

***Balanites Aegyptiaca* Fruits' Valorisation by Liquid Biofuels Production**

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Abstract: Today, the fight against global warming is a major challenge for the whole world. The widespread use of biofuels is indeed one of the credible alternatives that can lead to a significant reduction in greenhouse gas (GHG) emissions. This study aims to promote the fruits of the desert date in bioenergy. The various treatments showed that the fruits are composed of $52.67 \pm 0.18\%$ of nuclei, $40.08 \pm 0.50\%$ of mesocarps and $7.26 \pm 0.33\%$ of epicarps and other solid particles. From the mesocarps, bioethanol was produced with a yield of $14.74 \pm 0.06\%$; while by Soxhlet extraction of almonds with hexane gave a vegetable oil with a yield of $44.58 \pm 5.69\%$. The monitoring of the ethanolic fermentation reaction, carried out with *Saccharomyces cerevisiae* yeasts revealed that a pH of 4.0 optimized the reaction, with an attenuation limit of 54.17%. GC-FID analysis showed that other reactions which should compete with ethanolic fermentation, were almost inhibited by the effectiveness of the kinetic control. GC-FID analysis of the chemical composition of the biodiesel produced with the crude oil has showed the presence of oleic acid (41.90%), linoleic acid (29.27%), palmitic acid (12.47%), β -linolenic (10.89%) and stearic (1.17%). Physicochemical analysis and the comparison of energy characteristics indicated that the biofuels produced in this study have properties similar to those of petrodiesel and some standard biofuels. Therefore, the fruits of *Balanites aegyptiaca* are an interesting source of liquid biofuels that can replace petrol and conventional diesel, the most used fossil fuels in transportation.

Keywords: *Balanites Aegyptiaca* Fruits, Alcoholic Fermentation, Transesterification, Biofuels

1. Introduction

In the face of threats related to climate change, the urgent need to preserve the environment and the depletion of fossil energy resources, the exploitation of alternative energy sources such as biofuels has received strong support from the world international community, the Non-governmental Organization (NGO) and researchers. Therefore, sustainability presents a unique challenge to policy makers. Thus, nowadays, the use of renewable energies is a general interest and therefore no longer a voluntary desire at a time when the use of petroleum and its derivatives its derivatives on a large scale is inducing environmental pollution and

global warming [1-5]. In addition, over the past two decades, more than half of the world's petroleum reserves have been consumed, leading to risks shortages and price increases [6]. Paradoxically, it is poor countries that are paying the heavy costs for the dramatic consequences of air pollution and global warming, while big polluters, such as the USA and China, do not currently feel concerned about commitments to undertake and meet to slow down the GHG emissions. But to prevent the perverse effects of air pollution and climate change and their harmful consequences on the environment from and becoming worse and becoming absolutely unmanageable, more and more voices are being raised to find partial or definitive solutions to these problems. As a challenge, this work was initiated with the main objective of

promoting the use of plants in the production of renewable energy with competitive prices compared to petroleum products in order to contribute to the environmental protection and therefore sustainable human development.

In these circumstances, in order to respect the commitments made at international meetings, such as the Kyoto Protocol in 2003 and COP24 in 2018, bioethanol and biodiesel have been targeted as the most appropriate alternatives, intervene in the field of transport as legal substitute for conventional fuels such as gasoline and diesel. Thus, in order to respect the commitments made at international meetings, such as the Kyoto Protocols in 2003 and COP24 in 2018, bioethanol and biodiesel have been well targeted as the most appropriate transport alternatives as legal substitutes for conventional fuels such as gasoline and diesel. This unavoidable choice would be due to the fact that the physico-chemical properties of these two agrofuels are almost compatible with gasoline and diesel engines.

In Africa and South Asia, many wild-growing plant species are still little or almost undervalued by local populations. Among these neglected plant species include *Balanites aegyptiaca* (L.) Del (Zygophyllaceae), a big tree that is always green, often found in arid regions and dry savannahs in Sahel-Sudanese areas [7-8]. The fruits of this plant, composed of epicarps (5.9%), mesocarps (28.33%), endocarps (49.54%) and almonds (8.12%), have many advantages because it could be used both as raw material for the vegetable oil production, protein concentrate, ethanol and Sudanese steroids [7, 9-14]. However, the presence of saponins in the fruits hinders its use without any prior treatment both in the diet of humans and animals [11, 13]. Then, they can serve as a basic raw material for the production of first-generation biofuels.

In this study, our approach is to develop scientific

processes for the production of bioethanol and biodiesel from the fruits of desert date in order to contribute to the fight against global warming.

2. Material and Methods

2.1. Study Framework

The work of this study was carried out between April and September 2010 at the Laboratory of Vegetable Extracts and Natural Aromas (LEVAN), at the Faculty of Sciences (FDS) of the University of Lome (Togo).

2.2. Equipment

2.2.1. Plant Material

The fruits of *Balanites aegyptiaca* were harvested in Burkina Faso in April 2010 and were used as plant material for the production of both bioethanol and biodiesel. In fact, the mesocarps of the fruits was used for alcohol production while after Soxhlet extraction of the almonds with hexane, the obtained vegetable oil was used for biodiesel production.

2.2.2. Biological Material for Fermentation

The active dry yeasts of *Saccharomyces cerevisiae* were used as microorganisms for the ethanol fermentation reaction of the musts prepared with the mesocarps of fruits.

2.3. Experimental Protocols

2.3.1. Diagram of Bioethanol and Biodiesel Production Technology

The different stages of production of bioethanol and biodiesel from the fruit of *Balanites aegyptiaca* are shown in the diagram in Figure 1.

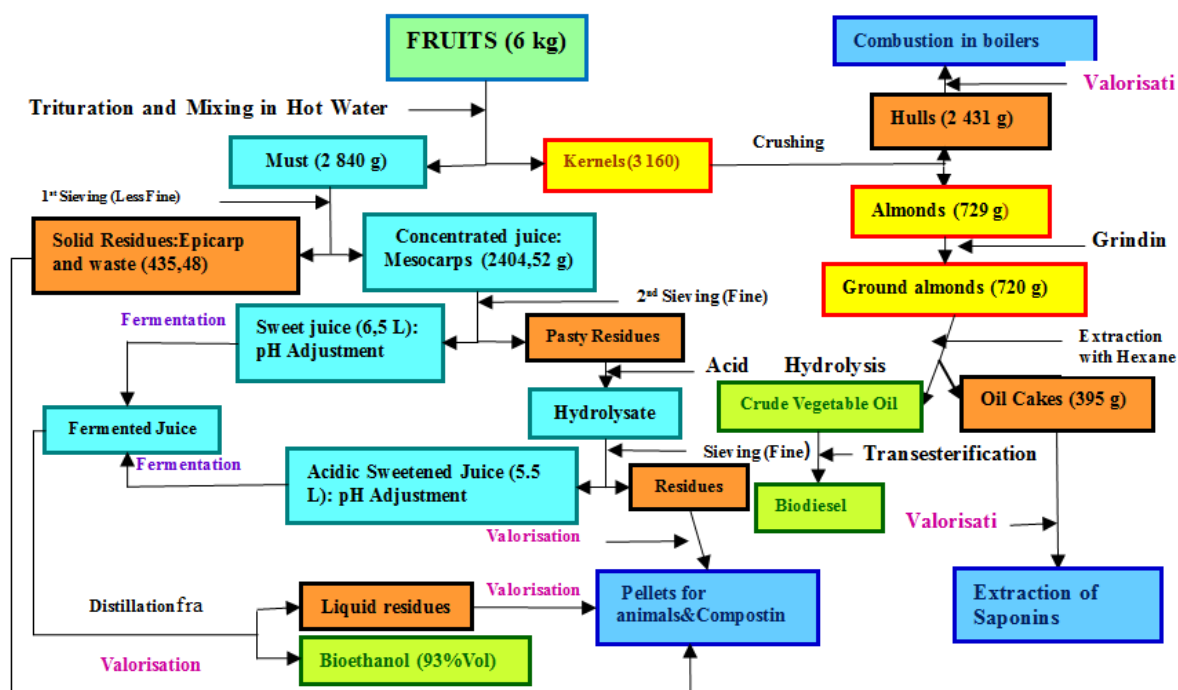


Figure 1. Diagram of bioethanol and biodiesel production technology from *Balanites aegyptiaca* fruits.

On this diagram, there are two parts: the first part on the left, exposes the different stages and different treatments carried out to produce bioethanol. While the second part on the right, describes the different steps and operations made to achieve the production of biodiesel. Once harvested and brought back to the laboratory, the fruits were triturated by hand in the water until the maximum extraction of the mesocarps. The sweetened liquid obtained is filtered by sieving after separation with a pasty residue containing suspended particles (epicarps and other particles) and the kernels. The syrup obtained after filtering was boiled to make it more concentrated in sugars and served as ripe must for fermentation. The paste formed during the juice extraction was hydrolyzed with sulfuric acid (H_2SO_4 : 2 M) and the collected hydrolate was filtered and then used as the second mature must for the ethanol fermentation. Ethanol fermentation of the ripe must followed by fractional distillation for bioethanol recovery.

In the case of biodiesel, the kernels recovered after extraction of the sweet juice were crushed and the collected almonds ground before being extracted with solvent. The recovered oil, which can be used in the raw state as a vegetable oil fuel, has been converted into biodiesel by the transesterification reaction with methanol.

In order for the biofuel production platform to be self-sufficient in energy source, the hulls produced as waste after crushing the kernels in the boilers can be burned to generate energy. Other wastes, such as liquid waste, oilcake and solid residues could be used for animal feed or as compost.

2.3.2. Extraction of the Sugars Contained in the Mesocarps

To facilitate the extraction of sugars, the ripe *Balanites aegyptiaca* fruits brought back to the laboratory are first soaked in hot water for at least 30 minutes before being triturated by hand. This gives a mixture which, after filtration, gives sweet juice and a pasty residue which is washed several times with distilled water to collect almost all the sugar substances. The sweet juices thus obtained are collected and concentrated by simple heating to boiling before serving as ripe must for fermentation. The sugar content was evaluated in musts extracted from the mesocarp of *Balanites aegyptiaca* by measuring the Brix using the Fabre-Mesurelec/RAM 0-80%; series-106 refractometer and the results were expressed in sucrose equivalents, that is to say for the same volume of solution, the mass of glucose which would give the same value of Brix than that of the must of *Balanites aegyptiaca* mesocarps. To do this, the calibration curve of Figure 2 was used for the determination of sucrose equivalents.

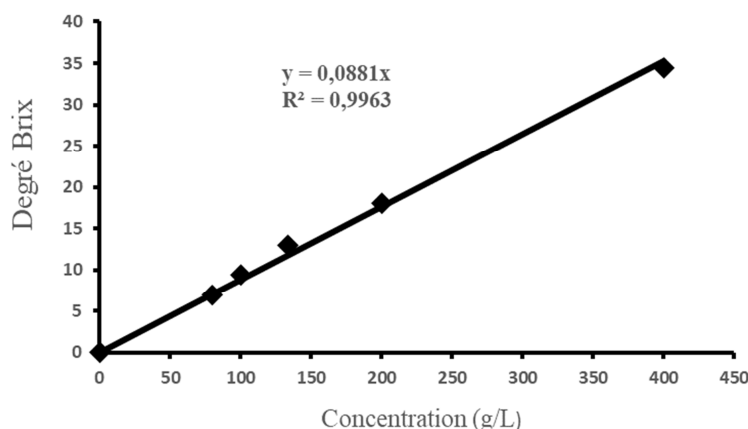


Figure 2. Variation of the Brix degree as a function of the concentration of the aqueous solution of sucrose.

2.3.3. pH Measurement

The pH of the juices extracted from the mesocarps was determined using the CRISON pH 25 pH meter, equipped with calibration solutions.

2.3.4. The Implementation of Ethanol Fermentation

The pH of the ripe must was adjusted using a solution of sulfuric acid (0.50 N) or a solution of sodium hydroxide (1.00 N). The fermentation inoculum was prepared by inoculation of 10% of the volume of the sterilized mature must by refluxing at 90°C for 20 minutes, with yeasts of *Saccharomyces cerevisiae* originating from a pre-culture made with glucose [15-16]. Ethanol fermentation was conducted anaerobically in the laboratory in a can fermenter that was 2/3 full in order to create asphyxiation conditions necessary for yeasts at room temperature ranging from 30 to

32°C at least 72 hours [16].

The alcoholic fermentation reaction was monitored either by measuring the Brix degree. When the release of CO_2 stops or the Brix must become stable, it indicates the end of the alcoholic fermentation.

2.3.5. Limit Attenuation

The limit attenuation, denoted LA and expressed in %, is the percentage of fermented sugars and was calculated using Formula 1. It represents the proportion of sugars that disappeared during the fermentation and gives an estimate of the level of sugars consumed or likely to be converted into alcohol during fermentation [17-18].

$$LA = \left(\frac{\text{Initial Brix} - \text{Final Brix}}{\text{Initial } ^\circ \text{Brix}} \right) \times 100\% \quad (1)$$

2.3.6. Alcoholic Distillation

After the fermentation, the musts that were extinguished were distilled in the laboratory on a Vigreux column. By means of a temperature regulator fixed on the heating cap, the heating temperature of the fermented must has been adjusted so that the thermometer fixed at the top of the column indicates a value close to 78°C. A second distillation was necessary for the rectification of the first collected distillate called phlegm. However, since obtaining a distillate pure ethanol (100% vol.) is never possible because of the azeotropic mixture formed by water and ethanol, calcium chloride has been introduced into the liquid sequence of distillation as a desiccant for the rectification of bioethanol produced.

2.3.7. Oil Extraction

Oil extraction of milled *Balanites aegyptiaca* kernels was done by the Soxhlet method with hexane for 12 hours. Hexane was then separated from the oil by evaporation using BUCHI/R-114 Rotavapor. The oil extraction yield (R_H) was calculated using Formula 2.

$$R_H = \frac{M_H}{M_A} \times 100\% \quad (2)$$

With: M_H = mass of the extracted oil and M_A = ground almonds mass.

2.3.8. Transesterification of Oil from *Balanites Aegyptiaca* Almonds

In a 2 L flask, 20 g of oil and 200 mL of sodium methanolate were introduced. The mixture is refluxed for 1 hour. Then, from the top of the condenser, 200 mL of hydrochloric methanol (50 mL of acetylchloride in 150 mL of HPLC grade methanol) were added. After refluxing for an additional hour, the mixture was allowed to cool to room temperature. One volume of 200 mL of hexane and another of 200 mL of distilled water was added to the flask contents. After stirring in a separatory funnel, the mixture was allowed to settle. The hexane phase is transferred to a 250 mL flask and the hexane is evaporated under vacuum using the BUCHI/R-114 rotary evaporator system. The residue thus obtained, called biodiesel, was then subjected to analysis by gas chromatography (GC).

2.3.9. Physicochemical Analyzes of Samples of Biofuels Produced

(i). GC analysis

GC-FID analyzes of the biofuels produced (bioethanol and biodiesel) were made using a Varian 3400 chromatograph HP-type, equipped with an apolar capillary column type HP-1 whose length is 60 m, internal diameter 0.32 mm and film thickness (stationary phase) 0.25 μ m. The carrier gas is N_{50} nitrogen whose flow rate has been set at 1 mL /min. The detector flame was maintained by a hydrogen/air mixture,

with respective flow rates of 30 mL/min and 300 mL/min. The identification of the compounds revealed on the pictogram of bioethanol and biodiesel analyzed was done simply using the peaks of the corresponding standards after analysis under the same conditions.

(ii). Lower Calorific Value Measurement (LCV)

The LCV of the biofuels produced (bioethanol and biodiesel) were measured in "West African Cement (WACEM)" laboratory of analysis using an Advance-Bomb-Calorimeter. The principle used is to ignite a volume of 10 mL of each biofuel in an adiabatic chamber coupled to a temperature integrator. The variation in temperature due to the heat released during the combustion of the biofuel after an electric discharge made it possible to determine the LCV of the biofuel analyzed.

(iii). Flash Point (FP) measurement

FP is the minimum temperature for which a given mixture of fuel, pressure and composition ignites spontaneously without contact with a flame. It is determined using Nabertherm/ Controller P 320 (30-3000°C) brand oven for Pure Plant Oil (PPO) and Biodiesel of *Balanites aegyptiaca*. The temperature variation is set at a speed of 17°C/min. The temperature read on the screen of the device under normal pressure and at which light has appeared in the oven was considered as the FP of the corresponding biofuel. However, this method could not be applied to bioethanol because of its high volatility in the oven.

2.3.10. Determination of Some Characteristics of Fats (Oils)

The indices of refraction (IR), acid (IA) and saponification (IS) were determined by complying with standards NF T 60-2012, NF T 60-204 and NF T 60-206, respectively [19]. The determination of the density with respect to water, the ash content and the water and volatile matter content were made according to NF T 60-214, NF T 60-209 and NF T 60-201 standards, respectively [19].

3. Results and Discussion

3.1. Bioethanol Production

3.1.1. Extraction of Sugary Substances Contained in Mesocarps

The results of extraction of the juice of mesocarps from the fruits of *Balanites aegyptiaca* (Table 1) show that a mass of 1,000.00 g of fruit is composed of $400.33 \pm 6.11\%$ of mesocarps, corresponding to an equivalent of sucrose almost equal to 276.00 g. This very appreciable level of mesocarps contained in these fruits represents the fraction rich in fermentable sugars which can be recoverable in bioethanol by the controlled reaction of the alcoholic fermentation. To preserve this sweet fraction, the juice must be first sterilized to avoid a potential risk of spontaneous alcoholic fermentation.

Table 1. Some physical parameters of the must extracted from the mesocarps.

Moût extrait à partir du mésocarpe de <i>Balanites aegyptiaca</i>						
Test N°	Fruit mass (g)	Mass of Mesocarps (g)	Volume of must (L)	Brix degree	Sucrose equivalent concentration (g/L)	Mass of sucrose equivalent (g)
1	6,000.12	2,399.40	12.06	12.5	141.88	1,711.12
2	6,000.48	2,370.66	12.18	13.0	147.56	1,797.28
3	6,000.18	2,443.50	12.30	12.0	136.21	1,675.37
Averages±Ecartypes	6000.33 ± 0.15	2404.52 ± 29.96	12.18 ± 0.10	12.5 ± 0.41	141.88 ± 4.63	1727.92 ± 51.17

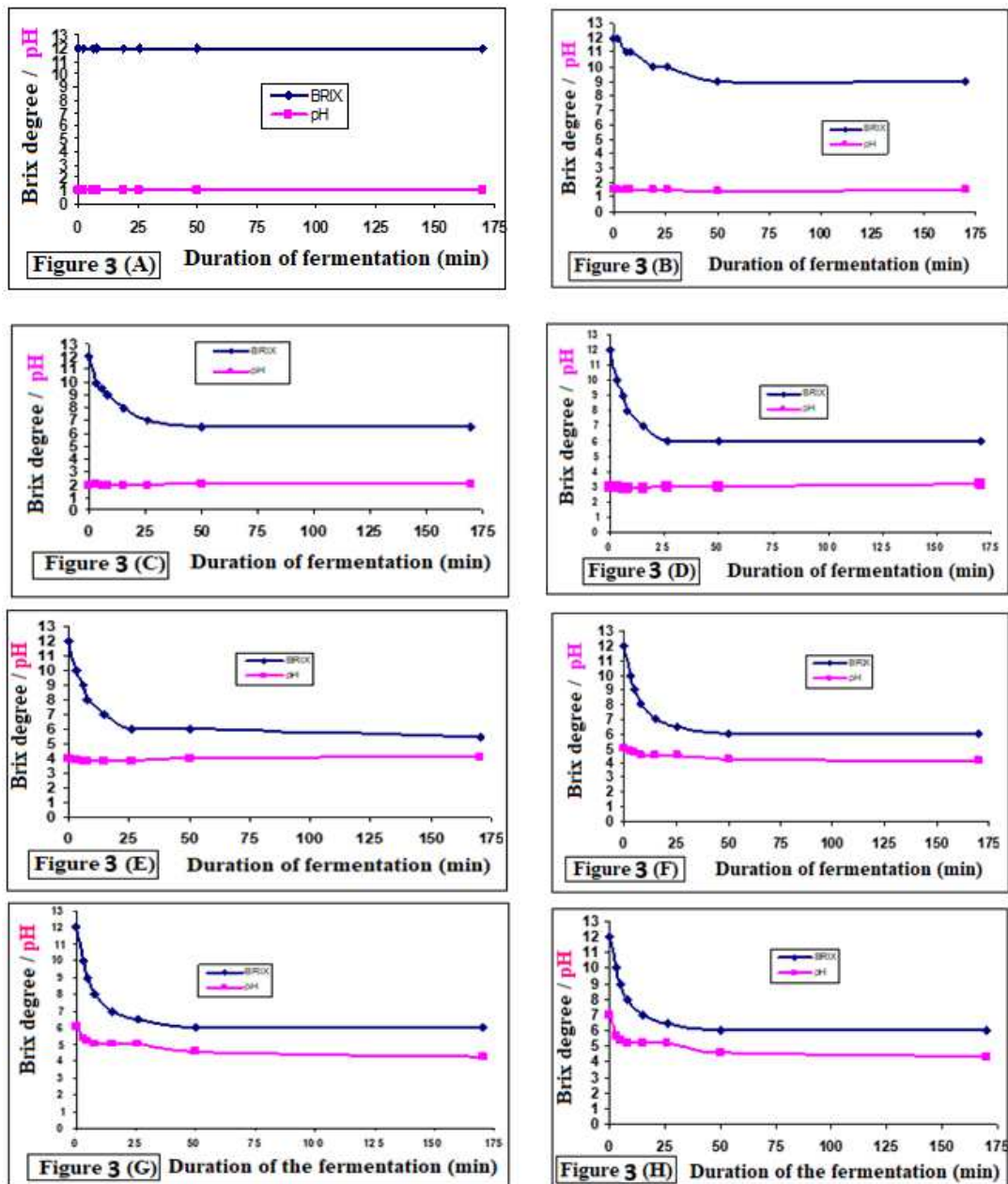
3.1.2. Alcoholic Fermentation

(i). Effect of pH of the reaction medium

The curves in Figures 3 (A-N) show the profiles of the Brix and pH variations as a function of the fermentation duration of *Balanites aegyptiaca* must. From these curves, we have been able to determine the values of the limit

attenuations necessary to appreciate the effect of the initial pH on the yield of the alcoholic fermentation of the musts of the *Balanites aegyptiaca* mesocarp.

Figure 4 presents the evolution of the limit attenuation as a function of the initial pH of the musts.



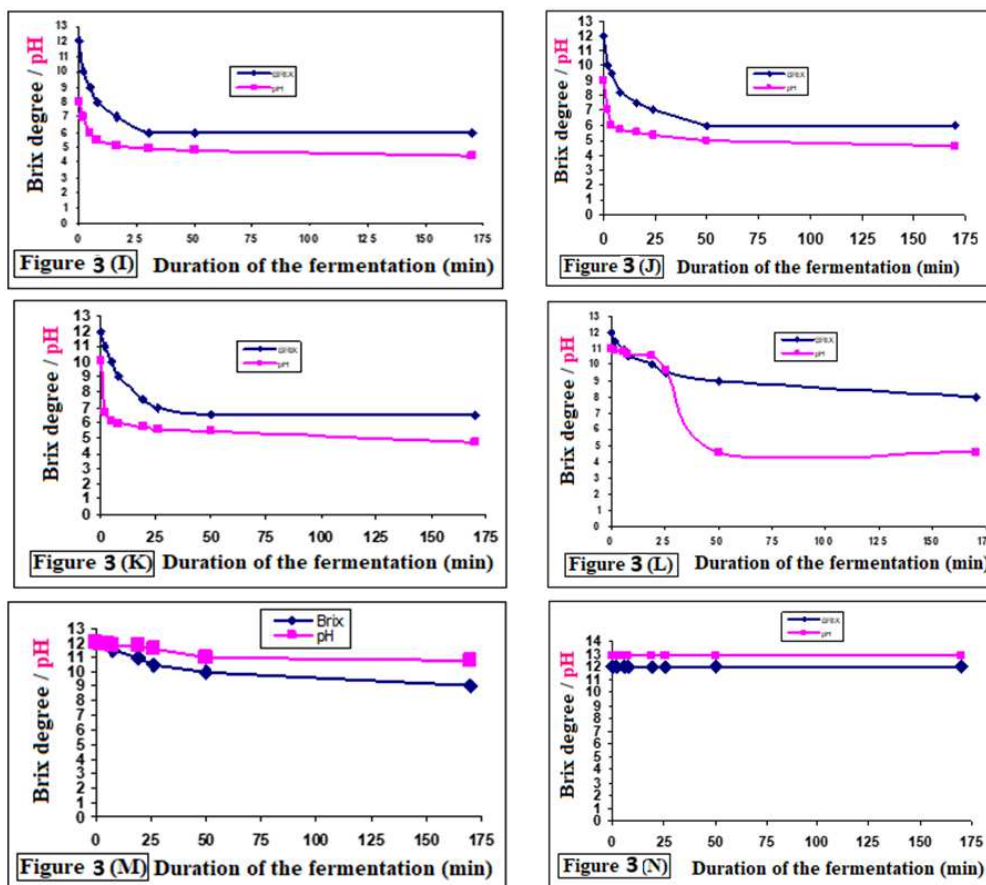


Figure 3. (A-N): Variations of Brix and pH as a function of the fermentation time of *Balanites aegyptiaca* musts.

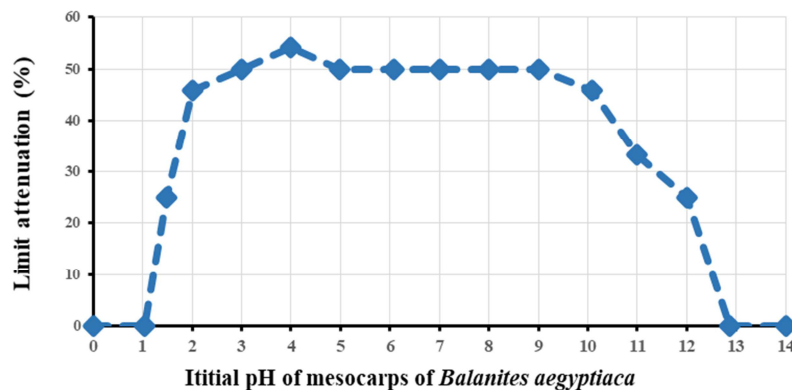


Figure 4. Variation of the limiting attenuation as a function of the initial pH of the musts of *Balanites aegyptiaca*.

For the musts with pH values of 1.03 and 12.86 as shown on the Figures 3 (A and N), no variation in Brix was observed during the whole period of alcoholic fermentation with yeast *Saccharomyces cerevisiae*. On the other hand, for pH values between 1.49 and 10.08, there is a gradual decrease of the Brix which is more or less sensitive until a cessation of the alcoholic fermentation [Figures 3 (B-K)]. However, for all the musts in which the alcoholic fermentation has taken place [Figures 3 (B-M)], it is noted a slight progressive decrease of the pH during the alcoholic fermentation, i.e a weak acidification of the reaction medium. The decrease in the Brix degree is explained by the conversion of the fermentable sugars into ethanol and other

secondary compounds during fermentation. The variation of the limiting attenuation as a function of the pH reveals to us that the fermentation took place under better conditions for the musts that had initially pH values between 3 and 9, with an optimum at pH = 4, 00 and a limiting attenuation of 54.17%. At pH values of 1.03 and 12.86, the fermentation is completely blocked. The physiological state of the yeasts would be highly disturbed because the enzymatic reactions which are essential for their survival, are no longer possible, since the pH range to maintain the growth of the yeast *Saccharomyces cerevisiae* is between 2.4 and 8.6, with a pH optimal between 4 and 4.5 [20].

The results obtained in this study corroborate with the

works of other authors who indicated that the alcoholic fermentation takes place under better conditions when the pH of the reaction medium is between 4 and 5 and incubating at 30°C [21]. In this interval, productivities and yields of ethanol are maximal [22]. This pH range avoids contaminations or parasitic reactions due to the presence of other microorganisms such as bacteria [23]. If, overall, the pH of fermented *Balanites aegyptiaca* must have decreased during alcoholic fermentation before stabilizing, this could probably be due to the fact that carbon dioxide or acid compounds are produced by yeasts during fermentation. Indeed, the CO₂ can be dissolved in the liquid medium in the form of carbonic acid (H₂CO₃) which is dissociated into bicarbonate anion (HCO₃⁻), carbonate (CO₃²⁻) anion and hydrogen cation (H⁺) [24-25]. However, this solubility of CO₂ in aqueous solution can be influenced by several factors such as pH and temperature [26]. During the ethanolic

fermentation of the juice, the pH can have a positive or negative influence on the consumption of sugars, depending on the value used and therefore acts differently on the production of alcohol. It has been noted that the yeasts which catalyze this reaction are acidophilic microorganisms, since their cellular activities become optimal at an acid pH close to 4.0.

3.1.3. Yields of Bioethanol Production

The various yields obtained for the production of bioethanol from the mesocarps of *Balanites aegyptiaca* (Table 2) indicate that to produce a volume equal to 1205 ± 5.25 ml of bioethanol with an alcoholic degree of 93%, it is necessary to take 6.00 kg of *Balanites aegyptiaca* fruits. During the various treatments carried out, 2,404.52 ± 29.96 g of mesocarps, 3,160.00 ± 10.96 g of kernels and 435.48 ± 20.06 g of epicarps and other solid wastes were obtained.

Table 2. Calculation of yields for bioethanol production of *Balanites aegyptiaca*.

Parameters	Fruit (kg)	Epicarps and waste (g)	Kernels (g)	Mesocarps (g)	Ethanol 93% product (mL)
Quantities	6.00	435.48 ± 20,06	3,160.00 ± 10,96	2,404.52 ± 629,96	1,205.00 ± 5.25
Proportion (%)	100.00	7.26 ± 0,33	52.67 ± 0,18	40,08 ± 0,50	14.74 ± 0.06

In terms of percentages, the production yield of bioethanol from the fruits of *Balanites aegyptiaca* is 14.74 ± 0.06% compared to the mass of fruits used. This production

generated 52.67 ± 0.18% kernels, 40.08 ± 0.50% mesocarps and 7.26 ± 0.33% epicarps and other wastes.

3.1.4. GC-FID Analysis of Bioethanol Produced

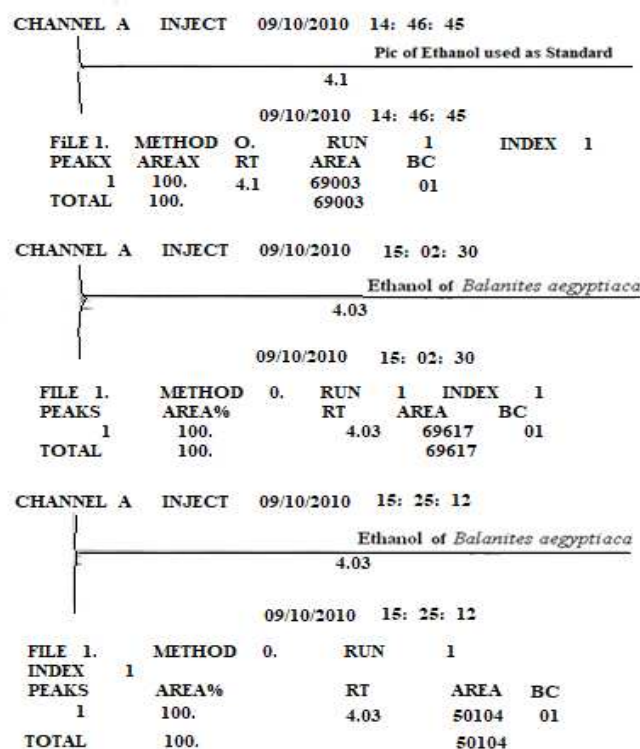


Figure 5. Chromatogram of the alcohol of *Balanites aegyptiaca* in comparison with the reference ethanol.

The chromatogram of GC-FID analysis of bioethanol produced from the mesocarps is reported in Figure 4. It can be seen that the bioethanol produced in this study is almost

100% pure when comparing its chromatographic profile with that of the standard (Figure 5).

This finding may be explained by the fact that the ethanolic

fermentation reaction, carried out with the yeast strain *Saccharomyces cerevisiae*, has been very efficiently controlled so that the parasitic reactions which should in principle compete with it, such as acetic fermentation, the production of methanol and alcohols with longer chains such as propanol and isopropanol, butanol and its isomers, are practically negligible.

3.2. The Production of Biodiesel

3.2.1. *Balanites Aegyptiaca* Oil Extraction

The various yields obtained for the extraction of *Balanites*

Table 3. Oil extraction yields of *Balanites aegyptiaca* oil.

Parameters mesured	Kernels (g)	Hulls (g)	Almonds (g)	Oilcakes (g)	Almonds oil (g)
Quantities	316.01	243.08 ± 7.19	72.92 ± 3.35	40.42 ± 0.80	32.51 ± 4.15
Yield (%)	100.00	76.92 ± 2.28	23.08 ± 1.06	12.79 ± 0.25	44.58 ± 5.69

The wastes generated during oil extraction represent approximately $89.71 \pm 2.53\%$ of the mass of kernels used, ie $76.92 \pm 2.28\%$ hulls and $12.79 \pm 0.25\%$ oilcakes. In this work, the yield of oil relative to the almond mass of *Balanites aegyptiaca* is within the range indicated by [27].

3.2.2. Chemical Composition of Fatty Acids of the Noisy Vegetable Oil of *Balanites Aegyptiaca*

The pure vegetable oil (PVO) of *Balanites aegyptiaca* can be blended at relatively low rates with conventional diesel to operate vehicles that have internal combustion engines. But

since its properties do not fit exactly with these vehicles, it is therefore necessary to transesterify the oil in order to have biodiesel which is much more compatible with internal combustion engines.

Figure 6 presents the results of GC/FID analysis of biodiesel produced by transesterification of crude vegetable oil of almonds of *Balanites aegyptiaca*. The identification of the 5 main peaks on the chromatogram of Figure 5 compared with those of the corresponding standards gave us results compiled in Table 4.

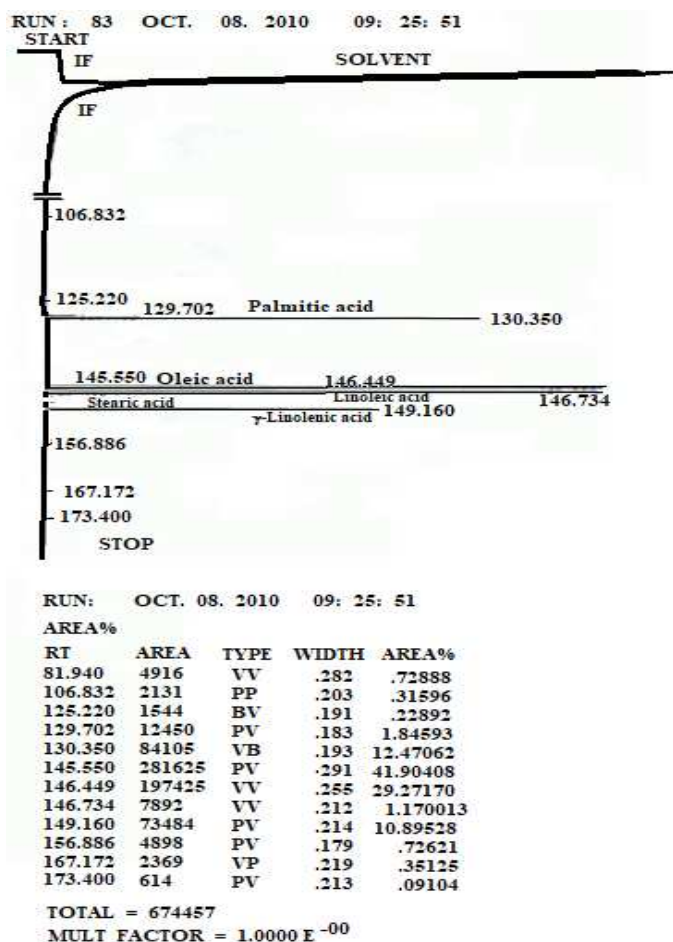


Figure 6. Chromatogram of *Balanites aegyptiaca* biodiesel.

Table 4. Fat content (%) of *Balanites aegyptiaca* oil in comparison with some oils.

Oil type	Palmitic acid	Stéaric acid	Oléic acid	Linoléic acid	Gamma linolénic acid
<i>Balanites aegyptiaca</i>	12.47%	1.17%	41.90%	29.27%	10.89%
<i>Balanites aegyptiaca</i> *	10-12%	9-10%	30-40%	40-48%	-
Soybean *	7-11%	2-6%	15-33%	43-56%	-
Sesame seed**	7-9%	4-5%	37-49%	35-47%	-
Peanut *	6-9%	3-6%	53-71%	13-27%	-
Cotton seed *	20-23%	1-3%	23-35%	42-54%	-

*: Data from our study.

**: Data from the analysis of *Balanites aegyptiaca* refined oil (Source: Industrial Research and Consultancy Institute (IRCI), Khartoum / Sudan.

♦: Data derived from American Oil Chemists Society (AOCS) Standards.

The analysis of the fatty acids chemical composition (Table 4) shows that oleic acid (41.90%) is the major in the oil of almonds of *Balanites aegyptiaca* analyzed. This result is the same for *Balanites aegyptiaca* of Sudanese origin (48%) and for *Balanites aegyptiaca* from Cameroon (44%) according to [28]. However, the oleic acid content of *Balanites aegyptiaca* almonds oil from Burkina Faso is low compared with Sudan and Cameroon.

The gamma-linolenic acid contained in the oil of Burkina Faso, with a content of 10.89%, is the particularity of this oil compared to the other oils presented in Table 4.

The stearic acid content shows that *Balanites aegyptiaca* oil (1.17%) from Burkina Faso is comparable to cottonseed

(1-3%) and sunflower (1-3%) oils, whereas these oils have a high contents in linoleic acid compared to the species from Burkina Faso. Finally, taking into account the data presented in Table 4, it can be generally accepted that *Balanites aegyptiaca* oil from Burkina Faso has a chemical composition of fatty acids closer to that of sesame seed.

3.2.3. Some Physicochemical Properties of Biofuels Produced

Some physico-chemical characteristics of bioethanol and biodiesel produced from *Balanites aegyptiaca* fruits from Burkina Faso compared to other fuels are recorded in Table 5.

Table 5. Some physical properties of bioethanol and biodiesel produced in this study in comparison with other fuels.

Propriétés	Bioéthanol*	HVB*	HVB**	EMHV*	EMHV**	Diesel**
Density at 25°C (kg/L)	0.826	0.902	0.886	0.860	0.860	0.840
Water an moisture content (%: m/m)	8.70	1.08	1.4	0.05	0.04	-
Ash content % (m/m)	0.01	0.18	0.03	0.03	0.017	0.01
pH	7	6	-	6,5	-	-
Lower Calorific Value (MJ/kg)	25.19	37.93	39.84	36.98	39,65	42.5
Flash Point at normal ne pressure (°C)	-	295	230	158	75	52
Refractive index at 20°C	1,367	1,472	-	1,468	-	-
Saponification index (mg KOH/g oil)	-	193	-	-	-	-
Acid number (mg KOH/g oil)	-	1,78	1,96	-	0,34	-

* Results of our study

** Data provided by ASTM (American Society for Testing and Material) [29].

(i). Density of biofuels produced in relation to water

The density for our bioethanol determined at 25°C, 0.826 kg/L, is substantially high and corresponds to an alcoholic degree of about 93% vol. But this value depends on the efficiency of our fractional distillation column. The density of our HVB, 0.902 kg/L, is higher than that given by ASTM, or 0.886 kg/L for HVB. This would imply that our oil contains suspended particles that must be removed by centrifugation. While the density of our biodiesel, generally called Vegetable Oil Methyl Ester (VOME), or 0.860 kg/L, is the same as that provided by ASTM for HVB. However, this value is a little higher compared to that of conventional diesel, ie 0.840 kg/L (Table 5).

(ii). Water content

The bioethanol produced in this study has a high water content of 8.70%. This is detrimental to its use as fuel in conventional vehicles that only tolerate mixing with pure ethanol up to 5%. However, it is possible that this alcohol can be purified by azeotropic distillation on benzene or by dehydration on calcium carbonate. On the other hand, the

water contents in our PVO (1.08%) and in our biodiesel (0.05%) are relatively close to those provided ASTM for PVO (Table 5). However, the water content in petrodiesel is practically negligible.

(iii). Ash content

Our bioethanol has a low ash content compared to our PVO. This can be explained by the fact that bioethanol is obtained by fractional distillation, while our PVO is obtained by extraction. However, the water content of our biodiesel is not too far from the value indicated by ASTM for VOME. The analysis of the ash contents (Table 5) shows that our three biofuels are very comparable compared to PVO and VOME according to ASTM

(iv). pH values

Our HVB and bioethanol had more or less neutral pHs, 6 and 7, respectively. It can therefore be said that these pH values do not compromise on use as blended fuels in conventional engines.

(v). Lower Calorific Value (LCV)

The LCV of our biodiesel, 36.98 MJ/kg, is about 2.50%

lower than that of our PVO, 37.93 MJ/kg. But compared to petrodiesel that has a LCV equal to 42.5 MJ/kg (ASTM), we see that the LCV of our biodiesel is about 13% low. In general, the LCV of PVO is 7–20% lower than that of petrodiesel whose values are between 42 and 46 MJ/kg [29–30]. This remark shows that our biodiesel's LCV is within the indicated range.

(vi). Flash Point (FP)

The FP of our PVO, 295°C and our biodiesel, 230°C, are higher than the values given by ASTM. These values do not comply with the ASTM standard that sets the FP of biodiesel at a maximum value of 130°C, and that of the European Union has sets FP for biodiesel at a maximum value of 120°C [31]. However, it is accepted that PVO and biodiesel are more practical than petrodiesel, if we only look at the storage aspect, since their FP are higher and therefore present a risk of ignition. weaker. Nevertheless, our PVO and our biodiesel must be stored in a stainless steel, aluminum or teflon mild steel tank in which humidity and temperature are controlled [32].

(vii). Refractive index

The refractive indices measured for our biofuels have values higher than the refractive index of water at 20°C (1.333). They are therefore in compliance with the standards.

(viii). Saponification index

The saponification value of *Balanites aegyptiaca* oil from Burkina Faso, ie 193 mg KOH/g of oil, is close to that given by Chiegang, ie 121.1 mg KOH/g for *Balanites aegyptiaca* oil from Cameroon and that of Israeli, ie 175.91 mg KOH/g [33].

(ix). Acid number

The acid value of the *Balanites aegyptiaca* oil from Burkina Faso, ie 1.78 mg KOH / g of oil, is close to the values found by Deshmuk and Bhuyar (1.96 KOH/g of oil) and Tciegang-Megueni (1.9 KOH/g oil) [33].

We can therefore say that overall, the biofuels produced in this study have physicochemical characteristics relatively similar to those of HVB, EMHV and conventional diesel according to ASTM.

4. Conclusion

As a result of this study, we managed to produce three types of liquid biofuels from *Balanites aegyptiaca* fruits from Burkina Faso. These include bioethanol, pure vegetable oil (PVO) for fuel and vegetable oil methyl esters (VOME) commonly referred to as biodiesel. Bioethanol was produced from fruit mesocarps by the controlled alcoholic fermentation reaction using a *Saccharomyces cerevisiae* yeasts. It has been found that the kinetics of the ethanolic fermentation reaction is either disturbed or improved by varying the pH in a range of 1.03–12.86, passing through an extremum obtained at a pH value close to 4.0. HVB was obtained from almonds contained in the kernels by the Soxhlet extraction method with hexane. While the VOME were synthesized by basic catalysis with the transesterification reaction in homogeneous phase. The analysis of the chemical composition by the GC-

FID revealed that the oleic, linoleic, palmitic, gamma-linolenic and stearic acids are the major fatty acids contained in PVO of *Balanites aegyptiaca*. Determination of physicochemical and energy characteristics indicates that the biofuels produced in this study have properties similar to those of petrodiesel and some reference biofuels.

In order to improve the value of *Balanites aegyptiaca* fruits as liquid biofuels, additional studies focusing on the evaluation of fuel performance from gasoline and diesel engine tests are needed.

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Conflict of Interest

The authors declare that they have no conflicts of interest in relation to this article.

Authors' Contributions

Conceived and designed the experiments: K. M. NOVIDZRO, K. DOTSE and K. H. KOUMAGLO. Performed the experiments: K. M. NOVIDZRO, K. DOTSE, B. AMOUSSOU FAGLA, B. S. HOUNJJI and M. MELILA. Analyzed the data: K. M. NOVIDZRO, B. AMOUSSOU FAGLA M. MELILA and B. S. HOUNJJI. Contributed reagents/materials/analysis tools: K. M. NOVIDZRO, K. DOTSE and K. H. KOUMAGLO. Wrote the paper: K. M. NOVIDZRO and M. MELILA.

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