Integrated Production of Fuels, Energy and Chemicals from *Jatropha curcas*: Multi-objective Optimisation of Sustainable Value Chains

Stephen S. Doliente[a,b], Sheila Samsatli[a,*]

[a]Department of Chemical Engineering, University of Bath Claverton Down, Bath BA2 7AY, United Kingdom
[b]Department of Chemical Engineering, College of Engineering and Agro-Industrial Technology, University of the Philippines Los Baños, Laguna 4031, Philippines
s.m.c.samsatli@bath.ac.uk

In this work, a comprehensive optimisation model, based on mixed-integer linear programming, was developed that can support complex decision-making related to multi-product Jatropha value chains and can capture the trade-offs between water, energy and land utilisation. The model can identify promising Jatropha value chains for sustainable and efficient production of energy, fuels and chemicals. This paper presents the optimisation model and the key findings from a preliminary case study on biodiesel production for the Philippines.

1. Introduction

Biofuels play a significant role in meeting the decarbonisation targets of the world's transport fleet. In 2016, world biodiesel production stood at 33 billion litres per year, which grew forty times from 2000. Most of the biodiesel produced is from oil rich food crops such as palm oil, soybean and rapeseed. The sustainability of biodiesel produced from these first generation feedstocks is a concern due to the competition of these crops with food production for land, water, and energy resources (Tapia et al. 2019). Biodiversity loss has also been associated with biomass feedstock production due to expansion into forest land (Beaver et al. 2016). The availability of food crop based feedstocks is another issue. In the Philippines, for example, biodiesel is produced only from coconut, which has high priority demands in both the food and oleo-chemical industries. Considering these challenges, there is a need to shift towards non-food based feedstocks for biodiesel production in order to improve its socio-economic and environmental sustainability. The inedible oil-rich seeds of *Jatropha curcas* (henceforth Jatropha) is a promising alternative to food crops. Moreover, the high-yielding potential, versatility to soil and water conditions, and drought resistant characteristics of Jatropha offer an advantage over land- and water-intensive feedstocks (Moioli et al. 2016). Jatropha-based biorefineries show that a variety of products, aside from biodiesel, such as bio-electricity, bio-ethanol, pyrolysis oil, bio-naphtha, soap etc., can be produced from whole-crop processing (Navarro-Pineda et al., 2016). A closed-loop bio-economy with various pathways for energy, fuels and chemicals production can be based entirely on Jatropha. The management of the activities across the value chains, such as cultivation, processing to generate the products, and distribution of the products to consumers, is essential for an efficient, profitable and sustainable implementation. While there have been a few studies on supply chain modelling for biodiesel production from Jatropha, to date there has been no modelling and optimisation study performed on multi-product value chains for Jatropha across various sustainability criteria. This work aims to determine sustainable Jatropha value chains for the integrated production of fuels, energy and chemicals. With the Philippines as the study region, land suitability modelling is used to determine the potential available land for cultivation of Jatropha but excluding forest cover, protected areas and existing land-uses. Then a multi-objective spatio-temporal mixed integer linear programming model for Jatropha value chains was developed for the Philippines. A case study on economically and environmentally favourable Jatropha value chains for the provision of biodiesel is reported in this paper.

2. Land Suitability Modelling

Utilising the Philippine land cover data from PhilGIS, the potential available land for Jatropha cultivation in the 81 provinces of the country was modelled using ArcGIS Desktop 10.5. The potential available land types considered were arable land, grassland, cultivated land mixed with grassland, barren land and eroded land. Figure 1 presents the distribution of these lands in the top 40 provinces with the highest potential availability. A total of 16 million ha is potentially available throughout the country for Jatropha cultivation. The majority of potentially available lands are cultivated land mixed with grassland (61 % of the total). Arable lands and grasslands are 27 % and 11 % of the total, respectively. Both the barren and eroded lands only account to less than 1 % of the total.
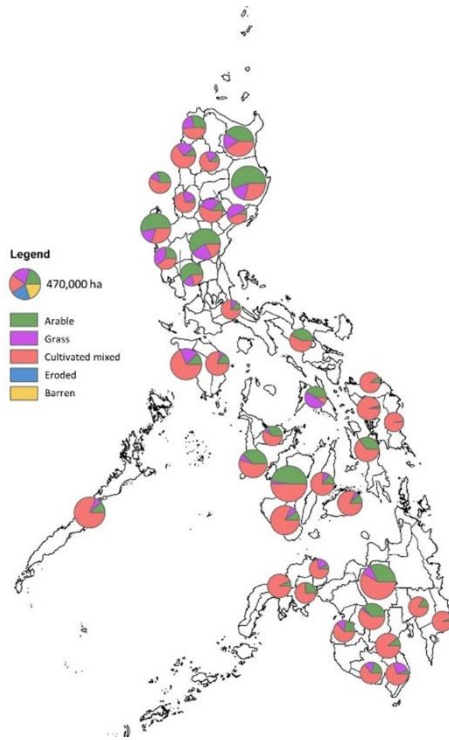

Figure 1. Distribution of potential available land in the Philippines for Jatropha cultivation. Only the 40 provinces with the highest land area are shown.

3. Problem Statement

The problem involves determining simultaneously the decisions for designing and operating the value chains such as: the location of Jatropha plantations; the amount of land allocated; the type and quantity raw materials to utilise and products to generate (e.g. energy, fuels and chemicals); the processing technologies to invest in and their locations; the pre-processing of raw materials before conversion and/or transportation; the transporting technologies for raw materials and products distribution; all of these in order to maximise of the net present value (NPV) while at the same time minimising greenhouse gas (GHG) emissions.

4. Mathematical Model

A spatio-temporal mixed-integer linear programming model was developed for the Philippine Jatropha value chains, based on the Value Web Model (Samsatli and Samsatli 2018, Samsatli and Samsatli 2019). A 30-year planning horizon, from 2020 to 2050, was considered. The model can consist of multiple time scales: planning periods $y \in \mathbb{Y}$, seasons $t \in \mathbb{T}$, day types $d \in \mathbb{D}$ and hourly intervals $h \in \mathbb{H}$. The Philippines is represented by 81 zones (corresponding to the Philippine provinces) in the model (Doliente and Samsatli 2019). Each zone, $z \in \mathbb{Z}$, has data on the potentially available land, Jatropha fruit yield, the impacts of Jatropha cultivation, existing processing technologies and existing transporting infrastructures. Moreover, each of the zones has coordinates (x_z, y_z) for the representation of the demand centres and calculation of transport distance $d_{zz'}$ (km) from zone z to zone z'.

4.1 Constraints

The resource balance is expressed in Eq(1) and considers the input and output terms for every resource $r \in \mathbb{R}$ in zone z during hour h of day type d in season t of planning period y. The rate of utilisation U_{rzhdty} in Eq(2) expresses that the maximum availability u_{rzhdty}^{max} (odt/h or MWh/h) cannot be exceeded. The total quantity of biomass (e.g. Jatropha fruit, Jatropha woody biomass), represented by index c, used in each season t cannot exceed the seasonal availability as stated in Eq(3). The local and national land footprint constraints are given in Eq(4) and Eq(5), respectively, which make sure that the allocated area A_{czy}^{Bio} (ha) for a biomass resource c in zone z during planting period y, cannot be more than the maximum fraction of the potentially available land in each zone z; and the total allocated area for biomass cannot be more than the maximum fraction of the total potentially available land at the national level, respectively. Eq(6) expresses the net rate of resource production (or consumption, if negative) P_{rzhdty} (odt/h or MWh/h); where α_{rpy} is the conversion factor of a resource r in processing technology $p \in \mathbb{P}$ in planning period y. Eq(7) is the expression for the rate of operation of a single processing technology $\mathcal{P}_{pzhdty}$, which is limited by its minimum and maximum values, $p_p^{\min}$ and $p_p^{\max}$, respectively. Furthermore, Eq(8) expresses that the number of commercial processing technologies invested N_{pzy}^{PC} must not exceed the maximum number, BR_{py}, that can be installed in planning period y. The net rate of transport Q_{rzhdty} (odt/h or MWh/h) of resource r between zones z and z' is expressed in Eq(9) where $\bar{\tau}_{lr,dst,y}$ and $\bar{\bar{\tau}}_{lr,dst,y}$ are the distance-dependent and distance-independent conversion factors for a transporting technology $l \in \mathbb{L}$ of resource r during planning period y, respectively. The rate of operation of a transport technology $q_{lzz'hdty}$ is limited up to its maximum capacity and the total rate of operation of all transporting technology is also limited up to the capacity of a transporting infrastructure $b \in \mathbb{B}$, as expressed in Eq(10) and Eq(11), respectively. There are two types of demand (odt/h or MWh/h) in the model: demands that must always be satisfied D_{rzhdty}^{comp} and demands that may be optionally satisfied D_{rzhdty}^{opt}. The optional demand satisfied D_{rzhdty}^{sat} is expressed in Eq(12) as the optimisation determines the type and quantity of product to generate from the resources and the demands to satisfy. Lastly, Eq(13) and Eq(14) expresses the rate of import I_{rzhdty} and rate of export E_{rzhdty}, respectively, which must not exceed their maximum capacities I_{rzhdty}^{max} and E_{rzhdty}^{max}, respectively.

$$U_{rzhdty} + I_{rzhdty} + P_{rzhdty} + Q_{rzhdty} \geq D_{rzhdty}^{comp} + D_{rzhdty}^{sat} + E_{rzhdty}$$

$$\forall\, r \in \mathbb{R}, z \in \mathbb{Z}, h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \tag{1}$$

$$U_{rzhdty} \leq u_{rzhdty}^{max} \qquad \forall\, r \in \mathbb{R} - \mathbb{C}, z \in \mathbb{Z}, h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \tag{2}$$

$$\sum_{hd} U_{czhdty} n_h^{hd} n_d^{dw} n_t^{wt} \leq A_{czy}^{Bio} Y_{czty}^{Bio} \qquad \forall\, c \in \mathbb{C}, z \in \mathbb{Z}, t \in \mathbb{T}, y \in \mathbb{Y} \tag{3}$$

$$\sum_c A_{czy}^{Bio} \leq f_{zy}^{loc} A_{zy}^{Bio,max} \qquad \forall\, z \in \mathbb{Z}, y \in \mathbb{Y} \tag{4}$$

$$\sum_{cz} A_{czy}^{Bio} \leq f_y^{nat} \sum_z A_{zy}^{Bio,max} \qquad \forall\, y \in \mathbb{Y} \tag{5}$$

$$P_{rzhdty} = \sum_p \mathcal{P}_{pzhdty} \alpha_{rpy} \qquad \forall\, r \in \mathbb{R} - \mathbb{C}, z \in \mathbb{Z}, h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \tag{6}$$

$$N_{pzy}^{PC} p_p^{min} \leq \mathcal{P}_{pzhdty} \leq N_{pzy}^{PC} p_p^{max} \qquad \forall\, p \in \mathbb{P}^C, z \in \mathbb{Z}, h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \tag{7}$$

$$\sum_c N_{pzy}^{PC} \leq BR_{py} \qquad \forall\, p \in \mathbb{P}^C, y \in \mathbb{Y} \tag{8}$$

$$Q_{rzhdty} = \sum_{z'|v_{z'z}=1} \sum_{l \in \mathbb{L}} \left[(\bar{\tau}_{lr,dst,y} + \bar{\bar{\tau}}_{lr,dst,y} d_{zz'}) q_{lz'zhdty} \right] + \sum_{z'|v_{zz'}=1} \sum_{l \in \mathbb{L}} \left[(\bar{\tau}_{lr,dst,y} + \bar{\tau}_{lr,dst,y} d_{zz'}) q_{lzz'hdty} \right]$$

$$\forall\, r \in \mathbb{R}, z \in \mathbb{Z}, h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \tag{9}$$

$$q_{lzz'hdty} \leq \sum_{b\in\mathbb{B}} q_l^{max} N_{bzz'y|LB_{lb}=1\wedge v_{zz'}=1}^{\boldsymbol{B}} \qquad \forall\, l \in \mathbb{L};\ z,z' \in \mathbb{Z};\ h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \tag{10}$$

$$\sum_{l\in\mathbb{L}} q_{lzz'hdty} LB_{lb} \leq b_b^{max} N_{bzz'y}^{\boldsymbol{B}} \qquad \forall\, b \in \mathbb{B};\ z,z' \in \mathbb{Z};\ h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \tag{11}$$

$$D_{rzhdty}^{sat} \leq D_{rzhdty}^{opt} \qquad \forall\, r \in \mathbb{R}, z \in \mathbb{Z}, h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \tag{12}$$

$$I_{rzhdty} \leq I_{rzhdty}^{max} \qquad \forall\, r \in \mathbb{R}, z \in \mathbb{Z}, h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \tag{13}$$

$$E_{rzhdty} \leq E_{rzhdty}^{max} \qquad \forall\, r \in \mathbb{R}, z \in \mathbb{Z}, h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \tag{14}$$

4.2 Objective Function

To evaluate the trade-offs between conflicting objectives, the model is formulated as a multi-objective optimisation problem. This is transformed into single objective optimisation problem through different combinations of weighting factors for the economic and environmental impacts. The weighting method expression is $\min Z = \sum_1^N w_m Z_m$, where Z_m are individual impacts; w_m are weighting factors that can assume values between 0 and 1; and $\sum_{1=1}^N w_m = 1$. The objective function to be minimised is shown in Eq(15):

$$Z = \sum_{my} w_m \left(\mathcal{I}_{my}^{\mathrm{P}} + \mathcal{I}_{my}^{\mathrm{Q}} + \mathcal{I}_{my}^{\mathrm{fp}} + \mathcal{I}_{my}^{\mathrm{fq}} + \mathcal{I}_{my}^{\mathrm{vp}} + \mathcal{I}_{my}^{\mathrm{vq}} + \mathcal{I}_{my}^{\mathrm{i}} + \mathcal{I}_{my}^{\mathrm{e}} + \mathcal{I}_{my}^{\mathrm{U}} - \mathcal{I}_{my}^{\mathrm{Rev}} \right) \tag{15}$$

The impacts in year y on performance metrics m are the following: the total net present capital impact of technologies for processing $\mathcal{I}_{my}^{\mathrm{P}}$ and transporting $\mathcal{I}_{my}^{\mathrm{Q}}$; the total net present fixed operating impact of technologies for processing $\mathcal{I}_{my}^{\mathrm{fp}}$ and transporting $\mathcal{I}_{my}^{\mathrm{fq}}$; the total net present variable operating impact of technologies for processing $\mathcal{I}_{my}^{\mathrm{vp}}$ and transporting $\mathcal{I}_{my}^{\mathrm{vq}}$; the total net present impact of importing resources $\mathcal{I}_{my}^{\mathrm{i}}$; the total net present impact of exporting resources $\mathcal{I}_{my}^{\mathrm{e}}$; the total net present impact of utilising resources $\mathcal{I}_{my}^{\mathrm{U}}$; and the total net present revenue from sale of resources (e.g. biofuels, bio-electricity, etc.) $\mathcal{I}_{my}^{\mathrm{Rev}}$. The performance metrics in this study are $m \in \{Cost, CO_2\}$. When $w_m \equiv \{1,0\}$, the problem is to maximise the NPV; and when $w_m \equiv \{0,1\}$, the problem is to minimise the GHG emissions.
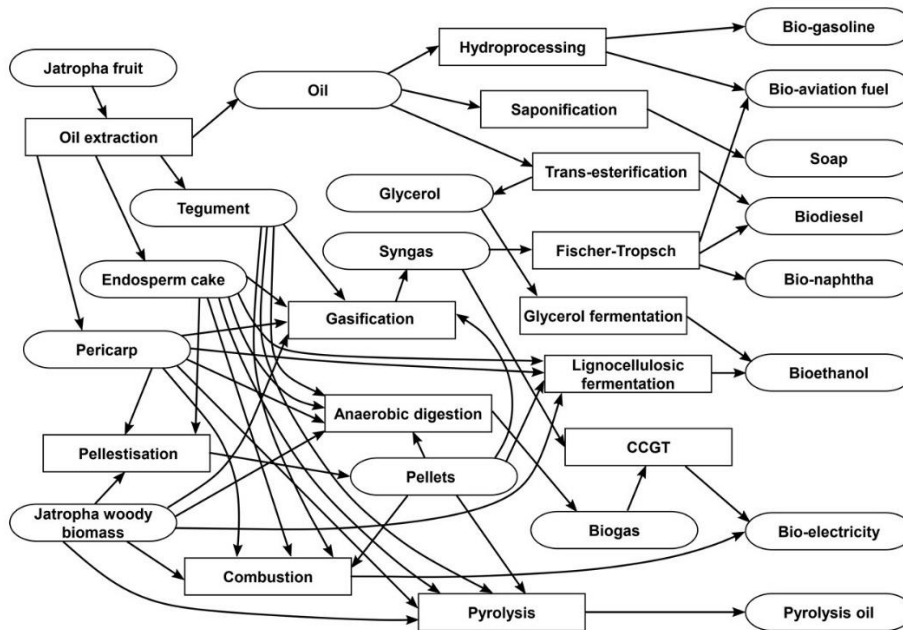
4.3 Network Superstructure

Figure 2: Jatropha value chain superstructure showing the various potential conversion pathways

The value chain superstructure in Figure 2 shows the potential pathways for multi-product generation from the fruit and woody biomass of Jatropha and the residues left after oil extraction of the seeds. The oil is mainly intended for biodiesel production, but it can also be saponified to produce soap and hydroprocessed to generate bio-aviation fuel and bio-gasoline. The woody biomass and the residues (endosperm cake, pericarp and tegument) can be converted through thermo- and bio-chemical technologies such as boiler-steam turbine, anaerobic digestion and combined cycle gas turbine (CCGT) for energy; lignocellulosic fermentation and pyrolysis for fuels; and gasification and Fischer-Tropsch synthesis for both fuels and chemicals. The valorisation of glycerol from biodiesel production to bioethanol is also considered, as is the densification of both the woody biomass and residues. The optimisation model inputs are the spatial and temporal availability of the biomass (in each of the potentially available lands) and the product demands. It also requires the characteristics of each of the processing and transport technologies (CAPEX, OPEX, conversion factors, etc). For a given objective, the model determines the optimal locations for Jatropha cultivation and the sites for processing technologies. The model can decide the type and amount of resources to utilise and generate based on the specified demands. The model can also choose between barge and/or truck transport of the biomass and the operation of these transport networks.

5. Case Study

The model is applied to a fuel only case study for the Philippines, wherein the NPV is to be maximised. At 2 % mandated blending, the average biodiesel consumption of the country is 2252 GWh/y. The economic and environmental performance of Jatropha value chains for the total provision of this biodiesel requirement was determined. Figure 3 below shows that complete satisfaction of the biodiesel by the Jatropha value chains is both economically and environmentally favourable. Within the planning horizon, the NPV is PhP 15.37 billion (or USD 302.68 million) and the GHG emission savings are 2.79 $MtCO_2eq$. The total resource import impact is the primary contributor to the total impact due to the expensive base catalyst required in the transesterification process. The benefits of recycling the base catalyst and its production by renewable sources can be further investigated.
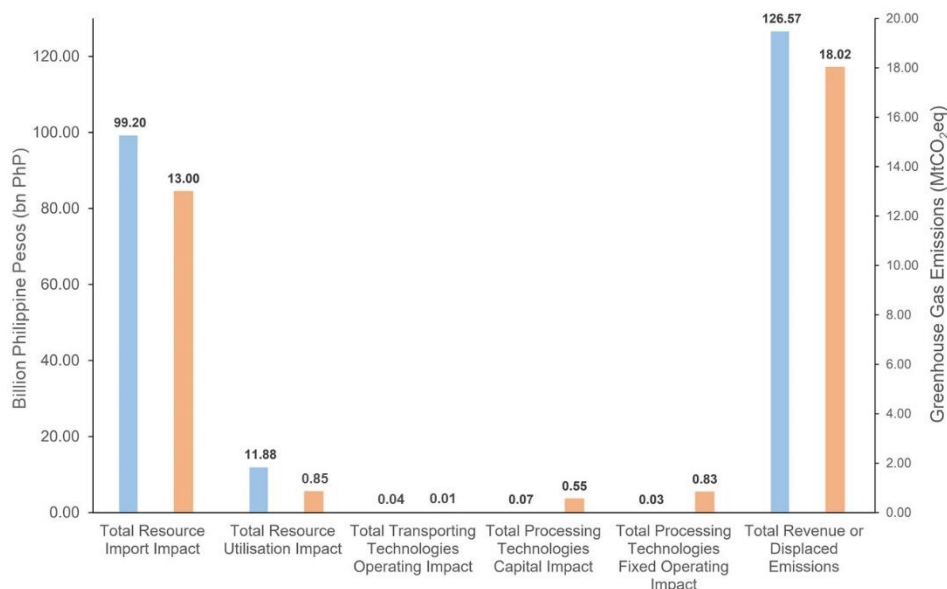

Figure 3. Breakdown of impacts of the optimal scenario for Jatropha-based biodiesel production in the Philippines. Blue bars are the NPV (bn PHP) and the orange bars are the GHG emissions ($MtCO_2eq$).

The optimal design and operation of the Jatropha value chains for biodiesel provision in the Philippines is presented in Figure 4. Figure 4(a) shows the allocated area of potentially available lands for Jatropha cultivation. A total of 1.49 million ha is to be allocated for Jatropha plantations, which is only 5 % of the total land area of the country. Bulacan (zone 22) has the highest allocated area at 166 kha among the provinces in order to supply Jatropha fruit to Metro Manila (zone 23), which has the highest biodiesel consumption of 287.15 MWh/y. Hence, Metro Manila would need two oil extraction-transesterification facilities while the other provinces need only a single unit, as shown in Figure 4(b). The transport of Jatropha fruit by barge shown in Figure 4(c) is recommended, especially for provinces, such as Batanes (zone 1), Sulu (zone 80) and Tawi-Tawi (zone 81),

which do not have potentially available lands for Jatropha cultivation. Overall, the optimisation results reveal a decentralised operation of the Jatropha value chains for biodiesel provision of the country.
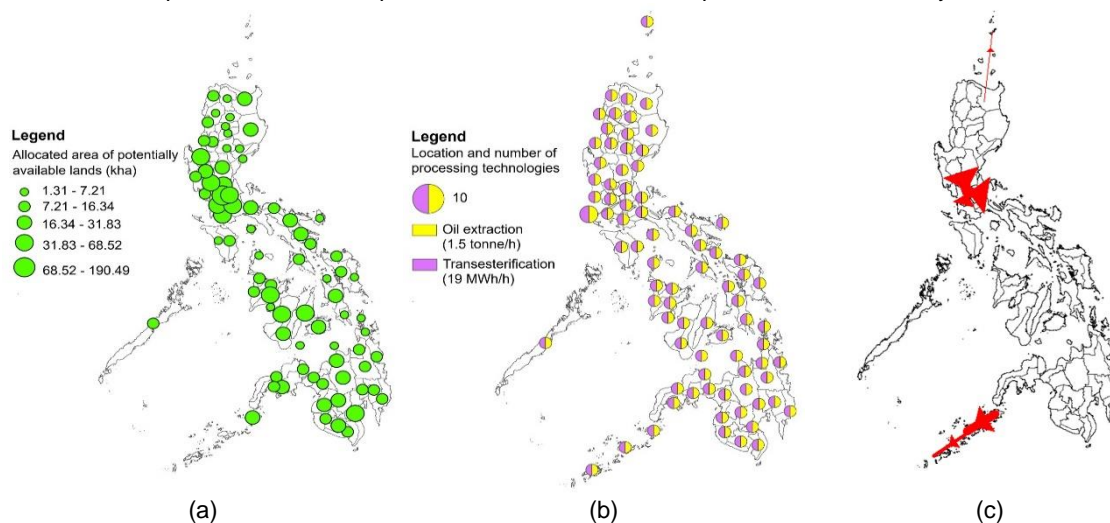

Figure 4. Optimisation results: (a) allocated areas for Jatropha cultivation; (b) location and number of processing technologies; and (c) barge transport of Jatropha fruit.

6. Conclusions

The land suitability modelling revealed 16 million ha of potentially available lands in the Philippines for sustainable cultivation of Jatropha, which would not result in land-use conversion of forests and protected areas. Then a mixed-integer linear programming model was developed for the simultaneous planning, design and operation of multi-product Jatropha value chains. The model was applied to a case study for the total provision of the annual biodiesel demand of the Philippines. The optimal Jatropha value chains were both economically and environmentally favourable within the planning horizon. A decentralised design and operation of the optimal Jatropha value chains for biodiesel provision of the country is recommended.

Acknowledgments

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