TOWARD A METHODLOGY FOR SUSTAINABLE DESIGN OF JATROPHA-BASED BIOFUELS PRODUCTION AND USE SYSTEMS, IN BURKINA FASO

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Abstract

In Burkina Faso, biofuels represent a great opportunity to address important economic development issues such as modern energy access and dependence on energy imports. *Jatropha Curcas* (Jatropha) has been identified as the most suitable feedstock for biofuel industry development. Considering the socio-economic issues and the commitment of the government in the Millennium Development Goals, the most promoted scheme for biofuel sector development is the production of straight vegetable oil (SVO) by small-scale oil plants, based on Jatropha oilseeds cultivation by smallholders. SVO can be directly used as a fuel in stationary diesel engines, through minor adaptations.

The sustainability of the biofuel sector, is submitted to a range of choices concerning conversion technologies, production capacities, processing conditions, and by-products valorisation. Our purpose is to develop a methodology to assess the best system designs towards sustainability criteria that are to be defined through a careful analysis of socio-economic context. A computing tool, called OSMOSE, allows the implementation of technology models, the simulation and optimization of overall production system.

In this paper, we present the techno-economic simulation of a small-scale oil production plant. The results show that the activity can be profitable from a minimum capacity of 100 tons.year^{-1} and that maximizing oil recovery leads to very high processing costs. Moreover, the analysis raises (i) the strong importance of seedcake valorisation in the sustainability of Jatropha biofuel systems and (ii) the influence of seedcake's oil content in its valorisation possibilities.

1- INTRODUCTION

Burkina Faso is a Sahelian land-locked country and is part of the least developed countries following the United Nations' classification. As access to energy at an affordable price is a key basis of any economic development [1], addressing the energy crisis in Burkina is expected to act as a lever in the achievement of Millennium Development Goals (MDGs). Particularly in rural areas, the expansion of energy access contributes to the improvement of living conditions and to the promotion of productive activities such as agricultural products transformation, joinery, welding...

Following the National Institute for Demography and Statistics (INSD) [2], 80% of the Burkinabe population lives in rural areas from farming and pastoral activities. The largest part (80%) of the energy consumption over the whole country is firewood used for cooking in both rural and urban areas. Modern energy supply mostly relies on expensive imports of fossil fuels that represented 24% of total imports in 2009 [2]. Even with governmental subsidies, access to electricity is, so far, very limited and reserved to urban populations with an electrification rate below 1% in rural areas [1].

In this context, private sector and NGOs are attempting to develop biofuel production activities based on the cultivation of oil-bearing trees, specifically Jatropha (*Jatropha Curcas)* that has been identified as one of the most suitable feedstock [1], thus offering the possibility to address both above-mentioned issues that are rural development and affordable energy prices. Indeed, Jatropha biofuel development will necessarily involve actors from agriculture, trade, energy and transportation sectors depending on the scenario, and thus, contribute in different ways to a sustainable (economic) development.

As an example, a small-scale biofuel production and use scenario would operate at the village level: local farmers produce Jatropha seeds that are transformed into Straight Vegetable Oil (SVO) by a small oil plant. SVO can be directly used as fuel in stationary Diesel engines driving mills, motopumps or electricity generators [3]. On the opposite, a large-scale biofuel scenario would foster the production of biodiesel for transports and rely either on farming or agro-industrial crops. The first scenario seems more likely to promote rural development while the second would probably have a stronger impact on national economy.

There is an infinite number of possibilities between these two scenarios. A large number of technical and organizational choices will condition the sustainability of the biofuel system. These include: production scale, spatial organization, agricultural practices, transformation technologies, processing strategies, by-product valorization and so on.

The purpose of our work is to propose a methodology to systematically evaluate these options towards sustainability criteria and thus highlight the best available system designs and operational strategies. A prior careful analysis of the socio-economic context should set the system boundaries and guides the definition of adequate sustainability evaluation criteria. A techno-economic model of the system is built and simulated using a computing tool called OSMOSE [4] which allows performing sensitivity analysis and multi-objective optimization. The analysis of the results will point out the most sensitive parameters and choices, the optimal solutions and thus constitutes guidelines to stakeholders and policy makers.

In this paper, we present the very first results of our study with the modeling and techno-economic analysis of an oil plant, which is the central process of the Jatropha biofuel system. The evaluation is restricted to a few criteria, but this already enables interesting discussion, especially on production scale and by-products valorization technologies.

2- MATERIALS AND METHODS

Regarding the context analysis, we chose to focus first on the development of small-scale SVO production units, which has been recognized the most promising development scheme [1]. Jatropha, an oil-bearing tree native to South-America, today worldwide spread, would be cultivated by smallholders as a sideline activity and the oilseeds would be transformed by oil plants set in rural areas. We present here the techno-economic model for an oil production unit of capacity ranging from 10 to 1000 tons.year^{-1}.

The feedstock is composed of ovoid seeds, around 15mm long, coated with hard black hull that counts for about 37% of the whole seed weight. The whole seeds have an average oil content of 35% [5, 6] with variation from 28% to 40%.

The oil extraction technique considered is screw pressing, also called oil expression, which is the most widespread technique for small and medium capacity oil extraction [7]. The press is composed of a barrel made of narrow spaced bars, in which a conical screw rotates and presses the seeds. The pressure increases along the screw, due to reduced volume, and the oil flows through the seed mixture and out of the barrel through the spaces between the bars. The seedcake is discharged at the end of the screw. The mechanical strains inside the barrel are high, up to 40 MPA [8], and friction phenomena increase the temperature of the mixture.

We assume here that the oil plant is configured for cold pressing, i.e. there is no thermal or moisture adjustment pre-treatment of the seeds, and the press barrel temperature does not exceed 70°C. Cold pressing is commonly used for SVO production because it preserves the fuel quality of the oil by preventing some impurities such as phospholipids to dissolve in oil [3, 7]. After extraction, the oil passes through a press filter for impurities removal and undergoes no chemical treatment.

Oil expression model. A model for oil expression has been proposed by Karaj and Muller [9] from laboratory experiments on Jatropha oil extraction using a small capacity screw-press (10-25 kg.h^{-1}). This model was adapted to an oil plant assuming an analogous behaviour at larger scale. Equation (1) gives the nominal throughput $\dot{m}_{seed\ nom}$ (kg.h^{-1}) as a function of applied throughput $\dot{m}_{seed}$ (kg.h^{-1}) and oil recovery O_{rec} (-) ; equation (2) correlates the process flow and specific mechanical energy consumption W_{pr} (kWh.kg^{-1}). The input parameters of the model are the annual quantity of seeds to transform Q_{seed} (kg.year^{-1}) and the desired oil recovery. Annual plant operating time is set to 2000 h. Standard oil recovery of an oil expeller is 75% but it can be operated at a lower oil recovery to achieve higher processing capacity with the same machine [7].

$$\dot{m}_{seed\_nom} = \frac{2{,}9895 \cdot \dot{m}_{seed}}{\ln(\frac{85{,}834 - O_{rec} * 100}{0{,}602})} \quad (1)$$

$$W_{pr} = 0{,}08348 - 0{,}03848 \cdot \frac{\dot{m}_{seed}}{\dot{m}_{seed\_nom}} \quad (2)$$

These equations reflect the general behaviour of an oil expeller. If $\dot{m}_{seed}$ increases, the residence time in the barrel decreases and the oil has less time to flow out, so the oil recovery decreases. W_{pr} also decreases with increased seed throughput. More generally, specific energy consumption increases exponentially with oil recovery. Thus low oil recovery implies high seed throughput and low energy requirements, and inversely.

After extraction, the oil directly passes through the press filter to remove solid particles. We assume that unfiltered oil contains 5% of solid particles and the filtration process generates 3% of oil losses. The SVO (filtered oil) flowrate, $\dot{m}_{SVO}$ (kg.h^{-1}), is given by equation (3).

$$\dot{m}_{svo} = \dot{m}_{seed} \cdot O_c \cdot O_{rec} \cdot (1-0{,}05) \cdot (1-0{,}03) \quad (3)$$

The total energy consumption of the oil production unit E_{sp}(kWh.kg^{-1} seeds) is extrapolated from W_{pr}. This assumption is made from the observation of oil production business plans performed by CREOL [10]. The required power is provided by a Diesel engine.

$$E_{sp} = \frac{\mathrm{W}_{pr} + 0{,}05}{n_{eng}} \quad (4)$$

where n_{eng} is the average engine efficiency, set to 30% [11].

Economic model. In this simulation, a simple profitability analysis is made. An investment cost function has been established from oil expeller prices data published by the Folkecenter in 2000, updated using the Chemical Engineering Plant Cost Index (CEPCI) for process machinery (2010 to 2000 ratio = 1,42) [10]. Equation (5) gives the price (XOF) of the oil expeller alone, Inv_{press} (XOF), as a function of the pressing capacity. Oil expeller manufacturers use to give processing capacity for most common seeds, such as sunflower and rapeseed, but it actually varies with feedstock properties, such as bulk density. According to FACT Foundation observations [12], the capacity with Jatropha seeds is around 70% of full capacity: this is accounted for in the investment calculation.

$$Inv_{press} = 477{,}86 \cdot \left(\frac{\dot{m}_{seednom}}{0{,}7} \right)^{0{,}8398} \quad (5)$$

The next assumption refers to the total oil plant investment. From observations of project proposals of the CETIOM, we noticed that the share of oil expeller's price in total investment increases linearly with increased capacity. For a nominal capacity of 50 kg.h^{-1}, the oil expeller accounts for 40% of total investment and for 400 kg.h^{-1} oil plant it accounts for 60%. This reflects that there is an important economy realized on side equipment when raising the scale of the process. However, as the available data on cold pressing installation was not abundant enough to deduce a proper statistical law we assumed the law presented in equation (6). Inv_{op} (XOF) is total oil plant investment.

$$Inv_{op} = \frac{Inv_{press}}{5{,}71 \cdot 10^{-4} * \dot{m}_{seed\ nom} + 0{,}371} \quad (6)$$

Annual maintenance expenses are 2% of initial investment [10]. Workforce is constant, independent of capacity and counts 4 people ($n_{wf} = 4$). Financial costs Int_{tot} are calculated over 10 years with an interest rate of 5%.

Processing cost C_{proc}(XOF.kg^{-1} seeds) is calculated following equation (7). It is expressed in currency unit by mass unit of feedstock, independently of seeds purchase's price and products sale's prices.

$$C_{proc} = E_{sp} \cdot \mathrm{Pr}_{gas} + \frac{\mathrm{n}_{wf} \cdot Pr_{wf}}{\dot{m}_{seed}} + \frac{Inv_{op}}{n_{year} \cdot Q_{seed}} + \frac{C_{maint}}{Q_{seed}} + \frac{Int_{tot}}{n_{year} \cdot Q_{seed}} + ECFN \quad (7)$$

where $\Pr_{gas} = 70\ XOF.kWh^{-1}$ is diesel fuel price ; $\Pr_{wf} = 300\ XOF.h^{-1}$ is workforce hourly cost ; C_{maint} (XOF) is annual maintenance cost ; ECFN is exploitation cycle funding needs. It is the financial cost of feedstock purchase, assuming 2 months laps time between feedstock purchase and first incomes, with an interest rate of 5%.

Eventually, specific profit $Prof_{sp}$ (XOF.kg^{-1}seeds) is calculated following equation (8), in currency unit by feedstock mass unit.

$$Prof_{sp} = \left(\frac{Pr_{svo} \cdot Q_{svo}}{\rho_{svo} \cdot 10^{-3}} + Q_{sc} \cdot Pr_{sc} \right) \cdot \frac{1}{Q_{seed}} - \left(C_{proc} + Pr_{seed} \right) \qquad (8)$$

where $Pr_{SVO} = 500\ XOF.l^{-1}$ is SVO selling price ; $Q_{SVO}\ (kg.year^{-1})$ is the annual SVO production ; $\rho_{SVO} = 930\ kg.m^{-3}$ is SVO density ; $Q_{sc}\ (kg.year^{-1})$ is the annual seedcake production ; $Pr_{sc} = 40\ XOF.kg^{-1}$ is seedcake selling price ; $Pr_{seed} = 75\ XOF.kg^{-1}$ is feedstock purchase price.

3- RESULTS AND DISCUSSION

To study the profitability conditions of a small oil plant, two sensitivity analyses have been made to observe the processing costs and specific benefit versus (i) processing capacity and (ii) oil recovery. Results of the first study, which reflects the economies of up-scaling, are represented on Figure 2. The activity is profitable from 100 tons of seeds per year. The second study, presented on Figure 1, emphasises that processing costs increase slightly from 50% oil recovery to 80% and then grow sharply, doubling when oil recovery increases from 80% to 85%.

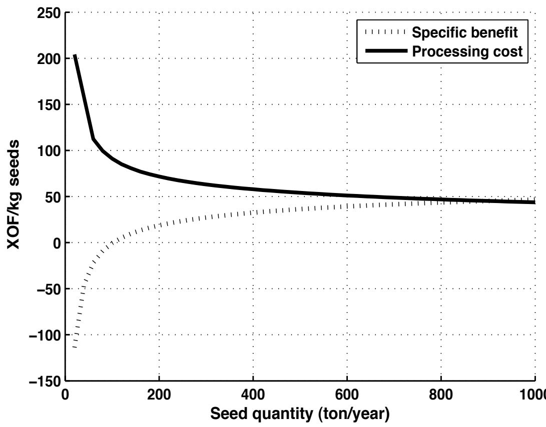

Figure 2. Processing costs and benefits versus annual seed quantity. O_{rec}=75%

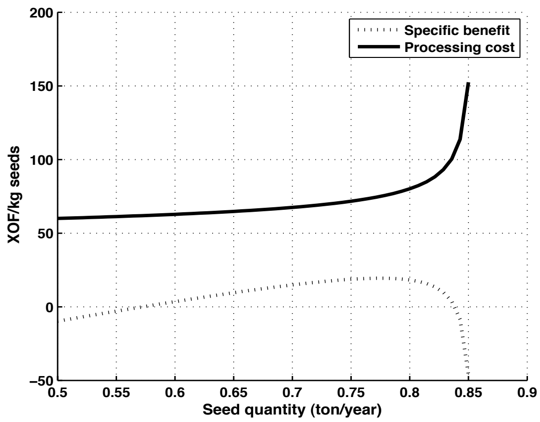

Figure 1. Processing cost and benefits versus oil recovery. Q_{seed}=100 t.year^{-1}

In fact, the activity is profitable due to seedcake's sale. Without it, the SVO production cost, including seeds purchase and processing costs, is higher than the selling price. More generally, the overall performances of the production system, in terms of economy (profitability and efficiency), energy and environment, are largely conditioned by seedcake valorization technique. The three most likely options in the context are direct use as fertilizer, combustion and anaerobic digestion.

Assuming the seeds oil content is 35% and oil recovery is set to 75%, the seedcake contains around 12% of oil. Such seedcake has a biochemical methane potential of 0.30 Nm3 CH_4.kg^{-1}

TS according to [13] and a lower heating value around 20 $MJ.kg^{-1}$ [5, 14]. For further discussion, it is important to keep in mind that both methane potential and energy content increase dramatically with seedcake oil content. Besides, nutrient content depends on oil extraction conditions, as part of the phosphorus can be dissolved in oil in the form of phospholipids [3]. Chemically de-oiled seedcake has an average nutrient content of N: 5.5% - P: 2.6% - K: 1.3% [5], which is relatively high compared to other organic fertilizer such cow manure.

Local field experiments of Jatropha seedcake application as fertilizer on edible crops have shown very good results [5]. Moreover, Devappa et al. have recently shown that the main toxic compounds of Jatropha, namely phorbol esters, are completely degraded in soil after 20 days or so [15]. This result removes most concerns on the safety of Jatropha seedcake application on edible crops. In addition, the seedcake have pesticide properties [5]. Therefore, seedcake appears to be a good substitute to chemical fertilizer, a scarce and expensive product. It requires transporting the seedcake back to the fields, which will probably be done using animal-driven carts, thus implying no extra energy costs.

Jatropha seedcake has proven to be a good feedstock for biogas production [16]. This option would provide extra energy while keeping production of a good organic fertilizer via the fermentation slurry. However, this option requires further technological equipment and technical competence. Biogas can either be used to fuel internal combustion engines for electric or shaft power generation, or for heat generation for example for cooking needs or drying process. The first option requires clean biogas, with constant properties, which implies heavy production equipment. The second option is technically simpler: it can be accomplished using a basic bio-digester. However, due to the seasonal availability of humid biomass in Burkina Faso, it seems uneasy to stably run a biodigester all year and from practical considerations, heating or cooking services may be better controlled with solid feedstock combustion. Anyway, one of the main drawbacks is the water requirement of bio-digestion, especially since Jatropha seedcake is dry and water resource is already an important issue in Burkina. Then mixing seedcake with other fermentable material is to be considered in order to (i) define optimal biochemical conditions for stable and efficient digestion process; (ii) ensure feedstock supply to the biodigester all year long; (iii) limit water consumption by mixing with more humid feedstock.

Eventually, the seedcake can be burnt for heat production needs. Its high energy content actually makes it an attractive solid fuel. However experiments [12] have shown that the combustion of seedcake in conventional cook stove releases a lot of smoke, due to oil content. It might be preferable to consider its use in an adapted industrial boiler.

4- CONCLUSIONS

Concerning oil production, the lowest unit size for profitable activity is about 100 $tons.year^{-1}$ following simulation results, which represents at least 100 ha of Jatropha in Burkina: this is already a much higher scale than what is envisioned by many NGOs on the field. Then, in a farming feedstock production scheme, there should be an upper limit where the distances are too long to bring the seeds to the oil plant and distribute the SVO. Seedcake valorization is crucial to consider since it can considerably increase added value of the sector without increasing cultivated area. In term of overall operating strategy, it might be useful to adjust seedcake oil content for higher biogas potential or energy content.

This study clearly raises the importance of production scale and adequacy of technology choices in the sustainability of Jatropha biofuel system. From the above discussion on production scale and seedcake valorization, one can imagine several foreseeable system configurations, but choosing the best ones is not straightforward. As a general trend, excessive centralization of transformation plants (oil and biogas plant) is more likely to benefit to urban communities and industry instead of rural development, whereas excessive decentralization presents an economic risk due higher costs. Furthermore, the use of advanced technologies for by-products valorization is crucial to increase the added value created from the same cultivated area, but requires a minimum production level to be profitable.

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