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Comparative exergy analyses of *Jatropha curcas* oil extraction methods: Solvent and mechanical extraction processes

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ABSTRACT

Vegetable oil extraction processes are found to be energy intensive. Thermodynamically, any energy intensive process is considered to degrade the most useful part of energy that is available to produce work. This study uses literature values to compare the efficiencies and degradation of the useful energy within *Jatropha curcas* oil during oil extraction taking into account solvent and mechanical extraction methods. According to this study, *J. curcas* seeds on processing into *J. curcas* oil is upgraded with mechanical extraction but degraded with solvent extraction processes. For mechanical extraction, the total internal exergy destroyed is 3006 MJ which is about six times less than that for solvent extraction (18,072 MJ) for 1 ton *J. curcas* oil produced. The pretreatment processes of the *J. curcas* seeds recorded a total internal exergy destructions of 5768 MJ accounting for 24% of the total internal exergy destroyed for solvent extraction processes and 66% for mechanical extraction. The exergetic efficiencies recorded are 79.35% and 95.93% for solvent and mechanical extraction processes of *J. curcas* oil respectively. Hence, mechanical oil extraction processes are exergetically efficient than solvent extraction processes. Possible improvement methods are also elaborated in this study.

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1. Introduction

Jatropha curcas L. is a small deciduous tree which originates from Mexico and Central America which has found its way in most tropical countries of the world especially Asian countries [1]. After 5 years of cultivation of *J. curcas* seeds, depending on the genetic variety of *J. curcas* seeds or cuttings; the climatic conditions as well as the management technologies used, *J. curcas L.* may yield 2–5 tons of dry seed/ha/year [1,2]. The *J. curcas* seeds have been analyzed to contain about 35–40% oil i.e. 1.75 tons/ha after extraction [2–5]. The *kernel* (i.e. the part of the seed after the seed coat have been removed) however contains about 50–60% oil content by weight. Upon critical analysis of *J. curcas* seeds, it has been reported in previous studies [5] that they contain 6.6% moisture, 18.2% protein, 38% fat, 17.3% carbohydrates, 15.5% fibre and 4.5% ash. The oil also contains about 21% saturated fatty acids and 79% unsaturated fatty acids [5]. *J. curcas* oil is found to be more environmentally safe on combustion; cost effective and has a high potential of being a substitute for petroleum diesel and kerosene. When the oil is converted to biodiesel which presents a high potential biofuel produced from vegetable oil and animal fat, the properties are much enhanced thus excellent to replace fossil based fuels [2,6].

Due to the incessant rise in crude oil prices coupled with its negative environmental impacts, numerous technologies of producing liquid biofuels have emerged. An efficient and profitable biodiesel plant depends largely on the cost of oil which is directly related to the oil yield after extraction. In order to effectively produce the oil, a more efficient technology as well as high oil-content feedstock must be used. Vegetable oil extraction processes consume a lot of energy (i.e. diesel, steam and electricity which are mostly sourced from fossil fuel) thus rendering the processes energy intensive and environmentally malignant. The energy required for a solvent extractor (~1692 MJ/ton oil) is much higher as compared with mechanical pressing (~97.2–486 MJ/ton oil) [7–9]. Any production process which is energy intensive records high destruction of useful energy (exergy) leading to thermodynamic inefficiencies [10] of the process. The cost of energy in most industries range from 20% to 80% of the variable cost [10–12] and therefore the reduction of energy intensity of any company would render it sustainable [12].

This study assesses the quantum of resource degradation in the extraction processes of jatropha oil and finds possible improvement options for efficient production. Exergy analysis is a thermodynamic assessment tool used to detect locations of resource degradation within production processes hence providing improvement options for efficient production.

The commonly used extraction technologies on various oil seeds include chemical (methanol, hexane, etc.) [8,13], mechanical (with a ram, hydraulic or screw press) [14], enzymatic [15], supercritical [16] and three-phase partitioning [9] extraction methods. People have been using screw presses and oil expellers since the

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Nomenclature

Ex_{tot}	total exergy (MJ)	Q	amount of heat produced (MJ)
$Ex^0_{ch,i}$	standard chemical exergy of ith component (MJ/kg)	S_{gen}	entropy generation (MJ/K)
$Ex_{ch,i}$	chemical exergy of ith component (MJ)	I	irreversibility (MJ)
$Ex_{ph,i}$	physical exergy of ith component (MJ)	T	temperature (K)
ΔG_{fo}	standard Gibbs free energy of formation (kJ/mol), (kJ/kg)	T_0	reference temperature = 273.15 K
$Ex_{destruction}$	total exergy destroyed (MJ)	p_0	reference pressure = 1 atm = 101.3 kPa
Ex_{out}	total exergy output (MJ)	N_i	number of moles of component i
Ex_{in}	total exergy input (MJ)	H	specific enthalpy (kJ/kg)
$Ex_{mass,in}$	exergy of entering material resource (MJ)	H_0	specific enthalpy at T_0, p_0 (kJ/kg)
$Ex_{mass,out}$	exergy of exiting material resource (MJ)	S	specific entropy (kJ/kg K)
Ex_{heat}	exergy due to heat interactions (MJ)	S_0	specific entropy at T_0, p_0 (kJ/kg K)
Ex_{work}	exergy due to work interactions (MJ)	η	exergetic efficiency

first century AD after they were developed and used by the Greeks in the Mediterranean regions for pressing olives. This basic method is still widely used presently by small, medium and large scale vegetable oil extraction companies throughout the world. In most part of the world including India, Ghana, Tanzania, Indonesia, etc., *J. curcas* oil is usually extracted by mechanical means (screw presses which are run on diesel engines) with about 60–70 °C heat treatment and oil yield of 47.2% [14]. However, the extraction rate of 18–23% of the oil content in *J. curcas* seeds is low for this technology. Solvent extraction has been reported to produce high yield of oil but consumes much energy due to long extraction time compared to the mechanical extraction method. With solvent extraction about 99.3% of the oil content in the seeds is extracted compared to 75–85% with a mechanical press [8].

In order to employ the most efficient technology in oil extraction for biodiesel production, exergy analysis has to be carried out to compare the quantum of resource degradation and thermodynamic efficiencies in the various processes. Solvent and mechanical extraction processes have been the main technologies currently used for vegetable oil extraction by most industries due to their low cost, efficiency and simplicity compared to other techniques. For these reasons, there must be an effective way of detecting the true magnitude of thermodynamic imperfections of the performances of various unit operations within these systems for improvements. In this study, solvent extraction with hexane and screw press oil extractions are used as case studies. Exergy destructions and efficiencies of these technologies are found and compared.

Mechanical extraction is the oldest and commonly used extraction method which can be operated on both batch and continuous processes. The mostly used process is the batch which is very slow and inefficient in the use of labour and rate of oil yield. Screw presses or expellers are presently designed for continuous extraction process [17,18]. The lower investment cost and short process time by mechanical extraction of oil makes it more advantageous to that of the solvent extraction. However, the major disadvantages are the high heat generation due to wear and tear of the machinery parts which increase the operational costs [19,20] and add to resource destruction as the heat is released into the environment without recovery. As a result of friction between the parts of the screw press, there is generation of heat which lower the quality of oil produced. Some of the heat is also lost into the environment contributing to exergy destruction of wastes and emissions.

Solvent extraction is a more efficient method of extracting the oil from the seeds which takes place either in batch or continuous process. The rate of extraction depends on the thickness and surface area of the seed flakes, the operating temperature, the type of solvent and the moisture content of the seeds [20]. The oil can be separated from the solvent by indirect heating (stripping) and direct steam injection (distillation) in which most of the solvents can be recovered for use [21]. For solvent extraction, the efficiency of oil extraction depends on the equilibrium rate between the solvent and miscella (mixture of oil and solvent) outside the seed particle (flake) and miscella within the flake [20].

New technologies that are used presently in vegetable oil extractions are the applications of high pressure carbon dioxide (CO_2) and enzyme extractions. In CO_2 extraction of vegetable oil, grounded seeds are mixed with high pressure CO_2 which serves as a solvent to dissolve and extract the oil. The use of enzymes such as lipase [15], is used by many oil extraction companies with the efforts to obtain more high value products. The seeds are heat treated, grounded and dissolved in water. Enzymes are then added to digest the solid material from the seed. The oil is then extracted with the help of a centrifuge [15,20].

1.1. Exergy analysis and sustainable energy development

Because most of the industrial processes are mainly energy conversion processes, it is highly imperative to address the issue of sustainable energy production in order to ensure efficient use of resources. Presently, the focus on environmental safety is gradually shifting towards energy efficiency in industrial processing. Exergy analysis, also called second law analysis, is a suitable scientific tool used to assess the thermodynamic sustainability of a production process [10,22,23]. In reality, there is no process which takes place in accordance with the first law of thermodynamics (which states that energy is conserved in all processes) but in almost all processes, there is the generation of entropy leading to the destruction of the quality part of energy called exergy. Hence, the concept of energy is not reliable in justifying the thermodynamic feasibility of a production process.

According to Cornelisse [24], the general exergy balance involving mass transfer for a control region relating the entropy generation to exergy destruction is given by:

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

where the terms represent the total exergy in, total exergy out, total exergy destruction, entropy generation and irreversibility respectively. Eq. (1) can be rewritten as Eq. (2) to involve the exergy due to heat and work interactions [24]:

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

where

$$\sum Ex_{work} = W \tag{2a}$$

$$\sum Ex_{heat} = \sum \left(1 - \frac{T_0}{T}\right) Q \tag{2b}$$

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

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

Eq. (2a) defines the exergy of the system due to work production. This can be calculated from the heat capacities and standard chemical exergies of the streams entering or leaving the system. Eq. (2b) also defines the quality of energy within the system. Q represents the heat duty of the system and T_0 and T represent the surrounding's temperature (25 °C) and temperature of the system. Eqs. (2c) and (2d) define the material exergy of input and output resources respectively.

For real processes the exergy input always exceeds the exergy output. This imbalance is due to irreversibility, also called exergy destruction, $Ex_{destruction}$, and is represented as a function of entropy generation. The exergy value of steady stream of fluid entering or leaving part of a process is the minimum amount of energy or work that can be obtained from the stream in bringing it to equilibrium with the environment [25–29]. With an enthalpy change of $(H - H_0)$ and an entropy change of $(S - S_0)$ at a reference temperature T_0 = 25 °C, the physical exergy can be calculated using Eq. (3):

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

With real irreversible processes there is always an increase in entropy resulting from the dissipative effects of energy within the production system. This extra entropy (exergy loss) generated are released into the environment or destroyed within the process [28–31]. Minimizing entropy generation within the system however would lead to reduction in exergy loss (in the form of heat and other emissions into the surrounding) hence a thermodynamic sustainable system. The sustainability of an industrial process is characterized by three main factors namely social, economic and environmental aspects [23,32]. Thermodynamic efficiency assessment combines both the economic and environmental aspects of sustainability. The quality of energy that is dissipated into the environment due to irreversibilities is clearly quantified in exergy analysis. Exergy analysis therefore allows the true magnitude of thermodynamic inefficiencies of industrial processes to be assessed, the primary causes of their inefficiencies to be established and the costs of obtaining their internal flows and productions to be assigned in a more comprehensive way [23,33,34].

2. Methodology

2.1. Process description and system boundary of J. curcas oil extraction processes

The pretreatment of the *J. curcas* seeds for oil extraction follow the same procedure for both solvent and mechanical extraction methods. *J. curcas* seeds after the cracking process are cleaned to remove foreign materials such as stones and leaves, before drying to prevent air flow blockage and the risk of experiencing hot spots and fires in a dryer. This process is done with the help of pneumatic aspirating chambers. Since this stage does not require much energy, it is not considered as part of the system boundary in this study. However, irreversibility assessment of the pretreatment unit has been carried out independently in this study.

Since moisture content is a critical factor in the storage and processing of the *J. curcas* seeds before oil extraction, drying is done. Cracking of seeds and dehulling are done with cracking rolls and aspirators respectively to remove as much seed shells which may impede oil extraction. Steam conditioning or cooking (heat treatment) of the *J. curcas* seeds is done to distort their cell structures in order to agglomerate or flocculate the oil droplets in the seed. This process helps improve the permeability of the cells within the seeds by reducing the viscosity of the seed oil for efficient oil extraction. Size reduction of the seeds increases the efficiency of oil extraction. Because of this, the seeds are flaked in order to increase the surface area during extraction. In this study, flaking is not part of the system boundary for mechanical extraction since steam conditioning would be enough to facilitate extraction of the oil.

2.1.1. Solvent extraction with hexane

Flaking is done prior to solvent extraction to enhance effective oil extraction. A smaller material (*J. curcas* kernel) size, gives a better penetration or allows a high degree of permeability of the solvent into the oil bearing cells. However, when the flakes' sizes are too small, the solvent would be prevented from percolation through the mass. Decreasing the flake thickness to 1/3 of its former size increases the extraction rate by 80 times. Generally, a recommended flake size of 0.25 mm or less as reported by Yan et al. [8] is absolutely essential for efficient extraction [7,8]. Fig. 1 shows the summary of the system boundary of solvent extraction processes of *J. curcas* oil. The processes were adopted from both literature [7,8] and industrial or commercial oil extraction technologies. The unit operations that are outside the broken lines are outside the system boundary. The unit operations that are outside the system boundary are the pretreatment unit operations whose exergy analyses are carried out independently. All emissions and wastes coming out the units within the system boundary are accounted for in the analysis as they are regarded as streams and not unit operations.

After flaking, the actual oil extraction is done with the help of hexane. For 1 ton of *J. curcas* seeds processed, 4 tons of hexane is required by continuous process [8]. *J. curcas* cake is removed after centrifuging the miscella (mixture of solvent and oil) from the whole mixture. The wet meal (*J. curcas* cake with some solvent) may carry some quantity of solvent (usually 27–40% by weight of solvent). The solvent can be recovered after desolventization of the cake by either direct or indirect heating of the wet meal with steam to a temperature slightly above the boiling point of hexane (68.7 °C at 1 atm) to ensure that no solvent is left in the meal. The solvent vapours are condensed and purified. The purification process of the recovered hexane is not part of the system boundary in this study because hexane purification is normally not done in most oil extraction companies (mostly with the small scale production companies which outnumber the commercial ones). For non-edible oil such as *J. curcas* oil, there would be no need for purification before reuse. The treatment and conversion of the *J. curcas* cake to other useful products is not considered as part of the system boundary. This is because presently, *J. curcas* seed cake is under research and development as to how they can be transformed into other useful products such as organic fertilizer and phytochemicals.

The miscella which contains about 40–60% hexane is also distilled to separate the oil from the hexane. Distillation is performed in three stages under vacuum to ensure that no oxygen is present (oxygen may render the oil rancid). The controlling measures and absorption of traces of evaporated solvent and other emissions are not part of the system boundary. The chosen functional unit for the study is 1 ton *J. curcas* oil produced by continuous process.

2.1.2. J. curcas oil extraction with mechanical screw press

The steam conditioned ground *J. curcas* seeds are fed into the screw-press, which consists of an interrupted helical thread (worm) which revolves within a stationary perforated cylinder called the cage or barrel [17,18]. The meal is forced through the barrel by the action of the revolving worms. The volume axially displaced

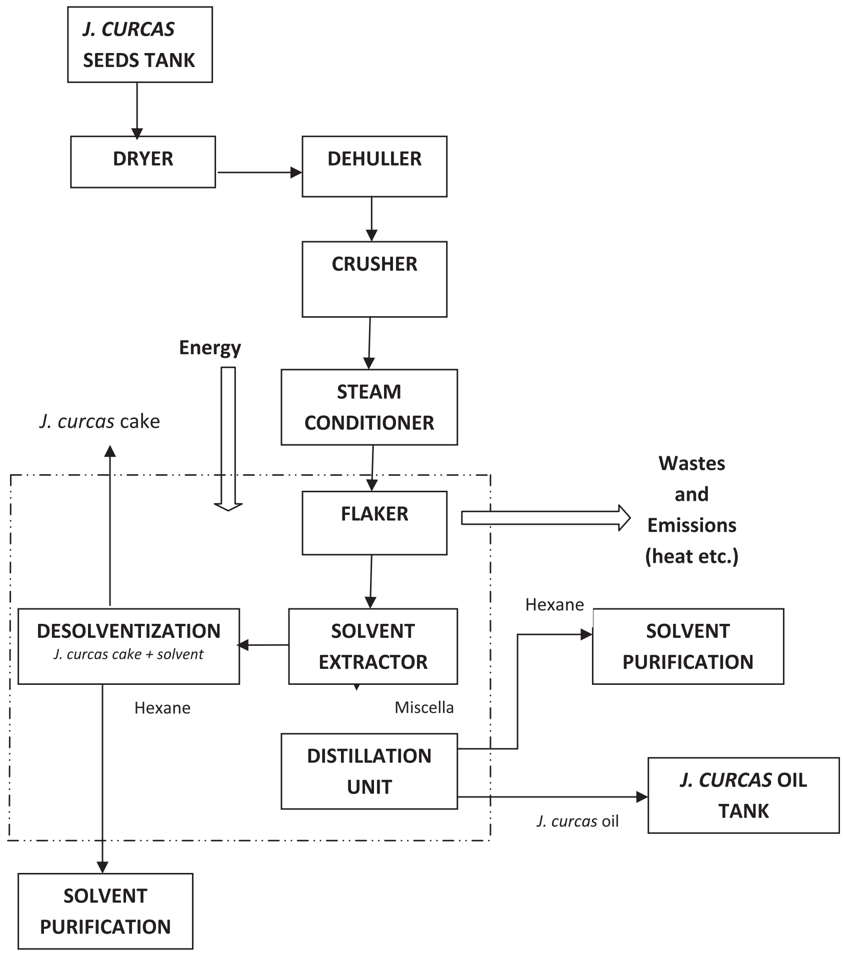

Fig. 1. System boundary of solvent (hexane) extraction of *J. curcas* oil.

by the worm diminishes from the feeding end to the discharge end, thus compressing the meal as it passes through the barrel. The expelled oil drains through the perforation of the lining bars of the barrel, while the de-oiled cake is discharged through an annular orifice [17,18]. In order to prevent extreme temperatures that could damage the quality of the oil and cake, the worm-shaft and barrel are always cooled with circulating water. Fig. 2 shows the system boundary of mechanical extraction processes of *J. curcas* oil.

The unit operations outside the system boundary are the pretreatment unit operations whose exergy analyses are carried out independently. The processes used for mechanical extraction of *J. curcas* oil in this study are the commonly used ones as reported in literature [7,8,14].

The expelled oil may contain some debris which can be removed with the help of a decanter or filter. The oil is then pumped to a filter press to remove the remaining solids and fines in order to produce clear oil prior to storage. The cake discharged from the press is considered not treated in this study. A continuous screw pressing process is chosen for this study since it is not energy and time consuming but produces high yield of oil (i.e. 85–90% oil) [17,18]. A functional unit of 1 ton *J. curcas* oil is chosen for this study.

2.2. Chemical and physical exergies calculations

In a biomass such as *J. curcas* seeds, exergy is mainly stored in a form of chemical exergy [35]. Chemical exergy refers to the maximum amount of work obtainable when a substance is brought from the environmental state to the dead state by virtue of its chemical composition or by a process involving heat transfer and exchange of substances only with the environment. The chemical exergy of *J. curcas* seeds (with composition 6.20% moisture, 38% fats, 17% carbohydrates and 15.50% fibre and 5.30% ash) and *J. curcas* oil (with composition 14.2% palmitic acid [36], 6.9% stearic acid [1], 44% oleic acid [36], 34.3% linoleic acid [1], and 0.6% other acids) were calculated based on their heating values given by [27]:

$$\varepsilon^0_{fuel} = \beta * LHV \tag{4}$$

where ε^0_{fuel} represents the standard chemical exergy of the biomass, LHV is the lower heating value of the fuel and β (i.e. the weighing factor that accounts for the information that the biomass or fuel carries) values are given in literature [37] for most fuels. The chemical exergy of *J. curcas* oil can also be calculated from the compositional method and the standard chemical exergies obtained from literature [23].

The chemical exergy for each pure substance, organic and utilities were calculated using their standard chemical exergies ($Ex_{ch,i}$) from literature [38,39] according to Eq. (5):

$$Ex_{ch,i} = \Delta G_{fo} + \sum_i v_i Ex^0_{ch,i} \tag{5}$$

where $Ex_{ch,i}$, $Ex^0_{ch,i}$, ΔG_{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 that are not listed by Ayres and Ayres, and Szargut [38,39] can be estimated by using the group contribution method based on information about their

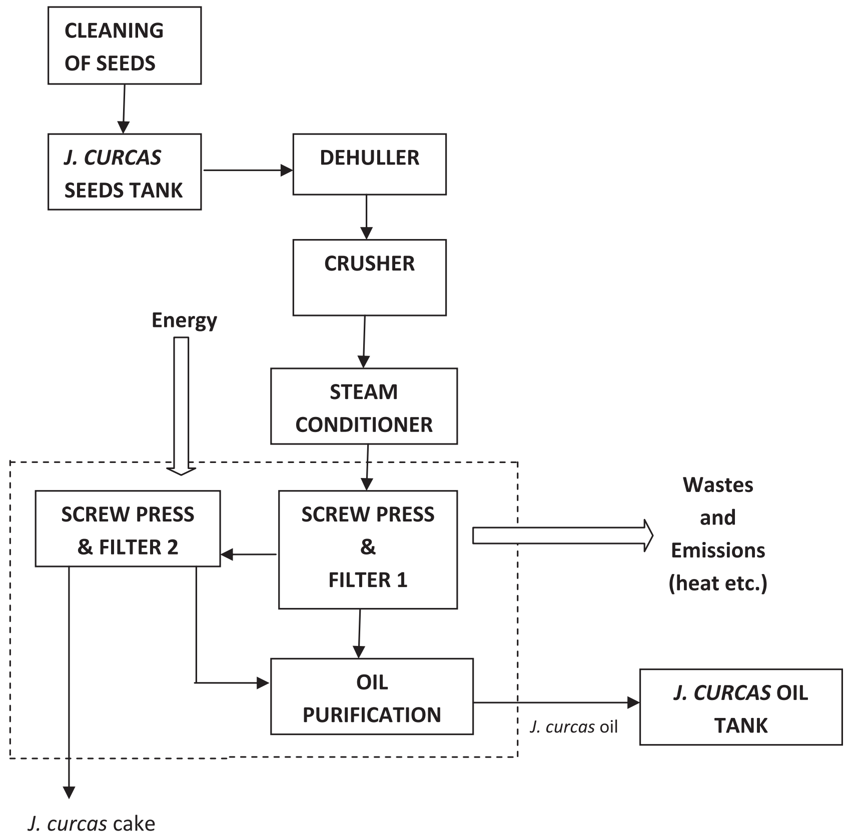

Fig. 2. System boundary of mechanical extraction processes of *J. curcas* oil.

molecular structure in determining the absolute entropy and enthalpy of formation values at standard conditions.

The physical exergy of each stream is therefore calculated using Eq. (1) [25–27]. Thermodynamic properties of each stream can be obtained from literature or database of reliable computer software such as Aspen plus software. For a chemical process, the exergy associated with multi-component material stream is divided into chemical and physical exergies thus an equation for total exergy of a system is defined by:

$$Ex_{tot,i} = Ex_{ch,i} + Ex_{ph,i} \tag{6}$$

Each term is determined separately and systematically for every unit operation in the biodiesel production plants as explained before. The overall exergy efficiency of the process is defined by [40]:

$$\eta_{total} = \frac{\sum Ex_{out}}{\sum Ex_{in}} \tag{7}$$

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

3. Results and discussion

Table 1 shows the chemical exergies of the major material streams in both the solvent extraction and mechanical extraction processes of *J. curcas* oil.

Chemical exergies for each individual stream within the system boundary of the oil extraction processes were estimated using their composition's standard chemical exergy values from literature [38,39] and/or their heating values. The total exergy destructions due to mass, heat and work interactions in the various unit operations are summarized in Table 2. The exergy analysis is performed based on the flow diagrams described in this study. Any changes (e.g. the type of oil and extraction processes) may alter the results drastically.

As shown in Table 1, the total input exergy of material resources and utilities into the oil extraction processes are 592,064 MJ and 34,084 MJ for solvent and mechanical extraction methods respectively. The high exergy content of hexane used in the solvent extraction unit contributed to the high input exergy content. The total exergies of products obtained from the input resources are 560,680 MJ (95% of input exergy) and 37,970 MJ (111% of the input exergy) for solvent and mechanical extractions respectively. This indicates that the *J. curcas* seeds upon conversion into oil are upgraded in terms of exergy (available energy to do work) for mechanical extraction. However, for solvent extraction, about 6% of the useful energy in *J. curcas* seeds is destroyed upon conversion into the oil. Also, due to high quality energy in hexane, 5% of the total amount used for solvent extraction which were lost during the process, carry a lot of exergy which is regarded as wastes. The efficiency of the distillation unit can be improved to enhance more recovery of hexane in order to minimize the loss of material wastes into the environment.

The total internal exergy destroyed (due to mass, heat and work interactions) for solvent extraction process is 18,072 MJ for 1 ton *J. curcas* oil extracted. The exergy of wastes recorded in the solvent extraction unit is 26,862 MJ which is the excess hexane which could not be recovered. This shows that almost 60% of the total exergy destruction is regarded as waste. This can be avoided by converting the *J. curcas* seed husks into other useful products such as fertilizer or bio-ethanol; and the use of high efficiency equipment.

The distillation unit recorded the highest exergy loss (due to entropy generation) of 8114 MJ forming about 45% of the total internal exergy destruction in the solvent extraction unit. In a system

Table 1
Chemical exergies of major streams in solvent and mechanical extraction processes.

Stream name	Unit	Quantity	Standard chemical exergy, $Ex^0_{ch,i}$ (MJ/kg)	Chemical exergy $Ex_{ch,i}$ (MJ)
Fresh *J. curcas* seeds	kg	3000	17.73	53,190
Dried *J. curcas* seeds	kg	2814	20.30	57,124
De-shelled seeds (kernels)	kg	1632	12.60	20,563
J. curcas seed husks	kg	1182	16.93[b]	20,011
J. curcas seed cake	kg	816	20.25[b]	16,526
J. curcas oil	kg	1000	37.00	37,000
Hexane (solvent extraction)	kg	11,256[a]	47.75	537,474
Steam (solvent extraction)	MJ	958[a]	0.526	504
Electricity (solvent extraction)	MJ	703[a]	4.17[c]	2932
Electricity (screw press)	MJ	30[a]	4.17[c]	1793

All other values were calculations done in this study.
[a] Obtained from Ref. [41].
[b] Obtained from Ref. [42].
[c] Obtained from Ref. [43].

Table 2
Total exergy destructions and efficiencies of the various unit operations.

Unit operations	Energy (MJ)	Total exergy destruction, $Ex_{dest.}$ (MJ)				Exergy efficiency
		$Ex_{dest.}$ (mass)	$Ex_{dest.}$ (heat)	$Ex_{dest.}$ (work)	$Ex_{dest.}$ (total)	
Solvent extraction						
Flaker	187	722	211	298	1231	92
Extractor/decanter	693	3978	754	801	5533	77
Desolventizer	299	1875	509	765	3149	85
Distillation unit	482	5363	1208	1543	8114	64
Total	1661				18,072	
Mechanical extraction						
Screw press 1	237	912	276	457	1645	93
Screw press 2	126	667	117	319	1103	95
Oil purification unit	67	83	77	98	258	99
Total	430				3006	

where the process involves heat transfer (e.g. heat exchangers, dryers, evaporators, distillation columns, etc.), entropy generation becomes an important parameter. For streams which have the same heat capacities, the driving force (e.g. temperature, pressure, etc.) is also the same. In a situation such as this, the driving force can be minimized (in order to minimize entropy generation leading to exergy destruction) by increasing the heat transfer area, or the overall heat transfer coefficient. This can further lead to a reduction in heat duty especially with distillation columns where the number of feed stages and reflux ratios are optimized. For complex systems where the driving force may keep changing, the design of the equipment plays an important role. For instance in a distillation column, the column height can be increased or the feed stage can be increased in order to approach equilibrium at one or two points.

The solvent extractor/decanter recorded about 31% of the total internal exergy destruction. This is as a result of mass and heat transfer interactions due to entropy generation dissipating heat and other emissions into the environment which cannot be recovered. The generation of entropy in unit operations can be minimized through effective process and equipment design. Whenever there is inconsistency in the change in temperature (non-isothermal) within the equipment, there is maximum exergy loss [44]. This can be improved by the use of isothermal process equipment e.g. with the extractive decanter. To have a realistic size of equipment and make a given process take place in finite time, there is a greater need for a minimum driving force [44]. It is thus, always necessary to give allowances for the minimum potential difference while carrying out the analysis of a system with the aim of reducing the exergy loss.

For mechanical extraction, the total internal exergy destroyed is 3006 MJ which is about six times less than that for solvent extraction unit. This is attributed to the intensive use of energy sourced from fossil fuel and the use of low efficiency equipment which employ heat interactions for solvent extraction. Also the exergy of wastes (external exergy destruction) within the mechanical extraction unit is zero. The *J. curcas* seed cake is assumed to be a useful product. However, in the solvent extraction unit, some amount of hexane could not be recovered and thus emitted into the environment contributing to external exergy destruction. The chemical exergy balance of main streams is presented in Figs. 3 and 4 for solvent and mechanical extractions respectively.

The total internal exergy destruction of the pretreatment processes for *J. curcas* seeds for oil extraction is estimated in this work to be 5768 MJ for 3 tons of *J. curcas* seeds processed (1 ton of *J. curcas* oil). The unit operation for steam conditioning of the

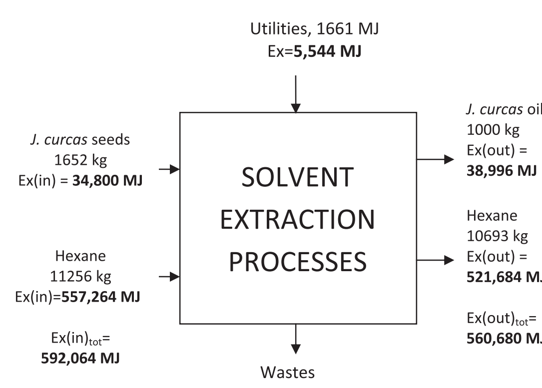

Fig. 3. Summary of exergy balance of solvent extraction processes of *J. curcas* oil.

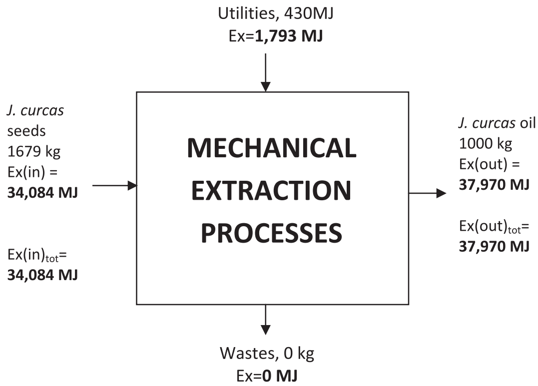

Fig. 4. Summary of exergy balance of mechanical extraction processes of *J. curcas* oil.

Table 3
Pretreatment of 3 tons of *J. curcas* seeds for oil extraction.

Unit process	Energy (utilities) input (MJ)	Total internal exergy destruction (MJ)	Exergy efficiency (MJ)
Drying	1250	998	80
Dehulling	721	443	82
Crushing	1940	1321	76
Steam conditioning	2453	3006	73
Total	6364	5768	

J. curcas kernel accounted for about 52% of the total internal exergy destroyed. The crushing and drying units also recorded quite significant amount of exergy destruction with 23% and 17% contribution respectively. This is attributed to the high consumption of energy within these units. Midilli and Kucuk [45] have also reported that due to the heavy utilization of energy in the drying industry, high amount of quality energy is destroyed thus reducing the thermodynamic efficiency of dryers and heat transfer equipment. Table 3 summarizes the energy and exergy inputs into the pretreatment unit. The major energy inputs were electricity and steam assumed to be sourced from fossil fuel.

The total exergy of wastes (i.e. external exergy destruction) recorded in the pretreatment unit is 20,010 MJ which is mainly the exergy content of the *J. curcas* seed husks. The total exergy destruction in the pretreatment unit alone is estimated to be 25,778 MJ per ton of *J. curcas* oil produced. This can be drastically minimized by converting the *J. curcas* seed husks into useful products. Again, the energy sources as inputs into each of the unit operations were sourced from fossil fuel whose standard chemical exergy is very high hence contributing to high input exergy and exergy destruction. If renewable energy sources are used, the exergy content of only the energy input would be minimized by a factor of 4 which would drastically decrease the input exergy hence minimizing the exergy destruction and increasing exergy efficiency.

Solvent extraction is less exergetically efficient (79%) compared to 96% exergetic efficiency of mechanical extraction of *J. curcas* oil. Solvent extraction of *J. curcas* oil is thermodynamically destructive compared to mechanical extraction. Highly efficient screw presses can be designed to increase the oil yield and extraction rate so as to improve the process. Heat transfer equipment such as the distillation column for hexane recovery can be improved by increasing the feed stages and reducing the reflux ratio. Fig. 5 summarizes the exergy destruction in the various unit operations within both extraction units.

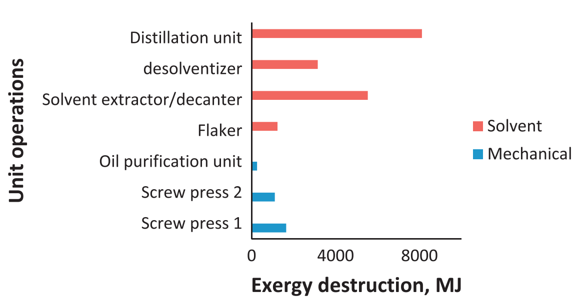

Fig. 5. Exergy destruction distributions within the unit operations of both extraction processes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Conclusions

In this study, the exergetic efficiencies and destructions of *J. curcas* oil extraction methods are carried out. The results indicate that:

- The total internal exergy destroyed as a result of entropy generation in solvent extraction processes of *J. curcas* oil is almost six times that for mechanical extraction.
- The unit operations that recorded the highest exergy destructions in solvent and mechanical extraction processes are the distillation unit and screw press 1 (i.e. first press used) respectively. Hexane recovery or separation of *J. curcas* oil from hexane contributed 45% of the total internal exergy destruction. The contribution of screw press 1 is 55% of the total irreversibilities that occurred in the mechanical extraction unit.
- 94.7% of the total input exergy for solvent extraction are the products' exergy whilst 111.4% of the total input exergy into mechanical extraction unit are the outputs' exergy. This implies that mechanical extraction method though low in oil yield, upgrades the oil making it possess high useful energy to do work compared to solvent extraction. Thus, the extraction of *J. curcas* oil using a solvent (hexane) generates higher entropy leading to higher internal exergy destruction compared to when screw press is used.
- The pretreatment of *J. curcas* seeds for oil extraction contributes to 24% of the total internal exergy destroyed for solvent extraction processes and 66% for mechanical extraction. This indicates that, the pretreatment unit alone degrades so much quality energy in the *J. curcas* seeds before actual oil extraction. When the pretreatment unit processes are improved, mechanical extraction would be more exergetically efficient.
- Solvent extraction of *J. curcas* oil is 79% efficient based on thermodynamics
- Mechanical extraction of *J. curcas* oil is 96% exergetically efficient
- Mechanical extraction is therefore found in this study, to be more exergetically efficient than solvent extraction.

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