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Research paper

# Evaluation of alternatives for the evolution of palm oil mills into biorefineries

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ABSTRACT

Six alternatives for the conversion of an average Colombian palm oil mill (30 t $h^{-1}$ of fresh fruit bunches (FFB) into biorefineries were evaluated. The alternatives studied were: (C1) Production of biogas from the Palm Oil Mill Effluents (POME), (C2) Composting of empty fruit bunches (EFB) and fiber, (C3) Biomass combustion for high pressure steam combined heat and power, (C4) Pellets production, (C5) Biochar production and, (C6) Biochar and bio-oil production. The available biomass could result in up to 125 kWh of electricity, 207 kg of compost, 125 kg of pellet, 44 kg of biochar and 63 kg of bio-oil per metric ton of FFB. The global warming potential (GWP), eutrophication potential (EP), net energy ratio (NER), capital expenditures (CAPEX), operational costs (OPEX), net present value (NPV) and internal rate of return (IRR) were calculated for all the alternatives. GHG reductions of more than 33% could be achieved. Anaerobic digestion and composting contributed to 30% reduction of the EP. The CAPEX for all of the biorefinery alternatives studied varies between 0.7 \$ $t^{-1}$ and 2.8 \$ $t^{-1}$ of FFB. The OPEX varies between 1.6 \$ $t^{-1}$ and 7.3 \$ $t^{-1}$ of FFB. The NPV for viable scenarios ranged between 2.5 million and 13.9 million US dollars. The IRR calculated varied between 3% and 56% and the payback periods were between 3 and 8 years. The total extra incomes reached values up to 15.2 \$ $t^{-1}$ of FFB. Overall the pellets production biorefinery was the preferred alternative.



## 1. Introduction

Crude Palm Oil (CPO) is the largest vegetable oil produced in the world. In 2014, CPO production was 59.2 million tonnes per year (30% of the mass of total vegetable oil produced in the world), followed by soybeans with 45.1 million tonnes per year, and rapeseed oil with 27.2 million tonnes per year [1]. The associated residual solid biomass produced at palm oil mills (POMs) is around twice the amount of CPO produced. This solid biomass is composed (mass fraction of fresh fruit bunches (FFB)) of empty fruit bunches (EFB) (at 22% mass fraction of FFB), oil palm fiber (fiber) (at 13% mass fraction of FFB) and oil palm shell (shell) (at 4.5% mass fraction of FFB). Additionally, 800 $dm^3$ $t^{-1}$ of FBB is produced as palm oil mill effluents (POME). Because of the availability of this biomass, in a single point during the entire year, and the environmental and economic concerns, the potential uses of this biomass for different purposes has gained increased attention [2–7].

The recognition of the potential environmental and social impacts of the palm oil agribusiness, led to the emergence of the Roundtable on Sustainable Palm Oil (RSPO) in 2003 [8]. Globally, countries producing CPO have been adjusting environmental standards to comply with the recommendations of the RSPO. In the case of Colombia, the Ministry of Environment and Sustainable Development has set environmental regulations regarding the emissions of particulate matter from stationary sources (such as boilers using biomass as fuel) and pollutants discharges into water bodies. The requirement of particulate material leaving new boilers has been reduced to 50 mg $m^{-3}$ [9]. The new regulations also

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require the establishment of targeted values for BOD (biological oxygen demand), COD (chemical oxygen demand), TSS (total suspended solids), chlorides, sulphates, and cadmium for POME [10], which cannot be achieved with the anaerobic and facultative oxygenation lagoons currently used.

The gradual evolution of POM into biorefineries is presented as an opportunity not only to comply with the new strictest environmental standards, but also to enable the creation of new products and opportunities for higher profitability [4,5,11]. The selection of biorefinery options requires a thorough analysis of the impact of each of the concepts studied on sustainability indicators [12]. Different methodologies have been published for selecting biorefinery options [13]. Some of them focus on environmental aspects [2,14], some include economic indicators [15–17], others include both environmental and cost analysis [11,18,19], some also include social aspects [12,13,20].

In the frame of a European Integrated Project called Biosynergy [21], Chong [13] developed a holistic methodology for socio-economic, technical, and environmental evaluation of 27 biorefinery options for the European Union. Different biomass, locations, supply chains, potential products etc. were analyzed to conceptualize new biorefinery alternatives. In the case of a POM, where the biomass is available the entire year in a single location close to an existing industrial infrastructure; the synergism between the POM, and the new processes should be taking into consideration.

The main goal of this paper is to compare alternatives for converting an existing palm oil mill into a biorefinery taking into account environmental, economic, and social sustainability indicators. From the environmental point of view, global warming potential GWP, eutrophication potential (EP), and net energy ratio (NER) in life cycle were considered. For the economic assessment, net present value (NPV), internal rate of return (IRR), payback period and extra incomes were calculated. Social aspects were covered taking into account the number of new workers and their expertise.

## 2. Materials and methods

### 2.1. Methodology for evaluation of biorefinery alternatives

In order to set up our proposed methodology for selecting a biorefinery coupled with an existing agroindustry, a literature review on biorefinery selection strategy was carried out [11,13,19,22,23]. This paper will follow the methodology shown in Fig. 1 [24]. The first step of this methodology is to collect data to build the baseline scenario for the POM studied and the corresponding plantation. Based on the literature we choose six emerging technologies with sufficient level of maturity (technology readiness level, TRL > 6) and potential to build the six biorefinery concepts studied. Mass and energy balance models of the baseline scenario and the selected biorefinery concepts were solved in Excel spreadsheets. The technically feasible alternatives were further analyzed to estimate economic, environmental and social indicators. For Life Cycle Assessment (LCA), GWP, EP and NER were considered. NPV, payback period, IRR, were considered during the economic evaluation. For evaluation of social aspects, the number of workers and the expertise of those workers were considered. A decision matrix was built to support the comparison between the alternatives.

### 2.2. Baseline scenario

We created a baseline scenario of a hypothetical oil palm agribusiness with a POM representative of a middle size production system in Colombia. The information used to build this baseline scenario was obtained through surveys and visits to *Aceites Manuelita S.A*, *Entrepalmas S.A.S*, and *Palmeras Morichal Ltda* located in Meta, *C.I. Tequendama S.A.S* located in Magdalena, and *Agroince S.A.S.* located in Cesar.

The POM baseline scenario has a capacity of 30 t $h^{-1}$ of FFB working 5000 h $y^{-1}$. The FFB yield of the associated plantation was 18.23 t $ha^{-1}$ $y^{-1}$. This corresponds to a POM receiving 150,000 t of FFB from approximately 8 200 ha. The agricultural inputs (chemical fertilizers, agrochemicals, and fuels) can be found elsewhere [24] (more information can be found in supplementary material A). The water, steam and electrical requirements; boiler and steam turbine efficiency; oil and kernel extraction rates; and yields of EFB (215 kg $t^{-1}$ of FFB), fiber (125 kg $t^{-1}$ of FFB), shell (60 kg $t^{-1}$ of FFB) and POME as well as the elemental and proximate analysis of the biomass were obtained from Ref. [24] (for more information in supplementary material A). The moisture mass fraction of the EFB, fiber and shell as 65%, 35% and 14% mass fraction respectively. In the baseline scenario the POME (0.8 $m^3$ $t^{-1}$ of FFB) is treated in anaerobic and facultative open lagoons with no biogas recovery. The cogeneration system at the mill supplies only the energy that is required to run the mill using a back pressure steam turbine (BPT). The efficiency of the cycle was obtained using GateCycleTM analysis software [25] assuming the turbine isentropic efficiency of 72% and using the data shown in Ref. [24] (See supplementary material A). No electricity from the Colombian electrical grid was considered. It was considered that 25% of energy requirements were generated in a diesel engine (5.5 kWh $t^{-1}$ of FFB) mostly to supply the electricity used during the start, failures and maintenance periods.

### 2.3. Biorefinery concepts

A literature review was conducted to identify the maturity level of the emerging technologies that have been used for the processing of palm oil mill (POM) biomass [2–6,23,26–33]. The selection of the emerging technologies to be used to build the biorefinery concepts was carried out using the technology readiness classification proposed by Ref. [34]. The authors assigned the TRL value for each technology based on the literature review [23] but with small modifications taking into account the level of use in POMs. The technologies analyzed were: (pellets and briquettes (TRL 8), cellulosic ethanol (TRL 4), torrefaction (TRL 4), biochar (TRL 6), fast pyrolysis (TRL 6), bio-composites (TRL 5), cellulose pulp and paper (TRL 4), bio-plastic (TRL 4), hydrogen and syngas (TRL 4), biogas (TRL 9), compost (TRL 9), food and ruminants (TRL 4), chemicals via catalytic technologies (TRL 3), enzymes production (TRL 3), phenol from effluents (TRL 3), electricity generation (TRL 9). Those with technology readiness level (TRL) values greater or equal than 6 were chosen. Thus, the biorefinery concepts selected were combinations of six technologies (pressing and drying, cogeneration, anaerobic digestion, composting, pellet production, and pyrolysis) that are described as follow.

*Pressing, cutting, and drying*: The EFB will be pressed to reduce the moisture mass fraction from 60–65% to 25–30%. A 5–6 t $h^{-1}$ EFB press will consume 75 kW [35]. The electricity consumption for the cutting and drying line was considered 386 kW for a 4–5 t $h^{-1}$ unit [36]. For pellets production and pyrolysis, it is considered that pressed EFB, fiber and shell will be dried to 10% mass fraction of water, using a rotating drum [37]. The flue gas from the biomass boilers (187 °C) and the hot gases from the combustion of the biogas in an internal combustion engine (generator) (450 °C) were the main two sources used for drying. Mass and energy balance equations of the solid and gases fluxes were used to determine the total energy requirements for drying [37]. 10% of the available total energy in the gas inlet was considered to be lost through the walls

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