

# Exergetic Efficiencies Evaluation of Flows and Operations on the Mechanical Extraction Process of *Jatropha curcas* Oil

Rolf Nirahina Rakoto Harifidy, Hery Tiana Rakotondramiarana

Institute for the Management of Energy (IME), University of Antananarivo, Antananarivo, Madagascar

Email: harifidyrolf@gmail.com

**How to cite this paper:** Harifidy, R.N.R. and Rakotondramiarana, H.T. (2019) Exergetic Efficiencies Evaluation of Flows and Operations on the Mechanical Extraction Process of *Jatropha curcas* Oil. *Open Journal of Energy Efficiency*, 8, 1-20.  
<https://doi.org/10.4236/ojee.2019.81001>

**Received:** December 6, 2018

**Accepted:** January 15, 2019

**Published:** January 18, 2019

Copyright © 2019 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

## Abstract

*Jatropha curcas* oil is one of the most promising renewable energy sources for rural areas due to its ease of production, which can be used as an alternative to diesel and fuel oil. The development of sustainable energy has been the issue of the discussion about biofuel production given the considerable consumption amount of fossil fuel during the transformation process. And any production process that consumes a lot of energy records a significant destruction of useful energy, which leads to thermodynamic inefficiencies of the process. Besides, the focus on environmental safety is gradually shifting towards energy efficiency in industrial processing. Exergetic analysis is an effective tool for measuring the performance of a production process since exergy is a quantity that measures energy quality. This study assesses the scale of resource degradation in *Jatropha* oil mechanical extraction processes and finds improving possible pretreatments options for more efficient production. Data from experiments combined with existing databases have permitted to establish the exergy flow balance at each stage of production. The process exergetic yield varies from 29.85% to 35.41% according to the chosen pretreatment process. Mass exergy accounts for 67% of incoming flows and, for outgoing flows, more than 60% is associated with the mass exergy generated by the process waste. The uncertainties analysis on the results was used to validate model results, and to visualize the minimum values for the most unfavorable cases and the maximum values when all the parameters are at their optimum values.

## Keywords

*Jatropha* Oil, Extraction Process, Exergetic Efficiency, Pretreatment, Mass Exergy

## 1. Introduction

Several research works on biodiesel production have recently focused on optimizing the transformation process [1]-[7] as well as on the selection of the most appropriate raw material [8]-[14]. Currently, the improvement of the process energy efficiency and the reduction of various component energy inefficiencies capture the interest of researchers [15]-[20]. Interest in the use of *Jatropha curcas* has developed over the last decade [21] [22] [23] [24].

Growing consumption of fossil fuel products leads to the search for alternative fuels limiting global warming and environmental pollution to meet energy demand. Biodiesel is one of the most prominent renewable fuels nowadays. Biodiesel has similar properties with diesel fuel. It can be mixed with diesel fuel or can be used directly in most diesel engines without major engine modifications. The other advantage is that biodiesel has lower sulfur content, with an upper limit of 10 mg/kg biodiesel, in accordance with European biodiesel standard (EN 14214).

Biodiesel from jatropha oil is a reliable source of energy that is efficient and conducive to sustainable economic development [25] [26]. Hence jatropha was chosen as raw material of the present study.

*Jatropha curcas* plantation can produce 2 to 5 tons of dry seed/ha/year. The yield varies according to the type of culture, by seeds or by cuttings; the climatic conditions as well as the management technologies used [27] [28]. *Jatropha curcas* seeds were analyzed to contain about 35% to 40% oil, or 1.75 tons/ha after extraction [27] [29] [30] [31]. White kernel contains all the oil. Moreover, it was reported from critical analysis of seeds in previous studies that *Jatropha curcas* seeds contain 6.6% moisture, 18.2% protein, 38% fat, 17.3% carbohydrate, 15.5% fiber and 4.5% ash. Oil contains about 21% saturated fatty acids and 79% unsaturated fatty acids [31].

As this kind of oil is inedible, its production should not affect the food security problem [32]. In addition, jatropha grows well on dry, marginal, and non-agricultural land, which does not compete with land required for food production and nature conservation [26] [29] [32]. Jatropha oil is considered more environmentally friendly raw material for energy production than any other food-related crop, such as palm, rapeseed, soybean or sunflower [29] [32].

While being converted to biodiesel, jatropha oil has a high potential of produced biofuel from vegetable oil as its properties are well improved and subsequently suitable for replacing fossil fuels [27] [33].

Most people in rural areas do not have access to energy sources in developing countries. An approach to provide the required energy is to enable the generation of energy from local resources. Jatropha oil is one of the most promising renewable and independent energy sources in rural areas due to the ease of its production [25] [26] [34]. The literature review on plantations and physico-chemical properties details the unexploited potential of jatropha. This information will be useful as it can serve as a reference in the framework of this study.

However, during the transformation processes, there are always losses and irreversibility which will directly affect the potential of the raw material. These data on degradations on raw materials have been infringed on the aforementioned studies to better focus on the transformation process improvement. In our case study, we will attach the same importance to transformation processes and raw material degradation.

There are commonly 4 kinds of oil extraction from seeds according to the used method, namely: solvent extraction, mechanical extraction, enzymatic extraction and aqueous extraction. For rural areas, mechanical extraction with screw press or hydraulic press is considered as the best way. It is adopted because of its lower initial and operational cost as well as its ease of use by unskilled workforce. Besides, the produced oil is relatively good quality compared to that obtained from chemical extraction process. Additionally, residual cake may be used for other purposes [35]. However, there is a disadvantage. The mechanically extracted oil amount is less than that obtained from solvent extraction. While it was reported that solvent extraction with n-hexane could recover about 70% - 99% of oil, a maximum of 60% to 80% is reported for mechanical extraction [29]. Pressure applied, pressing temperature and pressing time are important process parameters, as well as pretreatments such as moisture adjustment, shrinkage of shells, reduction of size or heat treatment [36]. *Jatropha* seeds and *jatropha* kernel pressed at higher pressures and/or temperatures provide higher oil yield [37]. All different types of extraction and treatment methods cited were conducted to have the possible best oil yield. The present study will therefore add complements to define the most efficient process taking into account the environmental impact.

Exergetic analysis goes further in the energy optimization of industrial processes than the purely thermal approach on which traditional energy analyses are based. Exergy combines the first and second law of thermodynamics to locate and quantify inefficiencies in an industrial process, taking into account not only the energy losses, but also the quality losses of this energy [38]. As results, these inefficiencies can be reduced and the performance of the process can be improved. Any production process consuming a lot of energy records a significant destruction of useful energy (exergy), which leads to thermodynamic inefficiencies [39]. The cost of energy in most industries is between 20% and 80% of variable cost [39] [40] [41]; therefore, reducing the energy intensity of any business would make it a sustainable business [39]. Exergy can also be defined as the maximum theoretical useful work that can be achieved when a system is thermodynamically balanced with its environment, resulting in interactions between the system and the environment.

Screw presses and oil expellers have been used since the first century of our era. Previously, the Greeks developed it for pressing olives. This method is still widely used by small, medium and large scale companies for vegetable oil extraction. In most parts of the world, especially in remote areas without access to electricity, *Jatropha curcas* oil is generally extracted from screw presses operat-

ing on diesel engines. This is preceded by a heat treatment at about 60°C - 70°C and gives 47.2% oil yield [10]. However, oil extraction rate of *Jatropha curcas* seeds is low for this technology. Solvent extraction method can result high oil yield in comparison to mechanical one. Indeed, the first enables to reach an extraction yield of approximately 99.3% of the oil contained in the seeds while the latter allows only 75% to 85% of yield. Nevertheless, solvent extraction consumes a lot of energy due to longer extraction time compared to that related to mechanical press [6].

So far, exergetic analyzes on jatropha oil extraction focused on the oil extraction steps and the improvement of the methods to be used. This is important, but not enough, because we must also integrate the effective use of natural resources. In order to use the most efficient technology for extracting oil for biodiesel production, an exergy analysis must be performed. Exergy analysis is an effective way to detect the true magnitude of thermodynamic imperfections in the performance of various unit operations within the process to be improved.

Screw presses are currently designed for a continuous extraction process [42] [43]. The investment cost and the processing time are both reduced. However, main disadvantages are high heat production due to friction of the machine parts, which increases operating costs [44], added to that the destruction of resources because the heat is released into the environment without recovery. Part of heat lost in the environment contributes to the exothermic destruction of waste and emissions.

Currently, focus on environmental safety is shifting towards energy efficiency in industrial processing [39]. In reality, there is no process consistent with the first law of thermodynamics (which states that energy is conserved in all processes), but in almost all processes, there is a generation of entropy leading to destruction of exergy or the quality of energy. Therefore, energy concept is unreliable to justify the thermodynamic feasibility of a production process.

General exergy balance involving a mass transfer linking entropy generation and exergy destruction is given by [45]:

$$\sum Ex_{in} - \sum Ex_{out} = Ex_{dest} = T_0 S_{gen} = I \quad (1)$$

where  $\sum Ex_{in}$  represents total incoming exergy,  $\sum Ex_{out}$  total outgoing exergy,  $Ex_{dest}$  destruction of total exergy,  $T_0 S_{gen}$  entropy generation, and  $I$  irreversibility, respectively.

Equation (1) can be rewritten as Equation (2) involves exergy due to heat/work interactions [45]:

$$\sum Ex_{heat} - \sum Ex_{work} + \sum Ex_{mass,in} - \sum Ex_{mass,out} = Ex_{dest} = T_0 S_{gen} \quad (2)$$

where

$$\begin{aligned} \sum Ex_{work} &= W \\ \sum Ex_{heat} &= \sum \left(1 - \frac{T_0}{T}\right) Q \end{aligned} \quad (2b)$$

$$\sum Ex_{mass,in} = \left( \sum_i m_i Ex_i \right)_{in} \quad (2c)$$

$$\sum Ex_{mass,out} = \left( \sum_i m_i Ex_i \right)_{out} \quad (2d)$$

Equation (2a) defines exergy of the system due to work production. This can be calculated from heat capacities and standard chemical energies of flows entering or leaving the system.

Equation (2b) also defines quality of energy in the system.  $Q$  represents thermal load of the system with  $T_0$  the ambient temperature (298 K) while  $T$  denotes the system temperature (K).

Equations (2c) and (2d) define physical exergy of input and output resources, respectively.

Consideration of mass exergy is more important in this study as the scope of the study extends from the drying process to oil extraction.

For real processes, exergy at input always exceeds that at exit of a system. This imbalance is due to irreversibility, also called destruction of exergy, and is represented as a function of entropy generation. The exergy value of a steady stream of fluid entering or exiting a part of a process is the minimum amount of energy that can be obtained from flow to bring it into equilibrium with the environment [38] [46] [47] [48]. With an enthalpy change of  $(H - H_0)$  and an entropy change of  $(S - S_0)$  at a reference temperature  $T_0$  equal to 298 K, the physical exergy can be computed using Equation (3):

$$Ex_{ph} = (H - H_0) - T_0 (S - S_0) \quad (3)$$

With real irreversible processes, there is always increasing entropy resulting from the dissipative effects of energy within the production system. This loss of generated exergy is released into the environment or destroyed during the process [38] [46] [49] [50]. Minimizing entropy generation within system would, however, reduce exergy losses (in heat form and other emissions to the environment), resulting in a sustainable thermodynamic system. Sustainability of an industrial process is characterized by three main factors, namely: the social, economic and environmental aspects [51] [52]. Thermodynamic efficiency evaluation combines the economic and environmental aspects of sustainability. The quality of energy that dissipates into the environment due to irreversibility is clearly quantified in the exergy analysis. The exergetic analysis thus makes it possible to evaluate the thermodynamic inefficiencies real extent of industrial processes, to establish the main causes of these inefficiencies and to associate more fully their obtaining costs with the internal flows and productions [51] [52] [53].

In 1995, the International Organization for Standardization [54] published the Guide of Measurement Uncertainty Expression on its behalf and six other international organizations. The de facto international standard recommended for the expression of uncertainty measurement to classify type A or B uncertainties

using the evaluation method [statistic (A) or otherwise (B)].

Schenck [55] quotes S. J. Kline as defining an experimental uncertainty as “what we think the error would be if we could measure it by calibration”. Uncertainty analysis is a powerful tool. When used in planning and designing experiences. The experimental result is not directly measured but is determined by combining several measured variables.

There is no perfect measure. All measures of a variable contain inaccuracies. Because it is important to understand these inaccuracies if we have to perform experiments or if we simply have to use values that have been determined experimentally, we need to carefully define the concepts involved.

Our approach is an appropriate scientific tool to evaluate the thermodynamic durability of a production process. This study assesses resource degradation extent in jatropha oil extraction processes and identifies possible improvement options for efficient production. A comparison of degree of resources degradation and yields at each level of the process will be analyzed.

Pretreatment and oil extraction with screw press are used as case studies. Exergy destruction and efficiency at each transformation stage are compared.

Exergetic analysis is also a thermodynamic sustainability tool that is used here to quantify the emission and waste streams of the studied process [52] [56], as it is always measured on the reference environment basis.

Uncertainty analyses will be conducted on results to better understand the distribution of probability densities of the process yields.

## 2. Materials and Methods

### 2.1. Materials

*Jatropha curcas* seeds used in the experimentation were collected from Mahabo, Menabe region, Madagascar. The ripe fruits were harvested and dehulled manually in February 2018. They were locally dried in sun, stored in woven polypropylene bags ventilated at temperature between 28°C and 35°C with a relative humidity ranging from 65% to 75% for three months. After being transported to Antananarivo, the seeds were stored at ambient temperature between 15°C and 25°C and a relative humidity between 70% and 80%. The seeds were shelled and analyzed for weight fraction, initial moisture, and total oil content (see **Table 1**). Seeds were subjected to energy conditioning, dehulling and heating treatments before being pressed. Pretreated kernels were directly used in pressing experiments to reduce storage time influence on oil yield.

### 2.2. Process Description and System Limit for *Jatropha curcas* Oil Extraction

For each batch, seeds undergo different pretreatment levels in order to evaluate each step of the process (**Figure 1**). *Jatropha curcas* seeds are cleaned after extraction of the bags for removing foreign substances such as pebbles and leaves, and other seeds amassed during drying. This process is done using a rice win-

nower. As this step does not require a lot of energy, it is not considered to be part of system's limit in this study.

### 2.2.1. Drying

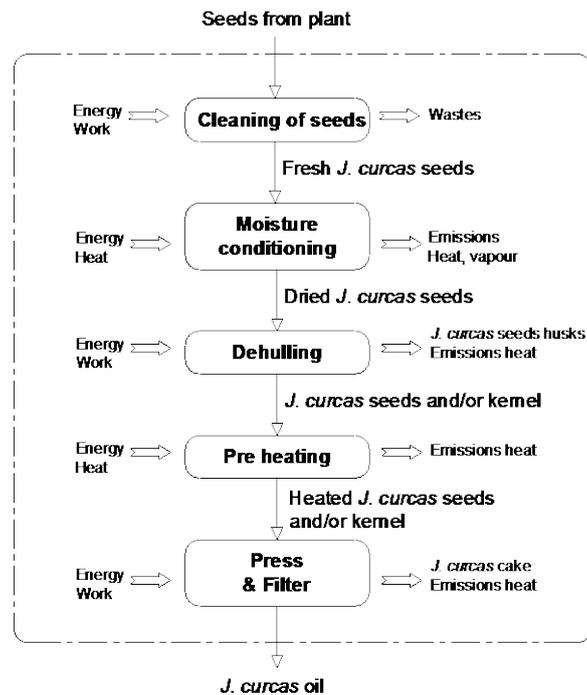
Moisture content is a determining factor in *Jatropha curcas* seeds storage and pretreatment. Seeds are well dried before being bagged so that it does not degrade during storage period.

Before performing the experiment, an initial moisture content calculation of seeds is done. For that purpose, 100 g of seeds are placed in an oven at a temperature of 150°C. They are weighed every 30 minutes until constant weight is obtained. The moisture content is calculated using the following formula:

**Table 1.** Chemical exergy of the main flow.

Stream name	Unit	Quantity	Standard chemical exergy (MJ/kg)	Chemical exergy (MJ)	Combustion exergy efficiency (MJ)
Jatropha seeds before treatment	kg	5.00	17.73	89	
Dried Jatropha seeds	kg	4.42	20.30*	90	31.17%
Jatropha kernel	kg	1.56	12.60*	20	70.30%
Jatropha Shell	kg	2.86	16.93*	48	3.40%
Jatropha cake	kg	0.75	20.25*	15	66.70%
Jatropha oil	kg	0.97	37.00	36	

\*Obtained from [62].



**Figure 1.** *Jatropha curcas* oil extraction system limits.

$$M = \frac{m_{ki} - m_{kf}}{m_{ki}} \times 100 \quad (4)$$

where  $M$  is the moisture content (%),  $m$  mass in (g), and subscripts  $k$ ,  $i$ ,  $f$  are for kernel, initial and final, respectively.

Oil recovery increases from a low moisture content of 1% (wb) to a maximum value at moisture contents between 4% and 5% (wb) for all applied pressures [37] [57]. Optimum moisture content for maximum oil yield during extraction process is 5% at low pressure [58]. During the drying process, 1 kg batches are oven dried at 30°C, 65°C, 80°C. **Table 1** indicates seeds initial moisture content at the bag outlet. Drying is performed until 5% moisture content is reached in the *Jatropha* kernels.

### 2.2.2. Dehulling

In experiments to study the effect of shell removal, the mean weight of samples (shells and kernels) was approximately 7 g for each seeds. The indicated percentage of shell removal is the shell removed percentage from the original sample. 0% elimination means that experiment uses 100% seed which is corresponding to 35.5% (weight basis) of shell content; while 100% removal means that experiment uses 100% kernels which corresponds to 0% of shell content. Oil recovery was calculated on oil content and dehulled sample weight basis. *Jatropha* shell, not containing oil, was removed and evaluated in mass rejected with the cake. Experiments were performed with 0%, 20%, 40%, 60%, 80% and 100% of shell removal. Unless otherwise indicated, the process consists of complete separation of kernel and shell. Seeds cracking is carried out using mechanical cracking rollers manufactured for this purpose. The shell-kernel sorting for removing all the shells is done manually.

### 2.2.3. Preheating

Heat treatment on *Jatropha curcas* seeds is necessary in order to deform their cell structures to agglomerate or flocculate oil droplets into the kernels. This process helps improve cells permeability in seeds by reducing seeds oil viscosity for more efficient extraction. Reducing seed size increases oil yield efficiency besides.

The various effects of heat treatment on the process are observed with different heating temperature levels.

Given the oil quality degradation, with heat treatments of the order of 80°C (increase of acidity, main cause of metallic elements abrasion), temperature stage 0°C, 40°C, 60°C, 80°C were selected.

### 2.2.4. Oil Extraction with Mechanical Screw Press

Experiment is carried out with a Cotter rotary screw press with a production capacity of 15 kg/h. It is powered by 2.2 kW electric motor. Shelled and heat treated *Jatropha curcas* seeds are introduced into the screw press, which consists of helical thread rotating in a fixed perforated cylinder called a cage or barrel

[42] [43]. The cake is forced through cage. Expelled oil flows through cylinder packing bars perforation, while the deoiled residue is discharged through an annular orifice.

The methods used for mechanical *Jatropha curcas* oil extraction in this study are those commonly used, as reported in the literature [59] [60].

The expelled oil may contain residue that can be removed using a decanter and a filter. Then oil is pumped into filter to remove remaining solids and fines to produce clear oil prior storage. Cake is valued with the shell because they can be used for other uses.

### 2.3. Calculation for Physical and Chemical Exergy

In a biomass such as *Jatropha curcas* seeds, exergy is mainly stored in chemical exergy form [22]. Chemical exergy refers to the maximum amount of work that can be achieved when a substance is brought to the environmental state, in dead state, due to its chemical composition or process, involving heat transfer and substance exchange only with the environment. The chemical exergy of *Jatropha curcas* seeds (composed of 6.20% moisture, 38% fat, 17% carbohydrates and 15.50% fiber and 5.30% ash) and *Jatropha curcas* oil (composed of 14.2% palmitic acid [61], 6.9% stearic acid [28], 44% oleic acid, 34.3% linoleic acid and 0.6% other acids) were calculated on the basis of their heat capacity values given by [62]

$$\varepsilon_{fuel}^0 = \beta * LHV \quad (5)$$

where  $\varepsilon_{fuel}^0$  represents standard chemical exergy of biomass,  $LHV$  the lower heating value of fuel, and  $\beta$  the weighting factor which takes into account information conveyed by biomass or fuel; their values are indicated in the literature [61] for most fuels. The chemical exergy of *Jatropha curcas* oil can also be calculated from the standard chemical energy composition method obtained from the literature [53].

The chemical exergy for each pure substance, organic and utilities was computed using their standard chemical energies  $Ex_{ch,i}$  taken [39] [62] according to Equation (6):

$$Ex_{ch,i} = \Delta G_{fo} + \sum_i v_i Ex_{ch,i}^0 \quad (6)$$

where  $Ex_{ch,i}$ ,  $Ex_{ch,i}^0$ ,  $\Delta G_{fo}$  and  $v_i$  are the chemical exergy of specie  $i$ , standard chemical exergy of species  $i$ , Gibb's free energy of formation of species  $i$  and the molar ratio of species  $i$ , respectively.

The Chemical exergy of organic substances not listed by Ayres [39] and Szargut [60] can be estimated using the contribution method of the group, based on information on their molecular structure by the determination of absolute entropy and enthalpy formation values at standard conditions.

The physical exergy of each stream is thus calculated using Equation (7) [47] [48] [62]. The thermodynamic properties of each stream can be obtained from the literature or a database of reliable software such as Aspen plus. For a chemi-

cal process, the exergy associated with a multi-component material flow is divided into chemical and physical energies; hence, an equation for the total exergy of a system is defined by:

$$Ex_{mass,i} = Ex_{ch,i} + Ex_{ph,i} \quad (7)$$

As indicated above, each term is determined separately and systematically for each stage of the oil production. The overall efficiency of the exergy process is defined by [63]:

$$\eta_{total} = \frac{\sum Ex_{Out}}{\sum Ex_{in}} \quad (8)$$

where  $\sum Ex_{Out}$  is the total exergy of output resources or products and  $\sum Ex_{in}$  is the total exergy of input resources.

## 2.4. Uncertainty Analysis

The uncertainty analysis is conducted with the @RISK software which enriches Microsoft Excel with an expert modeling and uncertainty analysis capability. The modeling represents the actual situation for its analysis. Entries values result from variable experiments; hence, the importance of uncertainty calculations on our research results.

Probability distributions provide a quantified uncertainty presentation method of a variable, @RISK uses it to describe the uncertain values of Excel spreadsheets and to present the results. There are several forms and types of distributions, each describing a range of possible values and probability. All distribution types use a set of arguments to specify a range of real values and probability distributions. The normal distribution, used in the present case, is defined by an average and a standard deviation resulting from the experimental data.

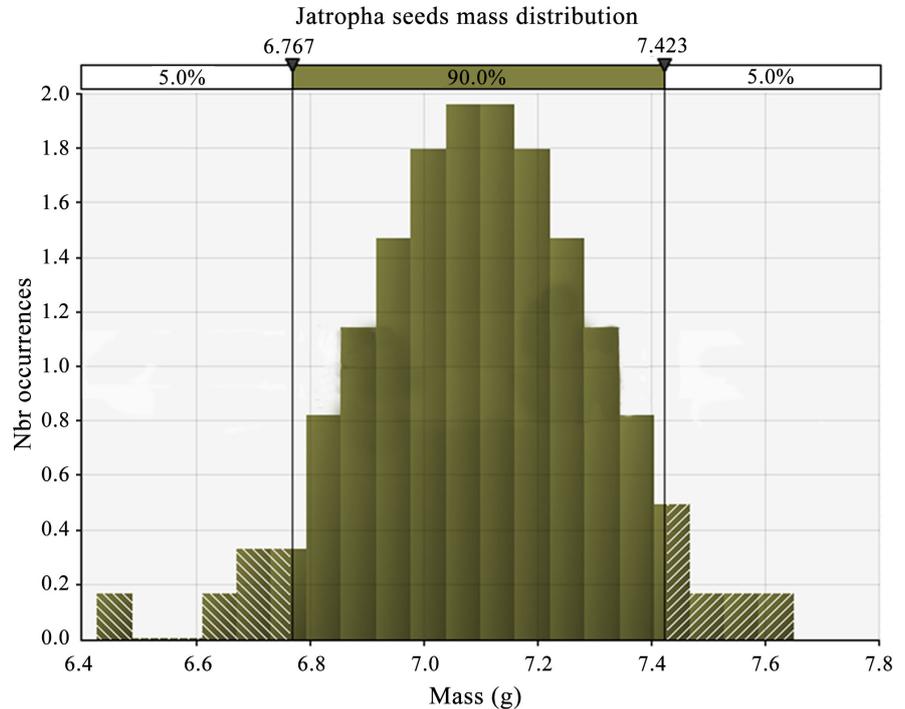
### 2.4.1. Development of a Model

The model is calculated on an Excel spreadsheet based on experimental averages. The variable nature of the input data prompts us to perform a simulation to determine the range and probabilities of all possible result outcomes.

### 2.4.2. Identification of Uncertainty

Measurements of variables are influenced by a number of elementary error sources such as calibration errors, errors caused by changes in ambient temperature, humidity, pressure, vibration, instability in the phenomenon of “balance” to measure. With each experimental measurement, we could draw a histogram, which shows the fraction of N total measurements which is shown in **Figure 2**. This allows us to visualize the distribution of N total measured values for the case of the mass of a jatropha seed. An average value is calculated, as is a standard deviation, which is an indicator of the width of the distribution.

When identifying uncertain values in Excel spreadsheet, we must determine whether the variables are correlated or not. Those considered here are indeed “correlated”. In @RISK, the Corrmat function is used to identify correlated variables. It is extremely important to correctly identify correlations between them.



**Figure 2.** *Jatropha curcas* seeds mass distribution.

#### 2.4.3. Model Analysis with Simulation

Once uncertain values in spreadsheet cells entered and the outputs of the analysis identified, we have an Excel spreadsheet that can be processed with @RISK. It uses Monte Carlo simulation to execute the uncertainty analysis. In this sense, simulation refers to the method by which possible outcomes distribution results from the computer executing repeated calculations of the spreadsheet, based on a set of different values each time, randomly selected from the probability distributions introduced in the cells values and formulas. The computer basically tries all the valid combinations of the input variables to simulate all possible outcomes, as if we were analyzing hundreds or even thousands of hypothetical scenarios at the same time.

#### 2.4.4. Output Variables

Like all other uncertainty analysis models, input values and output results are composed of large database. The @RISK uncertainty analysis produces its results on cells defined as inputs and outputs of the Excel worksheet. These results are the probability distributions of the values that may occur. At first glance, they correspond to the ordinary Excel analysis results carried out with the averages.

### 3. Results and Discussion

The chemical energies of the main material streams in the extraction process as well as the exergy efficiency in combustions are presented in **Table 1**. The quantities in this table represent the mass flow at each unit operation. Thus, 5 kg of fresh grain *Jatropha curcas* after drying decomposes into 1.56 kg of kernel with a

moisture content of 5% and 2.86 kg of shell. A maximum oil quantity of 0.97 kg can be extracted from this unit mass with 0.75 kg cake mass load.

Seeds, kernels, shell, and cake are, in their unprocessed state, used for combustion. They are evaluated in the present study by taking into account their exergy yields in heat production processes.

In order to perform uncertainty analysis on the exergetic efficiency of the process, the results are transcribed according to distribution functions.

In **Figure 2**, the unit mass distribution of *Jatropha* grains tends to have a larger number of measured values near the sample mean 7.1 g and exponential decreasing number of measured values as one moves away from the average. The respective minimum and maximum experimental masses of 6.42 g and 7.65 g are retained by the simulator after 100 iterations, with minimal modifications resulting from transformation into normal distribution however. The curve asymmetry is also low  $-0.138$ , hence the validation of the normal distribution law selected for the unit masses of dried seeds.

The drying heat treatments were carried out at calculated times of 8 h 35 min, 5 h 26 min and 3 h 05 min for drying at 30°C, 65°C and 80°C, respectively, to obtain 5% of moisture content (**Table 2**). The exergy destroyed to obtain the same moisture content varies according to the treatment temperatures. Drying at 80°C is the most interesting as it allows achieving high exergy efficiency. The treatment at 65°C is the most exergetic during this unit drying process with the destruction of 58.27 MJ. This is due to the fact that the drying time is longer while the temperature remains high enough. However, while heat treatments at high temperatures being acidifying for the extracted oil [62], it is more assured to carry out a treatment at lower temperature with a longer duration of treatment. Given the choice of the rotary press which works in continuous cycle, a long drying time would be penalizing for the entire oil production cycle. It is necessary to acquire a larger dryer or production and storage space to feed the press therefore.

Dependent variables such as input for starting materials press feed, outgoing exergies for oil, cake, shell as well as inputs in mass, labor and heat exergy are shown in **Table 3**.

The exergy destructions related to the incoming flows are functions of unit process parameters step. To achieve dehulling levels of 100%, 80% and 40%, required exergetic resources are 0.36, 0.29 and 0.14 MJ respectively. Compared to each other, his data relate a constant according to dehulling level. Quantitatively, it is very small and even negligible compared to the mass exergy of inputs.

The exergy used by the press for the mechanical oil extraction of the oil depends on the dehulling level. A small percentage of shelled seeds implies a larger mass of inputs. Both values are inversely proportional. It must be taken into consideration also that the kernels are softer than the seeds. Which is disadvantageous compared to electrical exergy consumed for the unitary pressing process. Exponential increase of the energy demanded by the press is noted with

0.33 MJ to process 1.56 kg of kernels while 1.96 MJ for 3.85 kg of mixture of seeds and kernels shelled at 20%. This increase in consumption is largely compensated by a higher oil yield due to greater pressure in the cage of the screw press. In the transformation process, this operation is the second least consuming of exergy while it greatly influences the overall efficiency.

**Table 2.** Total exergy destruction during drying process.

Unit operation:	Drying	
Masse unit	5 kg	
Temp (°C)	Drying time	Exergy (MJ)
30	8h35	42.49
65	5h26	58.27
80	3h05	40.70

**Table 3.** Extraction process exergy flows summary.

Unit operation	Mass in press	Exergy efficiency	Exergy out				Exergy in				
			Exergy (oil)	Exergy (cake)	Exergy (shell)	Exergy (preheat)	Exergy (press)	Exergy (dehull)	Exergy (mass)	Drying (exergy)	
Setup name	kg	%	MJ	MJ	MJ	MJ	MJ	MJ	MJ	MJ	MJ
D100-Prt80	1.56	30.39%	128.95	7.357	13.652	4.724	2.579	0.333	0.360	123.699	58.27
D100-Prt60	1.56	30.26%	128.59	6.656	13.848	4.724	1.719	0.333	0.360	123.699	58.27
D100-Prt40	1.56	29.85%	128.74	5.255	14.241	4.724	0.860	0.333	0.360	123.699	58.27
D80-Prt80	2.13	31.14%	127.78	11.209	18.354	3.779	2.579	0.740	0.288	123.699	58.27
D80-Prt60	2.13	30.47%	128.44	9.108	18.943	3.779	1.719	0.740	0.288	123.699	58.27
D80-Prt40	2.13	29.93%	128.84	7.356	19.435	3.779	0.860	0.740	0.288	123.699	58.27
D60-Prt80	2.70	32.71%	125.11	17.163	22.468	2.834	2.579	1.146	0.216	123.699	58.27
D60-Prt60	2.70	31.90%	126.01	14.711	23.155	2.834	1.719	1.146	0.216	123.699	58.27
D60-Prt40	2.70	31.09%	126.92	12.259	23.843	2.834	0.860	1.146	0.216	123.699	58.27
D40-Prt80	3.28	35.07%	120.92	25.218	25.992	1.889	2.579	1.553	0.144	123.699	58.27
D40-Prt60	3.28	34.69%	121.07	23.817	26.385	1.889	1.719	1.553	0.144	123.699	58.27
D40-Prt40	3.28	33.22%	123.24	19.614	27.564	1.889	0.860	1.553	0.144	123.699	58.27
D20-Prt80	3.85	35.41%	120.52	28.018	30.990	0.945	2.579	1.959	0.072	123.699	58.27
D20-Prt60	3.85	34.49%	121.67	25.216	31.776	0.945	1.719	1.959	0.072	123.699	58.27
D20-Prt40	3.85	33.69%	122.58	22.765	32.463	0.945	0.860	1.959	0.072	123.699	58.27
D0-Prt80	4.42	35.07%	121.37	29.067	36.479	-	2.579	2.365	0.000	123.699	58.27
D0-Prt60	4.42	34.55%	121.77	27.316	36.970	-	1.719	2.365	0.000	123.699	58.27
D0-Prt40	4.42	33.49%	123.18	24.164	37.853	-	0.860	2.365	0.000	123.699	58.27

Preheating requires less time but remains one of the most penalizing factors in assessing the exergetic efficiency of the process. It was evaluated with the greatest quantity of materials, that is, 0% dehulling, to retain the most unfavorable case possible. A maximum exergy quantity of 2.58 MJ is recorded for the treatment of 4.42 kg of grain at 80°C and 1.72 and 0.86 MJ respectively for 60°C and 40°C.

Inputs mass exergy is 123.70 MJ. It was evaluated from *Jatropha curcas* dried seeds chemical exergy product taking into account its exergy yield during its use in combustion. Despite the change in mass flow rates at the press, the exergy at the beginning of the process remains unchanged, consisting of the whole seeds of dried jatropha. The shells, not passing through the pressing circuit, are evaluated with the other outputs. Taking into account the mass makes it possible to better apprehend the flow of exergy within the process. The only drying operation is responsible for the 41% degradation of seed exergy. Drying methods permitting moisture recovery could further increase the production process efficiency. On the other hand, a high moisture content of seeds to be processed would reduce the final exergy yield more. This calls for expanding the limits of process to the sun drying before storage.

The main output of the process is the exergy of the extracted oil. It depends on the production parameters. From **Table 3**, a low extracted oil level, with an exergy of 5.25 MJ, can be offset by a higher cake exergy of 14.24 MJ and 35.29 MJ shells exergy. As result, a general exergetic efficiency of 128.74 MJ at rate of 29.85% was obtained.

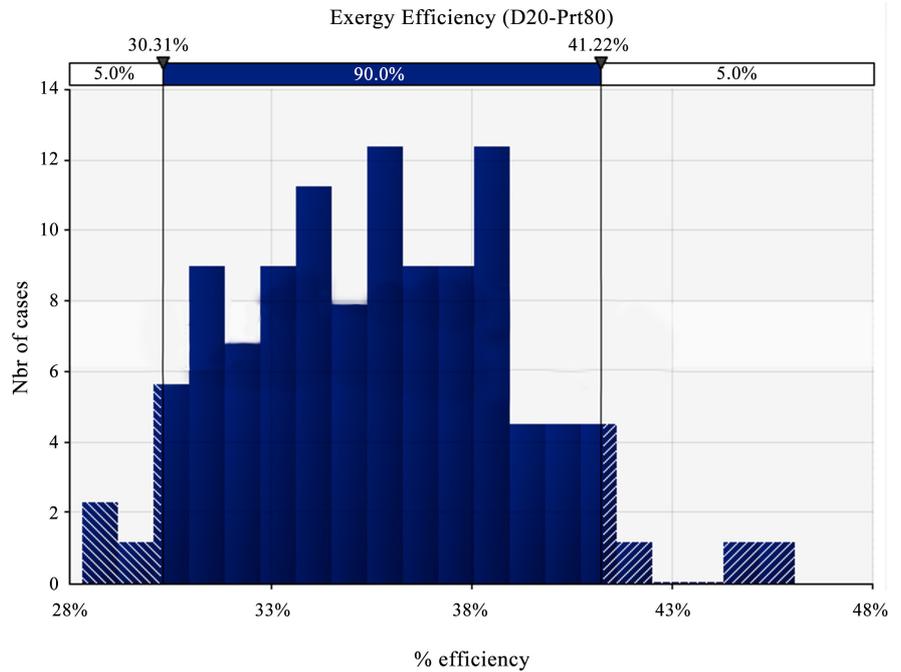
Changes of various parameters enable to identify the optimal operational parameters for jatropha oil production process. The settings are: preheating of the seeds with a level of dehulling of 20% at 80°C to obtain a maximum exergetic yield of 35.41% and 35.04% to 40% of seeds shelled at the same temperature.

However, treatments at 80°C are not recommended for reasons of increased acidity of the oil at the outlet, it is better to choose treatments at 60°C with 34.69% and 34.49% respectively yield at 40% and 20% of kernel.

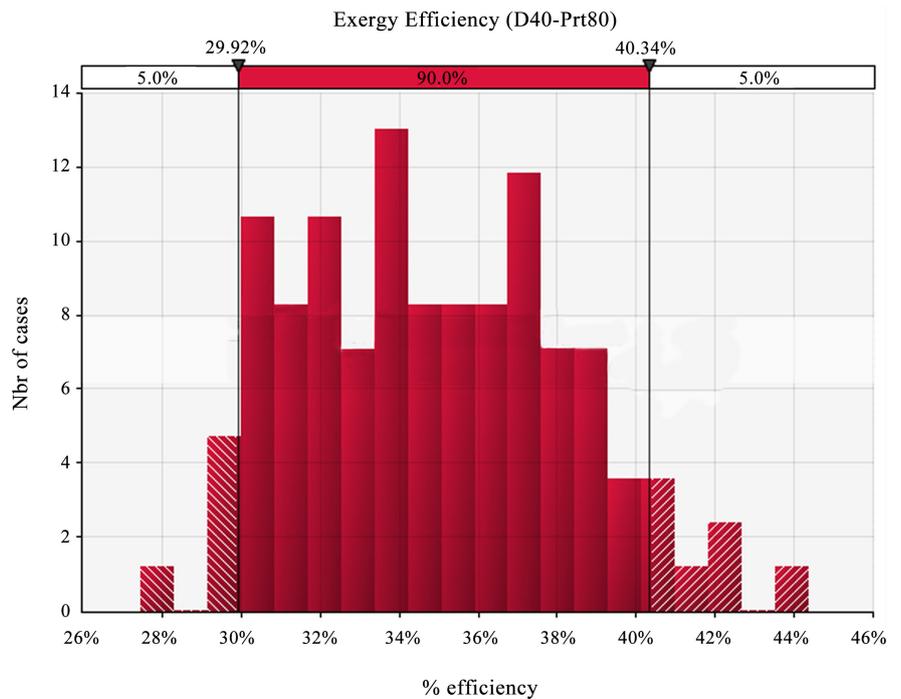
An uncertainty analysis is performed to validate all the results. **Figure 3** and **Figure 4** show the distributions of probability densities for pretreatments at 80°C with 20% and 40% dehulling.

According to **Figure 3** the trend of the results increases progressively up to 39% and then fall rapidly. The proportion is asymmetrical. It can be inferred that the probability of values of exergetic yield resulting between 30% and the average 35.6% may occur more often than the values between the average and 38%. Unlike **Figure 3**, in **Figure 4**, the probability density is concentrated towards the front. The probability of having results above the average 34.90% is thus greater. The reduction of the numbers of cases up to 40% of exergetic yield decreases gradually. These results can be explained by the fact that the dehulling level affects 5 parameters out of 8 (oil, cake, shell, press, dehull exergy) allowing computing the exergetic efficiency. An increase level of dehulling also indicates an increase in the separation of input materials. Each input or output has its own

probability densities. Hulls and kernels separation allow having more constant results because there are fewer materials in interaction during the pressing process. The parameter change interdependence during the simulation makes



**Figure 3.** Process exergy efficiency probabilities density with 20% dehulling and preheating at 80°C.



**Figure 4.** Process exergy efficiency probabilities density with 40% dehulling and preheating at 80°C.

the below-average results more important for the dehulling at 20%. By decreasing the percentage of interdependent elements in the calculation, the results for unfavorable cases combination regress. That result allows guiding the choice towards a dehulling rate of 40%.

#### 4. Conclusions

The exergetic analysis of the production process of *Jatropha curcas* oil was conducted by widening the process boundaries and taking into account the mass exergy of inputs and outputs throughout the present study. It can be inferred from the results that the maximum oil yield is not significant for a production process with high exergetic efficiency. The only drying operation is responsible for the destruction of 46% of incoming exergies. The choice of the processing temperature makes it possible to reduce this rate considerably. This parameter is however dependent on the equipment used. In this case study, a long drying time at low temperatures destroys less exergy than the treatment in a medium time with a medium temperature. This is due to seeds drying curve which is not linear.

The mass effect generates 67% of incoming exergy and even, for outgoing flows, more than 60% is due to the exergy generated by the waste. The uncertainties analysis allows us directing treatments choice on processes with similar yields. It also enables to glimpse the minimum values of exergy efficiency for the most unfavorable cases that may occur as well as the maximum value when all the parameters are at their optimum values. On the other hand, it is a way to validate the results according to their probability of realization. The improvement to be done would be to use the cakes and shells during the drying operation with a considerable improvement in the means of their uses to affect the overall efficiency of the process. Looking for other uses for waste treatments also would be another alternative to having a more exergy efficient process.

#### Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

#### References

- [1] Balat, M. and Balat, H. (2010) Progress in Biodiesel Processing. *Applied Energy*, **87**, 1815-1835. <https://doi.org/10.1016/j.apenergy.2010.01.012>
- [2] Lee, H.V., Yunus, R., Juan, J.C. and Taufiq-Yap, Y.H. (2011) Process Optimization Design for *Jatropha*-Based Biodiesel Production Using Response Surface Methodology. *Fuel Processing Technology*, **92**, 2420-2428. <https://doi.org/10.1016/j.fuproc.2011.08.018>
- [3] Leung, D.Y.C., Wu, X. and Leung, M.K.H. (2010) A Review on Biodiesel Production Using Catalyzed Transesterification. *Applied Energy*, **87**, 1083-1095.
- [4] Sahoo, P.K. and Das, L.M. (2009) Process Optimization for Biodiesel Production from *Jatropha*, *Karanja* and *Polanga* Oils. *Fuel*, **88**, 1588-1594.

- <https://doi.org/10.1016/j.fuel.2009.02.016>
- [5] Santori, G., Di Nicola, G., Moglie, M. and Polonara, F. (2012) A Review Analyzing the Industrial Biodiesel Production Practice Starting from Vegetable Oil Refining. *Applied Energy*, **92**, 109-132. <https://doi.org/10.1016/j.apenergy.2011.10.031>
- [6] Shahid, E.M. and Jamal, Y. (2011) Production of Biodiesel: A Technical Review. *Renewable and Sustainable Energy Reviews*, **15**, 4732-4745. <https://doi.org/10.1016/j.rser.2011.07.079>
- [7] Yusuf, N.N.A.N., Kamarudin, S.K. and Yaakub, Z. (2011) Overview on the Current Trends in Biodiesel Production. *Energy Conversion and Management*, **52**, 2741-2751. <https://doi.org/10.1016/j.enconman.2010.12.004>
- [8] Demirbas, M.F. (2011) Biofuels from Algae for Sustainable Development. *Applied Energy*, **88**, 3473-3480. <https://doi.org/10.1016/j.apenergy.2011.01.059>
- [9] Li, Z.X., Yang, D.P., Huang, M.L., Hu, X.J., Shen, J.G., Zhao, Z.M., *et al.* (2012) *Chrysomya megacephala* (Fabricius) Larvae: A New Biodiesel Resource. *Applied Energy*, **94**, 349-354. <https://doi.org/10.1016/j.apenergy.2012.01.068>
- [10] Maceiras, R., Rodríguez, M., Cancela, A., Urréjola, S. and Sánchez, A. (2011) Macroalgae: Raw Material for Biodiesel Production. *Applied Energy*, **88**, 3318-3323. <https://doi.org/10.1016/j.apenergy.2010.11.027>
- [11] Marchetti, J.M. (2012) A Summary of the Available Technologies for Biodiesel Production Based on a Comparison of Different Feedstock's Properties. *Process Safety and Environmental Protection*, **90**, 157-163.
- [12] Martín, C., Moure, A., Martín, G., Carrillo, E., Domínguez, H. and Parajó, J.C. (2010) Fractional Characterisation of *Jatropha*, *Neem*, *Moringa*, *Trisperma*, *Castor* and *Candlenut* Seeds as Potential Feedstocks for Biodiesel Production in Cuba. *Biomass and Bioenergy*, **34**, 533-538. <https://doi.org/10.1016/j.biombioe.2009.12.019>
- [13] Ong, H.C., Mahlia, T.M.I., Masjuki, H.H. and Norhasyima, R.S. (2011) Comparison of Palm Oil, *Jatropha curcas* and *Calophyllum inophyllum* for Biodiesel: A Review. *Renewable and Sustainable Energy Reviews*, **15**, 3501-3515. <https://doi.org/10.1016/j.rser.2011.05.005>
- [14] Qiu, F., Li, Y., Yang, D., Li, X. and Sun, P. (2011) Biodiesel Production from Mixed Soybean Oil and Rapeseed Oil. *Applied Energy*, **88**, 2050-2055. <https://doi.org/10.1016/j.apenergy.2010.12.070>
- [15] Behera, S.K., Srivastava, P., Tripathi, R., Singh, J.P. and Singh, N. (2010) Evaluation of Plant Performance of *Jatropha curcas* L. under Different Agro-Practices for Optimizing Biomass—A Case Study. *Biomass and Bioenergy*, **34**, 30-41. <https://doi.org/10.1016/j.biombioe.2009.09.008>
- [16] Deng, X., Fang, Z., Hu, L.Y. and Yu, C.L. (2011) Production of Biodiesel from *Jatropha* Oil Catalyzed by Nanosized Solid Basic Catalyst. *Energy*, **36**, 777-784. <https://doi.org/10.1016/j.energy.2010.12.043>
- [17] Juan, J.C., Kartika, D.A., Wu, T.Y. and Hin, T.Y.Y. (2011) Biodiesel Production from *Jatropha* Oil by Catalytic and Non-Catalytic Approaches: An Overview.
- [18] Ofori-Boateng, C., Keat Teong, L. and Jitkang, L. (2012) Comparative Exergy Analyses of *Jatropha curcas* Oil Extraction Methods: Solvent and Mechanical Extraction Processes. *Energy Conversion and Management*, **55**, 164-171. <https://doi.org/10.1016/j.enconman.2011.11.005>
- [19] Pandey, K.K., Pragma, N. and Sahoo, P.K. (2011) Life Cycle Assessment of Small-Scale High-Input *Jatropha* Biodiesel Production in India. *Applied Energy*, **88**,

- 4831-4839. <https://doi.org/10.1016/j.apenergy.2011.06.026>
- [20] Yee, K.F., Wu, J.C.S. and Lee, K.T. (2011) A Green Catalyst for Biodiesel Production from *Jatropha* Oil: Optimization Study. *Biomass and Bioenergy*, **35**, 1329-1338. <https://doi.org/10.1016/j.biombioe.2011.01.017>
- [21] Foidl, N., Foidl, G., Sanchez, M., Mittelbach, M. and Hackel, S. (1996) *Jatropha curcas* L. as a Source for the Production of Biofuel in Nicaragua. *Bioresource Technology*, **58**, 77-82. [https://doi.org/10.1016/S0960-8524\(96\)00111-3](https://doi.org/10.1016/S0960-8524(96)00111-3)
- [22] Lu, H., Liu, Y., Zhou, H., Yang, Y., Chen, M. and Liang, B. (2009) Production of Biodiesel from *Jatropha curcas* L. Oil. *Computers and Chemical Engineering*, **33**, 1091-1096. <https://doi.org/10.1016/j.compchemeng.2008.09.012>
- [23] Parawira, W. (2010) Biodiesel Production from *Jatropha curcas*: A Review. *Scientific Research and Essays*, **5**, 1796-1808.
- [24] Tamalampudi, S., Talukder, M.R., Hama, S., Numata, T., Kondo, A. and Fukuda, H. (2008) Enzymatic Production of Biodiesel from *Jatropha* Oil: A Comparative Study of Immobilized-Whole Cell and Commercial Lipases as a Biocatalyst. *Biochemical Engineering Journal*, **39**, 185-189. <https://doi.org/10.1016/j.bej.2007.09.002>
- [25] Kumar, A. and Sharma, S. (2008) An Evaluation of Multipurpose Oil Seed Crop for Industrial Uses (*Jatropha curcas* L.): A Review. *Industrial Crops and Products*, **28**, 1-10.
- [26] Makkar, H.P.S. and Becker, K. (2009) *Jatropha curcas*, a Promising Crop for the Generation of Biodiesel and Value-Added Coproducts. *European Journal of Lipid Science and Technology*, **111**, 773-787. <https://doi.org/10.1002/ejlt.200800244>
- [27] Tewari, J.P., Dwivedi, H.D., Pathak, M. and Srivastava, S.K. (2007) Incidence of a Mosaic Disease in *Jatropha curcas* L. from Eastern Uttar Pradesh. *Current Science*, **93**, 1048-1049.
- [28] Valdes-Rodriguez, O.A., Sánchez-Sánchez, O., Pérez-Vázquez, A. and Ruiz-Bello, R. (2011) Soil Texture Effects on the Development of *Jatropha* Seedlings—Mexican Variety “piñón manso”. *Biomass and Bioenergy*, **35**, 3529-3536.
- [29] Achten, W.M.J., Verchot, L., Franken, Y.J., Mathijs, E., Singh, V.P., Aerts, R., *et al* (2008) *Jatropha* Bio-Diesel Production and Use.
- [30] de Oliveira, J.S., Leite, P.M., de Souza, L.B., Mello, V.M., Silva, E.C., Rubim, J.C., *et al*. (2009) Characteristics and Composition of *Jatropha gossypifolia* and *Jatropha curcas* L. Oils and Application for Biodiesel Production. *Biomass and Bioenergy*, **33**, 449-53. <https://doi.org/10.1016/j.biombioe.2008.08.006>
- [31] Vaknin, Y., Ghanim, M., Samra, S., Dvash, L., Hendelsman, E., Eisikowitch, D., *et al*. (2011) Predicting *Jatropha curcas* Seed-Oil Content, Oil Composition and Protein Content Using Near-Infrared Spectroscopy-A Quick and Non-Destructive Method. *Industrial Crops and Products*, **34**, 1029-1034. <https://doi.org/10.1016/j.indcrop.2011.03.011>
- [32] Pinzi, S., Garcia, I.L., Lopez-Gimenez, F.J., DeCastro, M.D.L., Dorado, G. and Dorado, M.P. (2009) The Ideal Vegetable Oil-Based Biodiesel Composition: A Review of Social, Economical and Technical Implications. *Energy and Fuels*, **23**, 2325-2341. <https://doi.org/10.1021/ef801098a>
- [33] Pramanik, K. (2003) Properties and Use of *Jatropha curcas* Oil and Oiesel Fuel Blends in Compression Ignition Engine. *Renewable Energy*, **28**, 239-248. [https://doi.org/10.1016/S0960-1481\(02\)00027-7](https://doi.org/10.1016/S0960-1481(02)00027-7)
- [34] Francis, G., Edinger, R. and Becker, K. (2005) A Concept for Simultaneous Wastel- and Reclamation, Fuel Production, and Socio-Economic Development in Degraded

- Areas in India: Need, Potential and Perspectives of Jatropha Plantations. *Natural Resources Forum*, **29**, 12-24. <https://doi.org/10.1111/j.1477-8947.2005.00109.x>
- [35] Olajide, J.O., Igbeka, J.C., Afolabi, T.J. and Emiola, O.A. (2007) Prediction of Oil Yield from Groundnut Kernels in an Hydraulic Press Using Artificial Neural Network (ANN). *Journal of Food Engineering*, **81**, 643-646. <https://doi.org/10.1016/j.jfoodeng.2006.06.007>
- [36] Gutiérrez, L.F., Ratti, C. and Belkacemi, K. (2008) Effects of Drying Method on the Extraction Yields and Quality of Oils from Quebec Sea Buckthorn (*Hippophaë rhamnoides* L.) Seeds and Pulp. *Food Chemistry*, **106**, 896-904. <https://doi.org/10.1016/j.foodchem.2007.06.058>
- [37] Willems, P., Kuipers, N.J.M. and De Haan, A.B. (2008) Hydraulic Pressing of Oil-seeds: Experimental Determination and Modeling of Yield and Pressing Rates. *Journal of Food Engineering*, **89**, 8-16. <https://doi.org/10.1016/j.jfoodeng.2008.03.023>
- [38] Keenan, J.H. (1951) Availability and Irreversibility in Thermodynamics. *British Journal of Applied Physics*, **2**, 183-192. <https://doi.org/10.1088/0508-3443/2/7/302>
- [39] Ayres, R.U., Turton, H. and Casten, T. (2007) Energy Efficiency, Sustainability and Economic Growth. *Energy*, **32**, 634-648. <https://doi.org/10.1016/j.energy.2006.06.005>
- [40] Poredoš, A. and Kitanovski, A. (2002) Exergy Loss as a Basis for the Price of Thermal Energy. *Energy Conversion and Management*, **43**, 2163-2173. [https://doi.org/10.1016/S0196-8904\(01\)00156-X](https://doi.org/10.1016/S0196-8904(01)00156-X)
- [41] Rosen, M.A. and Dincer, I. (2003) Exergy-Cost-Energy-Mass Analysis of Thermal Systems and Processes. *Energy Conversion and Management*, **44**, 1633-1651. [https://doi.org/10.1016/S0196-8904\(02\)00179-6](https://doi.org/10.1016/S0196-8904(02)00179-6)
- [42] Evon, P., Vandenbossche, V., Pontalier, P.Y. and Rigal, L. (2009) Aqueous Extraction of Residual Oil from Sunflower Press Cake Using a Twin-Screw Extruder: Feasibility Study. *Industrial Crops and Products*, **29**, 455-465. <https://doi.org/10.1016/j.indcrop.2008.09.001>
- [43] Okoye, C.N., Jiang, J. and Hui, L.Y. (2008) Design and Development of Secondary Controlled Industrial Palm Kernel Nut Vegetable Oil Expeller Plant for Energy Saving and Recuperation. *Journal of Food Engineering*, **87**, 578-590. <https://doi.org/10.1016/j.jfoodeng.2007.01.030>
- [44] Appelqvist, L.-A. and Ohlson, R. (1972) Rapeseed Cultivation, Composition, Processing and Utilization. Elsevier, Amsterdam.
- [45] Cornelisse, R. (1997) Thermodynamics and Sustainable Development: The Use of Exergy Analysis and the Reduction of Irreversibility. Ph.D. Thesis, University of Twente.
- [46] Dewar, R.C. (2005) Maximum Entropy Production and the Fluctuation Theorem. *Journal of Physics A: Mathematical and General*, **38**, 371-381. <https://doi.org/10.1088/0305-4470/38/21/L01>
- [47] Kotas, T.J. (1985) Examples of Thermal and Chemical Plant Analysis. Butterworths, London.
- [48] Sussman, M.V. (1980) Standard Chemical Availability. *Chemical Engineering Progress*, **76**, 37-39.
- [49] Georgescu-Roegen, N. (1971) The Entropy Law and the Economic Process (German). Harvard University Press, Cambridge. <https://doi.org/10.4159/harvard.9780674281653>

- [50] Gibbs, J.W. (1878) On the Equilibrium of Heterogeneous Substances. *American Journal of Science*, **2**, 382-404. <https://doi.org/10.2475/ajs.s3-16.96.441>
- [51] Berthiaume, R., Bouchard, C. and Rosen, M.A. (2001) Exergetic Evaluation of the Renewability of a Biofuel. *Exergy: An International Journal*, **1**, 256-268. [https://doi.org/10.1016/S1164-0235\(01\)00029-2](https://doi.org/10.1016/S1164-0235(01)00029-2)
- [52] De Meester, B., Dewulf, J., Janssens, A. and Van Langenhove, H. (2006) An Improved Calculation of the Exergy of Natural Resources for Exergetic Life Cycle Assessment (ELCA). *Environmental Science and Technology*, **40**, 6844-6851. <https://doi.org/10.1021/es060167d>
- [53] Dos Santos, M.T. and Park, S.W. (2009) Exergy and Sustainable Development for Chemical Industry Revisited. *Computer Aided Chemical Engineering*, **27**, 1923-1928. [https://doi.org/10.1016/S1570-7946\(09\)70711-4](https://doi.org/10.1016/S1570-7946(09)70711-4)
- [54] Iso (1995) Guide to the Expression of Uncertainty in Measurement.
- [55] Schenck, H. (1979) Theories of Engineering Experimentation. McGraw-Hill, New York.
- [56] Hermann, W.A. (2006) Quantifying Global Exergy Resources. *Energy*, **31**, 1685-1702. <https://doi.org/10.1016/j.energy.2005.09.006>
- [57] Subroto, E., Manurung, R., Heeres, H.J. and Broekhuis, A.A. (2015) Mechanical Extraction of Oil from *Jatropha curcas* L. Kernel: Effect of Processing Parameters. *Industrial Crops and Products*, **63**, 303-310. <https://doi.org/10.1016/j.indcrop.2014.06.018>
- [58] Mpagalile, J.J. and Clarke, B. (2005) Effect of Processing Parameters on Coconut Oil Expression Efficiencies. *International Journal of Food Sciences and Nutrition*, **56**, 125-132. <https://doi.org/10.1080/09637480500082058>
- [59] Erickson, D.R., Pryde, E.H. and Brekke (1980) Handbook of Soy Oil Processing & Utilization. American Oil Chemists Society.
- [60] Karaj, S. and Müller, J. (2011) Optimizing Mechanical Oil Extraction of *Jatropha curcas* L. Seeds with Respect to Press Capacity, Oil Recovery and Energy Efficiency. *Industrial Crops and Products*, **34**, 1010-1016. <https://doi.org/10.1016/j.indcrop.2011.03.009>
- [61] Edem, D.O. (2002) Palm Oil: Biochemical, Physiological, Nutritional, Hematological, and Toxicological Aspects: A Review. Kluwer Academic Publishers, Dordrecht.
- [62] Morris, D.R., Steward, F.R. and Szargut, J. (1994) Technological Assessment of Chemical Metallurgical Processes. *Canadian Metallurgical Quarterly*, **33**, 289-295. <https://doi.org/10.1179/cmqr.1994.33.4.289>
- [63] Rivero, R. and Garfias, M. (2006) Standard Chemical Exergy of Elements Updated. *Energy*, **31**, 3310-3326. <https://doi.org/10.1016/j.energy.2006.03.020>