i,p} - ZT_{i,p} \quad \forall i, p \quad (13)$$

$$\sum_i Q_{i,j,p}^t \leq Cap_j \cdot y_j \quad \forall j, p, t \quad (14)$$

$$\sum_k Q_{j,k,p}^t = \sum_i Q_{i,j,p}^t \cdot a_{i,j} - ZT_{j,p}^t \quad \forall j, t, p \quad (15)$$

$$\sum_p Q_{j,k,p}^t \geq Dem_j \cdot y_j \quad \forall j, k, t \quad (16)$$

$$\sum_j Q_{j,k,p}^t - ZT_{k,p}^t = Q_{k,p}^t \cdot y_p \quad \forall t, k, p \quad (17)$$

Equations (1) ensure that the cultivated or harvested surface area of each selected biomass production site will not exceed the available surface area of each biomass production site.

Equations (2) to (4) enable linearization of the nonlinear expression $S_i \cdot y_b$ which calculates the cultivated and harvested surface area of a biomass production site i when cropping system b is adopted.

In order to standardize the biomass production cost, only one cropping system must be selected for all the biomass production sites. Equation (5) ensures the choice of this single cropping system

Constraints (6) to (8) enable linearization of the nonlinear expression $Q_i \cdot y_p$ which calculates the quantity of feedstock available at a biomass production site depending on the location of pre-processing.

Equations (9) to (11) calculate the quantities of by-product to be produced respectively on each biomass production site, at each collection point and at the biofuel production unit based on the location of pre-processing.

Equation (12) ensures that only one pre-processing location can be chosen.

Equation (13) ensures that the quantities of biomass transported from a chosen biomass production site to the chosen biomass collection points at each period cannot exceed the quantity of feedstock available at the biomass production site depending on the choice of the pre-processing location. This constraint also

defines the nature of the feedstock to be transported between biomass production sites and collection points.

Equation (14) ensures that the maximum capacity of a selected collection point will not be exceeded whatever the location of pre-processing.

Equation (15) ensures that the quantities of biomass transported from a collection points to the biofuel production unit cannot exceed the quantity of feedstock available at this collection point depending on the choice of the pre-processing location. This constraint also defines the nature of the feedstock to be transported between collection points and the biofuel production unit.

Equation (16) assigns a minimum value to the quantity of biomass to be transported between each selected collection point and the biofuel production unit.

Equation (17) ensures that the demand of the biofuel production unit is satisfied.

4. Implementation, results and discussion

4.1. Case study

The case study was based on common practices in Burkina Faso. Because of the lack of reliable data on some parameters related to feedstock production, assumptions were made based on expert opinion. The case study can be described as follows: two biofuel production units, one processing jatropha seeds and the other jatropha seed (each with a demand for dry seeds of 300t/year) are considered. The jatropha biofuel production unit is located in the southern Sudanian zone of Burkina Faso, a region where the soil and climatic conditions suit jatropha tree growth, for details of these characteristics see (Bazongo et al., 2016). The *B. aegyptiaca* biofuel production unit is in the Sahelian region of Burkina Faso. The demand for dry jatropha fruits is 480 tons/year if one considers that the dry jatropha seed represent 62.5 % of the dry fruit weight. The demand for *B. aegyptiaca* dry fruits is 2 500 tons/year if one considers that the seed represents 12 % of the dry fruit weight.

Several *B. aegyptiaca* production sites and some potential collection points are identified around the *B. aegyptiaca* biofuel production unit. Several farms for jatropha cultivation and some collection points are also identified around the jatropha biofuel production unit. For a potential collection point to be selected, it must be able to collect at least 10 tons of biomass, which represent the load capacity of the trucks generally used for the transport of goods in Burkina Faso. The maximum capacity of each collection point is unlimited. The surface areas of jatropha farms were randomized in the value range of 0.25 ha to 4 ha and with the distribution described by (Zongo, Serme, Somda, Gnankambary, & P. Sedogo, 2015) (56 %

for farms between 0.25 and 1 ha, 26 % for 1 ha farms, 13 % for 2 ha farms, 4 % for 3 ha farms and 1 % for 4 ha farms). Because *B. aegyptiaca* trees grow wild, the surface areas from which their fruits harvested were randomized in the range of 2 ha to 10 ha.

Concerning seed production, cultivation and harvesting unit costs were calculated based on their labor and input costs. Because we used a family farming approach, we assumed that farmers already have the land and equipment required for cultivation and harvesting. Therefore, equipment purchasing costs and land purchasing cost were not included. A man-day was assumed to be eight working hours. The minimum daily wage for farm workers is 1363.91 XOF/day (XOF is West African CFA francs) in Burkina Faso (MFB, 2007).

For *B. aegyptiaca* seed production, a productivity of 52 kg of fruits per tree per year was assumed (B. P. Chapagain et al., 2009) and tree densities ranging from 25 trees/ha to 45 trees/ha were randomly distributed for each biomass production site. According to (Hall, 1992), a density ranging from 25 to 50 trees per ha is acceptable for a region where *B. aegyptiaca* is abundant. The unit cost of harvesting was calculated based on a fruit picking rate of 9.24 kg/h reported by (Füllemann, 2015) for a tree density of 20 trees/ha and a fruit yield of 545.43 kg/ha. Since recurring passes are needed to harvest the fruit, it was assumed that the quantity of fruits harvested per pass varies with the variation in tree productivity, but the number of passes remains the same regardless of tree productivity. Therefore, the cost of harvesting *B. aegyptiaca* fruit per unit area is assumed to be constant. Indeed, the staggered maturity of *B. aegyptiaca* explains the need to multiple the passes required to harvest the fruit, which take place during the dry season (between October and January according to (Ndoye et al., 2004)). Harvesting data and costs are listed in Table 4.

Table 4. *Balanites aegyptiaca* harvesting data

	B. aegyptiaca				
Tree density tree/ha	25	30	35	40	45
Seed productivity kg/tree	5.2	5.2	5.2	5.2	5.2
Fruit productivity kg/tree	52	52	52	52	52
Fruit harvesting cost XOF/ha	10 915				

For *jatropha* seed production, two of the cropping systems (intercropping , intercropping intensely managed) described by (Baumert, Khamzina, & Vlek, 2018) were used for this case study. However, as the case study concerns family farming, irrigation and pesticide inputs used in the intensely managed

intercropping system were not considered. In addition, mechanical operations were replaced by their manual equivalent and a low value of the seed yield (0.95 t / ha instead of 1.25 t / ha) was used. The lifespan of jatropha plantations was assumed to be 20 years. The purchase price of urea and NPK fertilizer is 12 000 XOF/50kg each (MAAH, 2017). For jatropha harvesting, the model proposed by (Borman, von Maltitz, Tiwari, & Scholes, 2013) for the calculation of a harvester seed picking rate (in kg/man.day) was used to determine the labor requirement. Cropping systems, cultivation and harvesting data and costs are listed in Table 5.

Table 5. Jatropha cultivation and harvesting data.

	Cropping system 1	Cropping system 2
Tree density (tree/ha)	625	625
Seed yield (kg/ha)	810	950
Fruit yield (kg/ha)	1296	1520
Seed productivity (kg/tree)	1.3	1.5
Fruit productivity (kg/tree)	2.1	2.4
Urea per year (kg/ha)	0.0	100.0
NPK fertilizer per year kg/ha	0.0	150.0
Fruit cultivation labor per year (h/ha)	97.6	129.4
Seed harvesting labor per year (kg /man-day)	37.7	40.9
Fruit harvesting labor per year (kg /man-day)	60.3	65.5
Costs		
Urea cost XOF/ha	0	24000
NPK fertilizer cost XOF/ha	0	36000
Fruit cultivation labor cost (XOF/ha)	16640	22061
Total cultivation cost (XOF/ha)	16640	82061
Fruit harvesting labor cost (XOF/ha)	29300	31655

Pre-processing operations consist of de-husking jatropha fruits and pulping and de-hulling *B. aegyptiaca* fruits. Due to the difficult access to electricity in rural areas in Burkina Faso, and due to large quantities of feedstock to be collected at the biofuel production unit, it was assumed that pre-processing is manual when it takes place at biomass production sites and motorized when it takes place at the biofuel production unit. At the collection points, pre-processing operations can be manual or motorized depending on the choice of decision makers. To better account for this uncertainty, two scenarios (described in Table 6) were designed based on the type of pre-processing at the collection points.

Table 6. Description of the scenarios

Pre-processing location	Scenarios	
	Scenario 1	Scenario 2
On-site biomass production	Manual pre-processing	Manual pre-processing
At collection points	Manual pre-processing	Motorized pre-processing
At the biofuel production unit	Motorized pre-processing	Motorized pre-processing

Pre-processing costs for each energy crop (listed in Table 7) were calculated based on their operating parameters. The operating parameter for the manual de-husking of jatropha is 2 kg/h per person (Allard, 2010; Tréboux & Desquilbet, 2013). That for manual pulping and de-hulling of *B. aegyptiaca* is 2.5 kg/day per person (Clement A Okia, 2010). The operating parameters for motorized de-husking of jatropha are 500 kg/h per two persons and 11 kWh/t (Sarr, 2015) with an “ENGELBERG” de-hulling machine. The operating parameters for motorized pulping of *B. aegyptiaca* are 278.7kg/h per two persons, 30kWh/t and 2125 L/t (water consumption) (Fülleman, 2015). The operating parameters for motorized de-hulling of *B. aegyptiaca* are 1 009.5 kg/h per two persons and 30 kWh/t (Fülleman, 2015). Water cost is 1091 XOF/m³ (Burkina Faso Water Company in 2017) and electricity cost is 114 XOF/kWh (Burkina Faso National Electricity Company in (SONABEL, 2008)). All the above-mentioned machines have a lifespan of 10 years and their investment cost is amortized on the declining balance method at a rate of 5 %. The unit operating costs for each type of pre-processing are list in Table 7.

Table 7. Pre-processing costs

	Type	Manual	Motorized	
	Operations	De-hulling	De-pulping	Hulling
Jatropha	Labor (XOF/t)	53 380	680	
	Electricity (XOF/t)	-	1 254	
	Water (XOF/t)	-	-	
	Operating costs (XOF/t)	53 380	1 934	
	Fixed costs for one machine (XOF/year)	-	142 455	
<i>B. aegyptiaca</i>	Operations	Depulping and hulling	Depulping	Hulling
	Labor (XOF/t)	545 564	1 225	340
	Electricity (XOF/t)	-	3 420	3420
	Water (XOF/t)	-	2 320	-
	Operating costs (XOF/t)	545 564	6 965	3 760

	Fixed costs for one machine (XOF/year)	-	485 645	679 900
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At the collection points, the biomass is placed in polypropylene bags before it transports to the biofuel production unit where it is stored. Loading and unloading cost is 100 XOF for a full bag of biomass (SP/CPSA, 2002). The storage cost was assumed to be equal to the cost of the bags in which the biomass is bagged for transport. This storage cost amounts to 250 CFA francs for a bag full of biomass (Allard, 2010; SP/CPSA, 2002). A bag full of jatropha weighs 55 kg if it contains fruit and 60 kg if it contains seeds and bag full of *B. aegyptiaca* bag weighs 60 kg if it contains fruit and 70 kg if it contains seeds.

Regarding the feedstock supply network, for both energy crops, the geographical coordinates of biomass production sites, the collection points and the biofuel production unit were randomized once into value ranges reflecting the reality in Burkina Faso and the resulting supply network was used throughout the study. The randomization of the locations and the number of sites does not prevent the results of the model from reflecting the reality in Burkina Faso. Indeed, for a given real case, there is no guarantee that the supply network configuration will follow a particular logic. Yet our model must be able to treat a supply network, whatever its configuration. The considered supply network radius is 30 km, and all the distances are Euclidean distances to which a tortuosity factor was applied. Given the lack of knowledge about the road network in the study area, the value of the tortuosity factor was estimated. For this study, its value was set at $\sqrt{2}$ (as the straight-line distance was considered to be the diagonal of a square, whose sides represent the actual path (Chapuis, 2014)).

Carts pulled by donkeys were assumed to be used to collect the feedstock from the biomass production sites and transport it to the collection points. The maximum load per trip is 0.5 t. Old trucks were assumed to be used for the transport between the GP and the CU. Their maximum load per trip is 10 t. The unit cost of cart and truck transport are respectively 136 XOF/ton.km and 52 XOF/ton.km ((Lhoste, Havard, & Vall, 2010). Their fixed costs are respectively 7507 XOF/year and 129505 XOF/year (AMASSA, 2009).

4.2. Results and discussion

The model was implemented and solved in the optimization software Xpress IVE 8.3. The experiments were performed on an Intel Core i7- 5500U CPU 2.4 GHz with 8 GB RAM on a 64-bit platform. The solution was obtained using the branch and bound algorithms available in the software solver.

The model determines the number of biomass production sites, the optimal surface area to be harvested as well as the optimal cropping systems for biomass cultivation; the location and allocation of

biomass production sites; the number, location and allocation of collection points; the quantities of fruit to be harvested and pre-processed; the location of pre-processing; the quantities of fruit or seed to be transported, handled and stored depending on the pre-processing location; total supply costs.

Below, the resulting total supply cost of Scenario 1 and Scenario 2 are first presented and discussed for each energy crop. Then, biomass production costs, logistics costs, network configuration and agricultural aspects of the two energy crops are presented, compared and discussed in the scenario with the lowest total supply cost. Logistics cost is the sum of the costs of transport, loading, unloading, pre-processing and storage.

4.2.1. Scenarios 1 and 2 total supply costs.

The cost result of scenarios 1 and 2 are presented in Table 8. The total supply cost in this table represents the cost per kg of processed biomass.

Table 8. Scenario 1 and scenario 2 implementation results

Energy crops	<i>Jatropha curcas</i>		<i>Balanites aegyptiaca</i>	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Total supply cost (XOF/kg)	81.48	76.77	212.08	169.14
Logistics cost (XOF/kg)	25.48	20.77	170.04	126.69
Number of selected biomass production sites	188 out of 1 120	179 out of 1 120	149 out of 444	166 out of 444
Total harvested surface area (ha)	365.71	365.71	1 155.42	1 166.80
Number of selected collection points	3	3	8	3
Location of the pre-processing operations	At the biofuel production unit	At the collection points	At the biofuel production unit	At the collection points
Number of trips required to transport the feedstock by cart.	960	960	5 000	5 000
Number of trips required to transport the feedstock by truck.	48	30	250	30
Total amount of feedstock transported between biomass production sites and collection points (t).	480	480	2 500	2 500
Total amount of feedstock transported between collection points and the biofuel production unit (t).	480	300	2 500	300

For jatropha, the seed supply total cost of Scenario 1 is higher than that of scenario 2. This cost is about 76.8 XOF / kg for Scenario 1 and about 81.5 XOF / kg for Scenario 2. For *B. aegyptiaca*, the trend is the same with the supply total cost of about 169.2 XOF / kg in Scenario 1 and of about 212.1 XOF / kg in Scenario 2.

The explanation for the difference in cost between Scenario 1 and Scenario 2 for the two energy crops lies in the composition of the supply total cost presented in Figure 3 for jatropha and in Figure 4 for *B. aegyptiaca*.

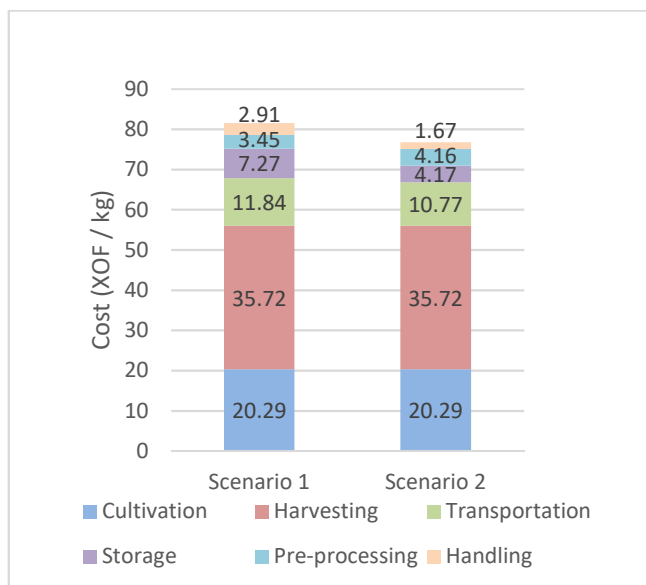


Figure 3. Composition of jatropha seed supply total cost

Indeed, when analyzing the results in Table 8, Figure 3 and Figure 4, it is noticeable that transportation, storage, handling and costs in Scenario 1, are higher than those in Scenario 2. It is also noticeable that pre-processing operations are located at the biofuel production unit in Scenario 1 while located at the collection points in Scenario 2; And on the contrary of transportation, storage, handling and costs, the pre-processing cost in Scenario 1 is lower than that in Scenario 2. These observed differences between Scenario 1 and Scenario 2 are due to the fixed and operational costs of each pre-processing technology and by the quantities of biomass to be processed resulting from the choice of the location of the pre-preprocessing. Indeed, motorized pre-processing is more than 2 times cheaper than manual one and, the location of the pre-processing has an influence on the quantities of material flowing in the whole supply network as these quantities of material are considerably reduced when pre-processing is performed earlier in the supply chain. Therefore, as in Scenario 1 motorized pre-processing is available only at the biofuel production unit, this location is chosen for performing the pre-processing operations, explaining

the highest pre-processing cost of Scenario 1. And because pre-processing operations are located at the biofuel production unit, fruits are handled and there is more material to be transported throughout the supply network, explaining the highest transportation, storage and handling costs of Scenario 1. There would certainly be less material to be transported if one of the two other pre-processing location options were selected. However, the savings made with the two other options thanks to the reduction in the quantity of biomass to be transported are lower than the savings made by choosing to locate pre-processing at the biofuel production unit, which is more than 2 times cheaper (see Table 7) because it is motorized in Scenario 1.

In Scenario 2, as the motorized pre-processing (which is more than 2 times cheaper) is available at the collection points in Scenario 2, this location is chosen, explaining the lowest pre-processing cost of Scenario 2. Moreover, the choice of the location of pre-processing at collection points means less material has to be transported, loaded, unloaded and stored between collection points and the biofuel production unit because only seeds are handled. This explain the lowest transportation, storage and handling costs of Scenario 2.

In view of the above supply costs analysis, it is clear that when pre-processing takes place earlier in the supply network and before biomass transportation, logistic operations costs are reduced because of the reduction in the quantity of material induced by the pre-processing operations. A similar result has already been reported by (Bajwa, Peterson, Sharma, Shojaeiarani, & Bajwa, 2018; Rentizelas, Tatsiopoulos, & Tolis, 2009) in their paper. Nonetheless, the model favors the choice of pre-processing location with the least expensive technology at the expense of reducing the quantities of material to be handled, when the savings made by choosing the pre-processing location in question, cover biomass transportation, loading, unloading and storage costs. Hence, the model chooses the location of the pre-processing that represents the best compromise between the quantities of feedstock to be transported, handled, and stored and pre-processing costs. Thus, it can be concluded that in the biomass supply chain, the most upstream facilities with the least expensive pre-processing technology are optimal for the location of the pre-processing operations.

Since Scenario 2 has the lowest total costs for the two biomasses, the rest of the analysis uses this scenario for each biomass.

4.2.2. Comparative analysis of the components of jatropha and *B. aegyptiaca* total seed supply cost

Figure 5 shows the distribution of the total supply cost for each energy crop.

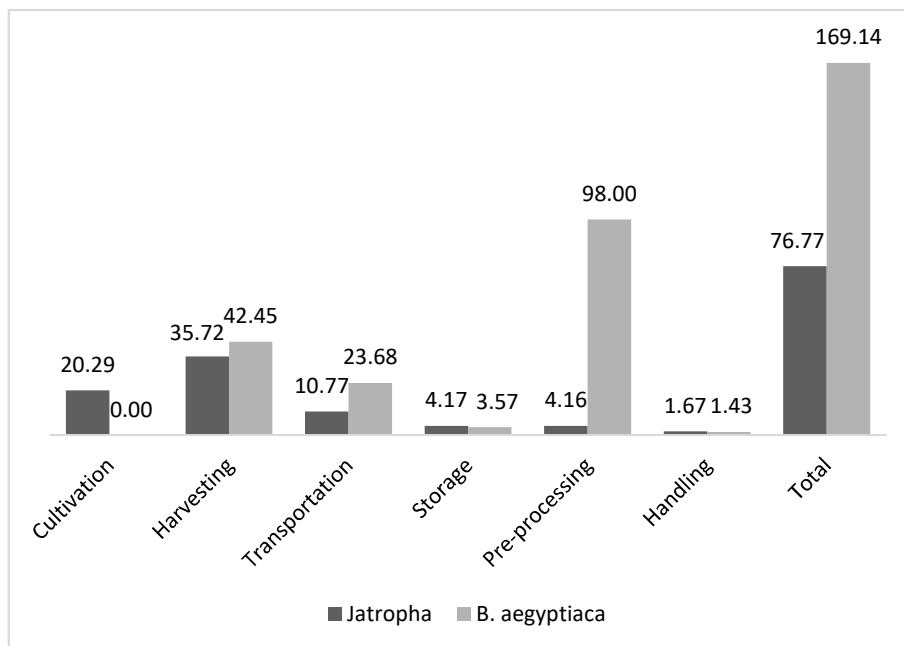


Figure 5. Components of the total supply cost for *Jatropha curcas* and *Balanites aegyptiaca*

These results show that the total supply cost of *B. aegyptiaca* seeds is higher than that of jatropha. Concerning the production of biomass, the results also show that the cultivation and harvesting cost of jatropha is more than 1.3 times higher than that of *B. aegyptiaca*. This biomass production cost represents about 75% of the total supply cost of jatropha seeds. For *B. aegyptiaca*, the biomass production cost is the cost of harvesting and represents 25% of the total seed supply cost. The lower biomass production cost for *B. aegyptiaca* compared to that of jatropha is due to the fact that *B. aegyptiaca* is a wild plant and does not have to be cultivated whereas jatropha does. This advantage of not generating any cultivation costs has been highlighted by (Angelsen & Wunder, 2003) in (Pouliot & Treue, 2013) who reported that most wild non-cultivated plants require low investment to be produced.

Concerning logistics costs, the distribution of the total supply cost shows that the cost of transporting jatropha is twice as low as that of transporting *B. aegyptiaca*. This transport cost represents 14 % of the total supply cost of both jatropha and *B. aegyptiaca* seeds. The pre-processing cost of jatropha fruits is about 23 times lower than that of *B. aegyptiaca* and represents only 5 % of the total supply cost while the pre-processing cost for *B. aegyptiaca* represents 58 % of the total supply cost. The difference in the cost of transport and pre-processing between the two energy plants can be explained by the fact that seeds

represent respectively 12 % and 62.5 % of the whole *B. aegyptiaca* and *J. curcas* fruit weight. As a result, 5.2 times more *B. aegyptiaca* feedstock has to be transported between the biomass production sites and collection points. There are also 5.2 times more *B. aegyptiaca* fruits to be pre-processed, explaining the high cost of *B. aegyptiaca* transport and pre-processing. In addition, the fact that fixed and operational costs of *B. aegyptiaca* pre-processing operations are more than 5 times higher than that of *jatropha* (Table 7) contribute to increase the cost difference between the pre-processing of the two energy crops. ((Aviara, Mamman, & Umar, 2005; E. Mamman, Umar, & Aviara, 2005) have already addressed this difficulty of *B. aegyptiaca* fruits pre-processing and have worked on the physical properties of the fruits to allow the development of machines to facilitate their dehulling. The loading, unloading and storage costs of the two energy crops are similar and represent less than 6 % of the total supply cost for both *B. aegyptiaca* and *jatropha*. Loading, unloading and storage costs are similar for the two energy crops because the same quantity of feedstock (300 t) has to be handled between collection points and the biofuel production unit (Table 2).

The above comparison of the components of *jatropha* and *B. aegyptiaca* total seed supply cost show that when the configuration of the supply network is optimized and if pre-processing is carried out mechanically before the feedstock is transported, the total supply cost of *B. aegyptiaca* seeds is higher than that of *jatropha*. The higher total supply cost of *B. aegyptiaca* seeds is due to its high pre-processing operations costs and to its fruit composition.

4.2.3. The supply network configuration

The configurations of the supply networks are presented in Table 8, Figure 6 and Figure 7. The results in Table 8 show that the surface area required to harvest *B. aegyptiaca* is more than four times bigger than that required to grow and harvest *jatropha*. This can be explained by the fact that, as *B. aegyptiaca* is a wild plant, it is mixed with other plant species in the wild and, its tree density per unit area is low and uncontrolled. In contrast, *jatropha* trees are planted and tree density is controlled. However, despite the fact that *B. aegyptiaca* requires more land, it does not occupy land devoted to food or cash crops, and what is more, it grows in areas with a semi-arid or arid climate that are often unsuitable for growing food crops. Its exploitation does not also require clearing new land or using land already allocated to agriculture. Thus, it does not create competition for land uses as could be the case of *jatropha*.

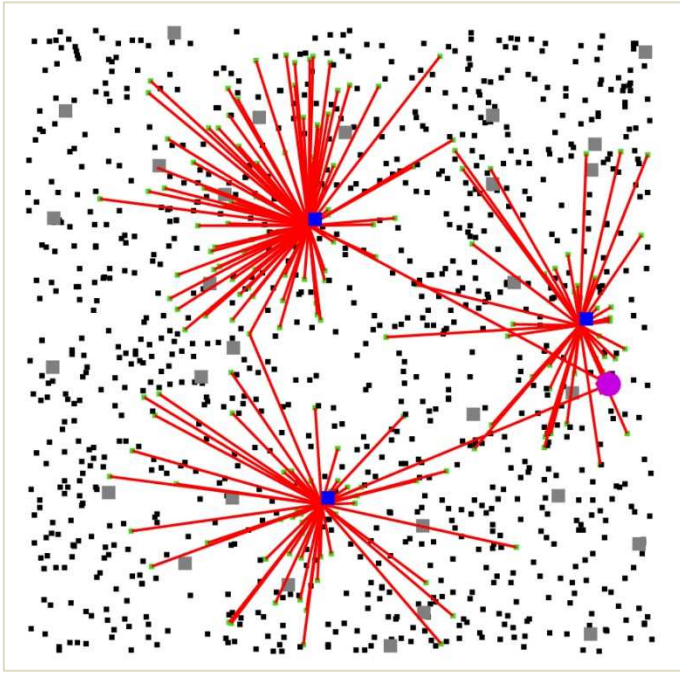


Figure 6. Schematic appearance of jatropha seed supply network with the allocated biomass production sites - collection points and collection points - biofuel production unit

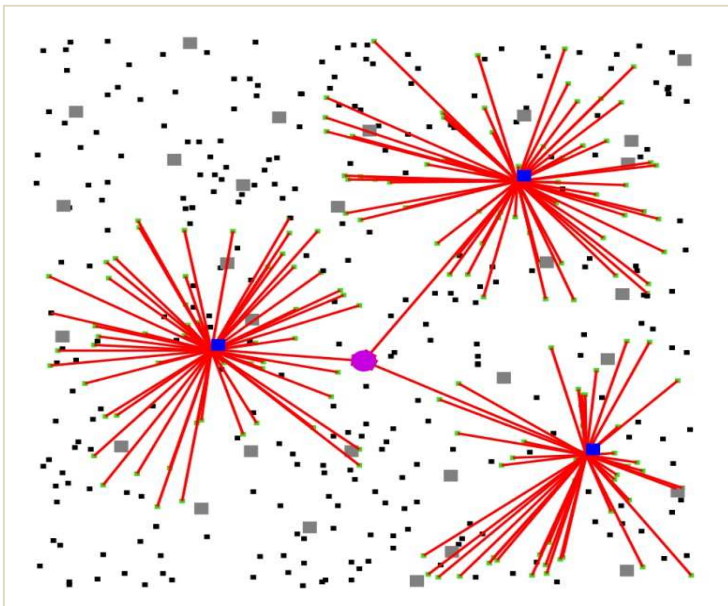


Figure 7. Schematic appearance of *B. aegyptiaca* seed supply network with the allocated biomass production sites - collection points and collection points - biofuel production unit

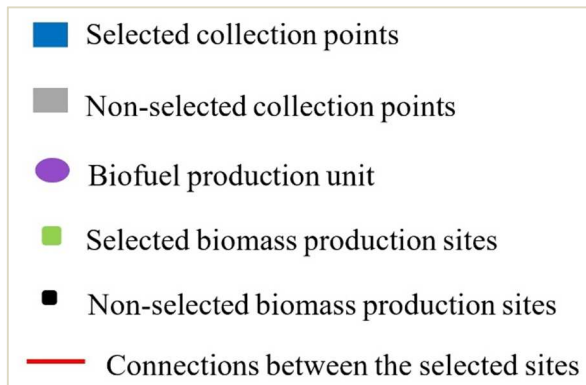


Figure 8. Legend for figures 6 and 7

4.2.4. *Agricultural aspects*

Concerning agricultural aspects, the results of running the scenarios show that the cropping system 1 is optimal for the cultivation of jatropha fruits. Both the cropping systems considered in the case study are encountered in Burkina Faso and have the advantage of occupying only 50% of the surface area of the farms on which they are implemented. Hence, farmers who adopt them do not have to devote their entire farm to cultivating an energy crop (it should be recalled that the agricultural context of the majority of West African countries is characterized by family subsistence farming). However, even if cropping system 1 has a lower seed yield than the culture system 2, its total cultivation cost is five times lower. Indeed, as shown in Table 5, cropping system 1 does not include the use of fertilizers applied directly on the plants. This reduces its total cultivation cost. In cropping system 1, jatropha plants take advantage of fertilizers and care of the adjacent plant, as stipulated by (Baumert et al., 2018).

Still concerning agricultural aspects, Figure 9 presents the percentage of selected jatropha production sites depending on their surface area, and Figure 10 presents the percentage of selected *B. aegyptiaca* production sites depending on their number of trees per surface unit. These results show that, the more productive the biomass production sites (either because they have a large surface area or because they have a large number of trees), the more they are selected. This can be explained by the fact that this kind of biomass production site facilitates the production of large quantities of biomass on a concentrated surface area. Their selection therefore makes it possible to reduce the number of biomass production sites and hence the distance to be covered to collect the fruits. It can be inferred from this result that for the design of a jatropha or *B. aegyptiaca* seed supply network, the choice of biomass production sites with an increasingly large surface area and number of trees per surface unit, helps reduce biomass supply costs.

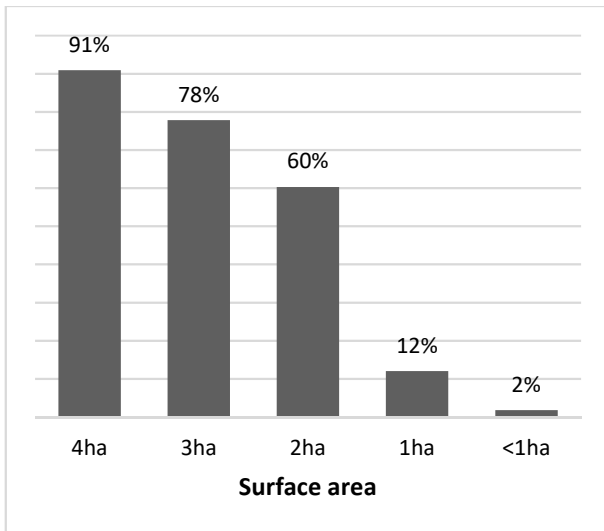


Figure 9. Percentage of selected jatropha production sites depending on their surface area



Figure 10. Percentage of selected *B. aegyptiaca* production sites depending on the number of trees per surface unit

5. Conclusion

This paper reports the results of a comparative study of the optimal supply cost and optimal supply network configuration of a cultivated and a wild energy crop. The optimal supply cost and supply network configuration was determined with a mathematical model designed to help decision making in oilseed-based biomass supply chains for biofuel production. The model developed here is a generic one, as it can be used to optimize the supply chain of other biofuel value chains. The variables and parameters can be adapted to the problem to be solved.

It was applied to a case study for the supply of jatropha and *B. aegyptiaca* seeds to a biofuel production unit, in the Sudanian region of Burkina Faso for jatropha, and in the sub-Saharan region of

Burkina Faso for *B. aegyptiaca*. In the case study, different options for pre-processing locations and technologies as well as different cropping systems for jatropha cultivation were considered.

Firstly, the results of the case study show that *B. aegyptiaca* requires more land for seed production but does not occupy land devoted to food crops or cash crops as it grows under arid climates that are often unsuitable for growing food crops. Thus, it does not create competition for land use which could be the case of jatropha. The results also show that the use of an intercropping system that generates a seed yield of at least 800 kg/ha could produce the quantity of jatropha seeds required to feed a small biofuel production unit. However, the production of jatropha fruits requires farms that are ideally bigger than 1 ha. What is noteworthy about this result is that the intercropping system would enable farmers to use only part of their farms for the cultivation of an energy crop. This could help mitigate, or even reduce potential competition for agricultural land use mentioned above.

Secondly, the results of the case study show that the motorized pre-processing is to be preferred in the design of oilseed-based biomass supply chains because it reduces the cost of transporting feedstock to the biofuel production unit. However, this pre-processing technology is only possible where access to electricity is also possible, which once again underlines the need for - and the benefits of - increasing access to energy in rural West Africa to promote the economic development of these rural areas. Pending access to electricity in these rural areas, a solution that could help reduce the cost of supplying oilseed biomass could be improving pre-processing operations by developing affordable mechanical pre-processing devices.

Thirdly, when the configuration of the supply network is optimized and if pre-processing is performed mechanically before the feedstock is transported, the total supply cost of *B. aegyptiaca* seeds is higher than that of jatropha.

Finally, the results of the case study implementation show that in contexts like those in Burkina Faso, more than 70 % of the total cost of supply of *B. aegyptiaca* seed is attributable to logistics, compared to 27 % in the case of jatropha, where cultivation and harvest account for more than 70 % of the total supply cost. This result underscores the importance of designing *B. aegyptiaca* supply networks carefully and the need to properly cultivate and harvest jatropha fruits.

Our future work will concern the valorization (as energetics, as livestock feed or as fertilizers) of the material produced by fruits pre-processing and seeds pressing. The aim is to examine the benefits that this valorization might have on the feedstock cost.

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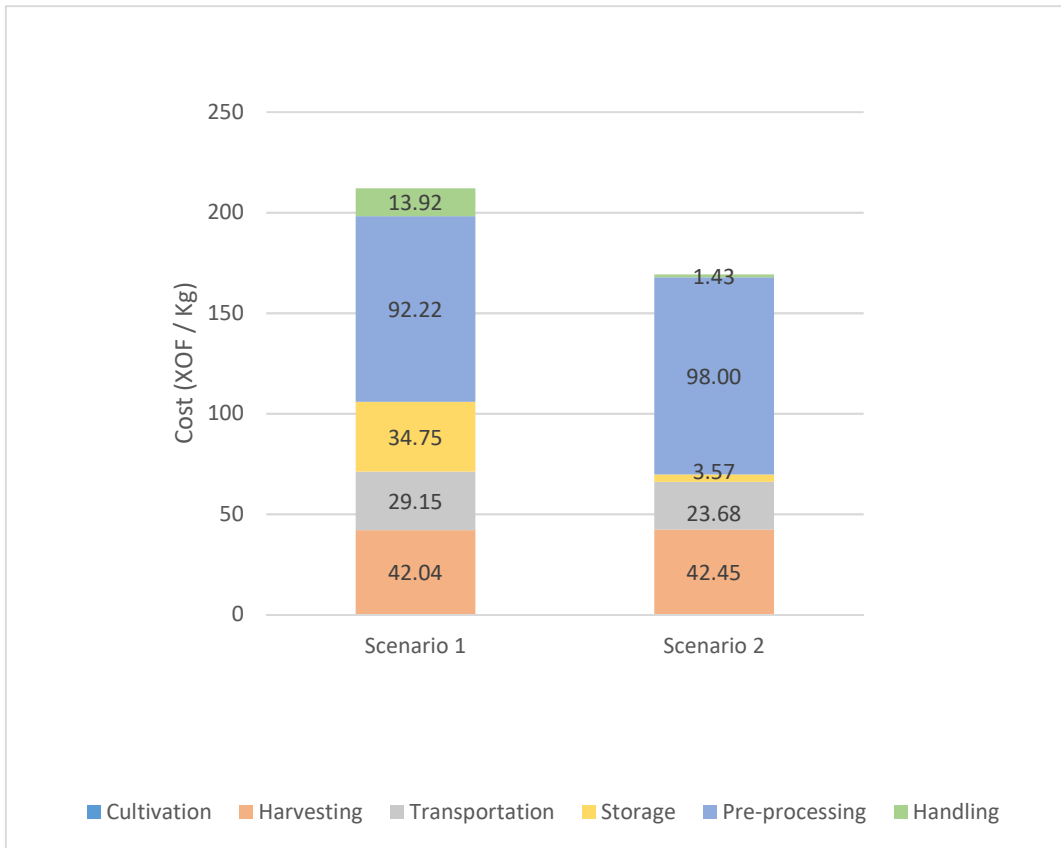


Figure 1. Composition of *B. aegyptiaca* seed supply total cost