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Optimization of Oil Extraction from Jojoba Seeds of Mesaoria Plain in Screw Expelling Using Taguchi Design

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Abstract- Jojoba oil is widely used in cosmetic, pharmaceutical and lubricant applications. It can also be used as a feedstock in biodiesel production or as a substitute to fuels to improve their properties. Due to its unique characteristics, the present study was focused on the optimization of the oil extraction yield from jojoba seeds in a screw expeller while retaining the oil quality. The seeds used were harvested from the new experimental jojoba plantation grown on Mesaoria Plain of Cyprus Island. The effects of the seed size, humidity level and temperature together with residual discharge opening of the expeller were studied in details and optimized using Taguchi method. The larger-the-best signal to noise ratio (S/N ratio) analysis together with the analysis of variance (ANOVA) were used during optimization. The order of influences was found as (1) seed temperature, (2) seed size, (3) seed humidity level and (4) residual discharge opening according to the S/N ratio analysis. The ANOVA yielded a comparable result however, seed size and temperature exchanged places in the sequence due to slight differences. The optimized extraction conditions were found when seed size was halved, seed temperature was kept at 22°C, no drying was applied on the seeds prior to extraction and residual discharge opening was adjusted to its fully open position. The optimum conditions were verified with the confirmation experiments. The kinematic viscosity and lubricity remained almost unchanged during the experiments.

Keywords Jojoba oil, Mesaoria Plane, optimization, screw expeller, Taguchi method.

1. Introduction

The jojoba shrub (*Simmondsia chinensis*) is one of the non-edible industrial crops that can survive on arid, wastelands including deserts [1]. It is possible to cultivate it across the world where food agriculture cannot be made and in addition, as a measure against further degeneration of soil [2]. Unlike, other industrial oil seeds which contain mainly triglycerides, the jojoba seed is composed of 48-56% liquid wax [3]. This is a unique oil that can substitute the whale sperm oil and widely exploited in cosmetic, pharmaceutical and lubricant applications [4]. For instance, it can be an excellent lubricant at high temperatures and pressures in hydraulics due to its thermal stability [5].

Investigations on the performances of different types of biodiesel fuels and their blends have been performed [6-11]. Jojoba oil can also be used in biodiesel production and as a substitute to fuels to improve their properties. El Kinawy [12] compared jojoba oil as a substitute to petroleum for lubrication with other vegetable and mineral oils and determined that jojoba oil was the best among the others since it gave the minimum change in viscosity gradient. It was stated that due to its high thermal stability it is possible to use the oil in high temperature applications like jet engines. Rawajfeh and Al-Hamamre [13] conducted a study to predict the temperature dependent viscosities of jojoba oil-biodiesel and jojoba oil-diesel blends.

Presence of complicated wax esters molecules in the jojoba oil causes inconvenience in biodiesel production. Al-Shanableh et al. [14] stated that the production of biodiesel from jojoba oil could not be achieved using base catalyzed transesterification method however, the production was successful via supercritical methanol transesterification method. Nayak and Mishra [15] observed substantial advancement in oil and emission characteristics of a diesel engine fueled with blends of jojoba oil methyl esters in comparison to those of neat diesel. Investigations have also been performed on the effect of temperature on the density and viscosity of jojoba-based biodiesel and its blends with diesel fuel [16].

United Nations encourages projects on jojoba agriculture in an attempt to relax poverty and sustainable progress in the unfertile and poor regions around the world including the sub-Saharan Africa [17]. Although the jojoba shrub is inherent in the deserts of Northern Mexico and Arizona, its commercial farming has been made also on the unfertile lands of Australia, Argentina, Chile, etc. Following the success of jojoba agriculture and trade of jojoba oil by Israel, jojoba plantations spread also in the Middle East [5,18]. The Cyprus Island of the Middle East has a Mediterranean climate, i.e. hot, dry summers and cool, relatively wet winters [19]. The Mesaoria Plain of the island suffers a semi-arid soil where a jojoba test plantation was cultivated in 2004. Since it is a brand-new test crop on the island, it has become mandatory to investigate fully the jojoba seeds particularly, the jojoba oil harvested from this local plantation [20]. The physicochemical qualities of the wax were found to be consistent with the analyses of the other jojoba waxes around Middle East [21-23], across the world [24-26], and also the IJEC (International Jojoba Export Council) standard [27]. The comparison revealed also that the characteristics of the jojoba oil/wax remained almost independent despite different ecotypes. Nonetheless, the yield of seed from a plantation depended strongly on the management [4, 20, 28].

Following the harvesting of jojoba seeds, it was necessary to maximize the oil yield without degrading the quality of the jojoba oil. Taguchi experimental design method together with signal to-noise ratio (S/N ratio) and analysis of variance (ANOVA) has been widely used to optimize the extraction of oil from seeds and leaves of various plants. The Taguchi approach [29] allows to construct robust systems by adapting the control factors, i.e. design parameters, to their optimal levels. Taguchi's ideas have been popular particularly, among the manufacturers due to the results in creating high ranking production techniques at lower costs. A well-known quote from Taguchi that can be traced in the literature is "Cost is more important than quality but quality is the best way to reduce cost" [30].

There seems to be three common procedures available in oil extraction from oil seeds, i.e. screw expelling, hydraulic pressing and solvent extraction [31, 32]. Modeling and optimization of jojoba oil extraction yield by solvent extraction process using response surface methodology has been conducted recently by Al-Sheikh and Yamin [33].

A screw expeller in which the jojoba seeds were squeezed under high pressure was employed in the current survey [20]. Being the first attempt, the aim of the present study was to find out the optimum process parameters to ensure the maximum jojoba oil yield during screw expeller pressing of jojoba seeds. The optimization of process parameters in expeller pressing was carried out using the Taguchi design in which the basic idea was to maximize a target yield for a given input of resources available [34-37].

2. Methodology

The procedure developed using Taguchi method for optimization of the process parameters to ensure the maximum jojoba oil yield by screw expelling of jojoba seeds can be followed from Fig.1 and explained below in details. Size, humidity and temperature of the seeds together with residual discharge opening were considered as the four control factors influencing the objective. For each control factor three-levels were considered. The control factors and their levels are shown in Table 1. Four independent variables with three levels for each requires 81 runs (i.e. 3^4) in the traditional factorial design. However, Taguchi design of experiment resulted that a Taguchi L-9 orthogonal array was convenient for the current survey reducing the number of necessary experiments to 9. The L-9 orthogonal array design experiment of the present work is shown in Table 2.

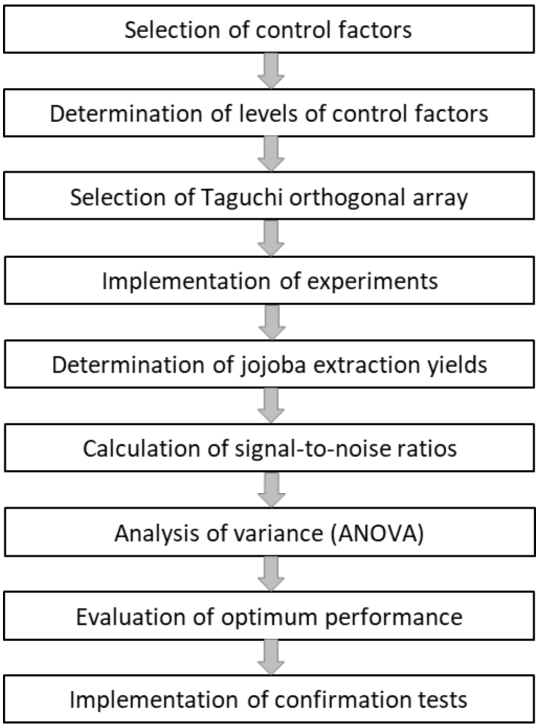

Fig. 1. Taguchi design of experiment procedure.

Table 1. The four control factors at three levels in the extraction of jojoba oil

Control Factors		Levels		
		1	2	3
A	Seed size	Whole	Half	Quarter
B	Seed humidity level	Humid	Half dried	Fully dried
C	Seed temperature (°C)	22	40	60
D	Residual discharge opening	1/4 open	1/2 open	Fully open

Table 2. The L-9 orthogonal array design of present work

Exp. No.	Control factors and levels			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The jojoba seeds were harvested from the local jojoba shrubs grown in the test plantation near Nicosia. A typical jojoba seed was in an oblong to oval shape that was produced by a female jojoba plant. Seeds were washed and dried in the laboratory where the temperature and relative humidity were varied between 21 - 23°C and 56 - 63%, respectively. The average diameter, average length and average weight of the ten jojoba seeds were found as 9 mm, 15 mm and 0.6 g, respectively. The whole jojoba seeds were sectioned into half and also to quarter without removing their shells. Hence, three seed sizes were made available for the oil extraction in the screw expeller described before [20].

The drying method described in ISTA [38] was followed to adjust the humidity levels of the seeds. The moisture content in each stage of drying was calculated using the relation

$$H = (m_b - m_a)/m_b \times 100 \qquad (1)$$

where, H was the moisture content in %, m_b and m_a were the masses of the seeds before and after drying, respectively. The jojoba seeds initially consisted of 6% moisture by mass were half and fully dried before oil extraction. Batches of 100 g seeds at three different humidity levels, namely humid, half dried and fully dried were fed into the screw expeller.

The oil extraction was achieved on a screw that presses the seeds against the wall of a cylindrical chamber to collect the jojoba oil through oil outlet holes at the bottom of the chamber which does not permit the passage of solid press cake. The process pressure was adjusted indirectly by controlling the residual discharge opening area which corresponded to the areas of 1/4 open (18.8 mm^2), 1/2 open (50.4 mm^2) and full open (100.48 mm^2) positions. The seeds were supplied at three different temperatures into the screw expeller, namely 22ºC, 40ºC and 60ºC. After extraction, the jojoba oil was left for rest for three days to allow the settlement of debris in it. Each of the nine experiments of Table 2 was repeated three times.

The percent yield of jojoba oil recovery was defined as the ratio of the mass of jojoba oil extracted to the total mass of the jojoba seeds and can be presented as follows [39].

$$Y = m_{oil\,yield}/m_{seed} \times 100 \qquad (2)$$

where, Y is the percent oil yield (%), $m_{oil\,yield}$ is the mass of the jojoba oil produced and m_{seed} is the total mass of the jojoba seeds pressed.

The experiments were analyzed then optimized via the graphical method of signal to noise ratio (S/N ratio). The larger-the-best S/N ratio was used since the aim was to maximize the jojoba oil yield. The S/N ratio was evaluated using the equation below.

$$S/N\ ratio = \eta_i = -10\ log\left(\frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{y_i}\right)^2\right) \qquad (3)$$

where n is the number of repetitions of each experiment and y_i is the yield of jojoba oil.

S/N ratio was also used to identify the control factor settings that minimize the variability caused by the noise factors. Each control parameter was considered individually and the interactions at the assigned levels were calculated by taking the average of all the S/N ratios. Magnitude of the mean S/N ratio gives idea about which parameter and which level on that parameter has more impact on yield of jojoba oil extracted. The larger the S/N ratio will be the higher the jojoba yield. The mean S/N ratio of control parameter A, B, C and D were calculated as follows:

$$\eta_{A1} = (\eta_1 + \eta_2 + \eta_3)/3 \qquad (4)$$

$$\eta_{A2} = (\eta_4 + \eta_5 + \eta_6)/3 \qquad (5)$$

$$\eta_{A3} = (\eta_7 + \eta_8 + \eta_9)/3 \qquad (6)$$

$$\eta_{B1} = (\eta_1 + \eta_4 + \eta_7)/3 \qquad (7)$$

$$\eta_{B2} = (\eta_2 + \eta_5 + \eta_8)/3 \qquad (8)$$

$$\eta_{B3} = (\eta_3 + \eta_6 + \eta_9)/3 \qquad (9)$$

$$\eta_{C1} = (\eta_1 + \eta_6 + \eta_8)/3 \qquad (10)$$

$$\eta_{C2} = (\eta_2 + \eta_4 + \eta_9)/3 \qquad (11)$$

$$\eta_{C3} = (\eta_3 + \eta_5 + \eta_7)/3 \qquad (12)$$

$$\eta_{D1} = (\eta_1 + \eta_5 + \eta_9)/3 \qquad (13)$$

$$\eta_{D2} = (\eta_2 + \eta_6 + \eta_7)/3 \qquad (14)$$

$$\eta_{D3} = (\eta_3 + \eta_4 + \eta_8)/3 \qquad (15)$$

where for example η_{A1} is the mean S/N ratio of factor A at level 1, η_{C2} is the mean S/N ratio of factor C at level 2, etc. and η_i are the S/N ratio of the mean yield of i^{th} experiment.

To indicate the relative effect of each factor on the response, the difference between the highest and lowest average response values (Δ) for each factor was calculated and the highest difference was indicated as the first in the ranking and the lowest as the last.

Analysis of Variance (ANOVA) was also used to render the importance and percentage contribution of all process parameters on yield of jojoba oil extracted, since it is a statistical decision-making tool used to perceive any differences in mean performance of the group of items analyzed taking variation into account rather than using pure judgment. The analysis was carried out based on S/N ratio data in order to determine the significance of the control factors on jojoba extraction process. The basic property of ANOVA [40] is that the total sum of the squared deviation SST (total variation) and can be calculated as follows:

$$SS_T = \sum_{i=1}^{n}(\eta_i - \eta_m)^2 \quad (16)$$

where n is the number of experiments in the orthogonal array, η_i is the mean S/N ratio for the i^{th} experiment and η_m is the mean S/N ratio of n experiments.

Variation of each factor can be calculated as

$$SS_x = \sum_{j=1}^{3} n\left[(\eta_{xj} - \eta_m)^2\right] \quad (17)$$

where n is the number of experiments at level j of factor x.

The percent effect of each control factor on the jojoba extraction yield identifying the significance of process parameters can then be calculated as:

$$\%\, Contribution\ of\ Factor\ X = SS_x / SS_T \times 100 \quad (18)$$

The viscosity measurements of the samples were also conducted in triplicate at 40°C using an Ubbelohde viscometer according to the EN-ISO 3104 [41] standard designed to determine the kinematic viscosity of transparent and opaque liquids.

3. Results and Discussion

The results of each experiment for yield and viscosity of jojoba oil extracted can be followed in Table 3. The kinematic viscosity of the jojoba oil extracted with respect to eight experimental runs were varied between 25.04 to 25.52 mm^2/s as seen in Table 3, i.e. in the vicinity of 25.41 mm^2/s. These values were in close agreement with the literature [33] and close to the viscosity of the meadowfoam seed oil that has been claimed as an alternative to the jojoba oil in cosmetics [3]. On the other hand, these values were below the viscosities of common plant oils including jatropha (34-36 mm^2/s), soybean (31 mm^2/s), cottonseed (36 mm^2/s) and sunflower (43 mm^2/s) oils [31].

The HFRR (High Frequency Reciprocating Rig) wear tests of the jojoba oil samples were carried in different accredited laboratories following the ASTM D 6059 and EN ISO 12158-1:2006 standards for fuels and lubricants. The wear scars were found to vary between 166 μm to 183 μm at 40°C and 278 μm to 316 μm at 60°C which were below the upper limits of 460 μm at 40°C and 520 μm at 60°C given in the standards. Hence, the lubricity of jojoba oil remained within the limits of the standards under the experimental conditions in oil extraction. The observation appears to be in agreement with its viscosity behavior.

Various physicochemical characteristics of jojoba oil pressed from those local jojoba seeds of Mesaoria Plain were investigated and compared with the literature in an earlier publication [20]. For the integrity of the current study a part of those physicochemical characteristics is given in Table 4.

It was found that the mean yields of jojoba oil extracted reached to 41.2% in the experiment no. 8 whereas the lowest yields (17.3%) were observed in the experiment no. 3. The overall average yield of the experiments was calculated as 29.1%. The S/N ratios calculated for the nine sets of experiments are shown in Table 5. The levels of control parameters of Experiment no. 8 can be chosen as the optimum since the largest S/N ratio was obtained in addition to the highest mean jojoba oil yield.

Table 3. Experimental data obtained using the Taguchi design

Exp.	**Extraction Yield** (%)				**Kinematic viscosity** (mm^2/s)			
No.	Run 1	Run 2	Run 3	Mean	Run 1	Run 2	Run 3	Mean
1	32.8	33.6	32.6	33.0	25.19	25.25	25.36	25.26
2	19.1	22.0	18.9	20.0	25.42	25.49	25.52	25.48
3	16.2	17.0	18.7	17.3	25.48	25.50	25.51	25.50
4	39.4	38.1	37.4	38.3	25.17	25.16	25.04	25.12
5	28.0	27.2	27.6	27.6	25.23	25.17	25.23	25.21
6	27.8	31.1	30.5	29.8	25.21	25.24	25.20	25.22
7	30.7	28.1	28.2	29.0	25.82	25.92	25.93	25.89
8	41.8	39.5	42.3	41.2	25.42	25.34	25.37	25.37
9	25.6	26.0	26.4	26.0	25.67	25.63	25.63	25.64

Table 4. Characteristics of jojoba oil of Mesaoria Plain [20]

Characteristics	Values	IJEC Std.
Fatty Acids		
C16:0 Palmitic acid (%)	1.89	≤ 3.0
C16:1 Palmitoleic acid (%)	0.07	≤ 1.0
C18:0 Stearic acid (%)	0.46	-
C18.1 Oleic acid (%)	12.28	5.0 - 15.0
C20:0 Arachidic acid (%)	0.13	-
C20:1 Eicosenoic acid (%)	71.10	65.0 - 80.0
C22:0 Behenic acid (%)	0.18	≤ 1.0
C22:1 Erucic acid (%)	11.69	10.0 - 20.0
C24:1 Nervonic acid (%)	1.15	≤ 3.0
Other fatty acids (%)	1.0 (max)	≤ 3.0
Wax esters		
C40 (%)	28.2	26.0 - 34.0
C42 (%)	46.3	44.0 - 56.0
C44 (%)	8.0	8.0 - 12.0
C46 (%)	0.5	0-3
Physicochemical characteristics		
Specific Gravity (g/cm^3)	0.86	0.86 - 0.87
Refractive Index	1.47	1.45 - 1.47
Saponification (mg KOH/g)	92.6	88 - 96
Viscosity (mm/s) at 40°C	24.5	-
100°C	6.45	-
Acid Value (mg KOH/g)	0.5	≤ 1.0
Iodine Value (gram)	88.9 /100	82 - 87/100
Peroxide Value (meqO_2/kg)	< 1.0	≤ 2.0

Table 5. S/N ratios of the nine experiments

Exp. No.	S/N ratio for yield	S/N ratio for kinematic viscosity
1	30.370	28.049
2	26.021	28.123
3	24.761	28.131
4	31.664	28.002
5	28.818	28.031
6	29.484	28.034
7	29.248	28.262
8	32.298	28.088
9	28.299	28.179

All of the statistical analyses in the study were conducted by Minitab 18 software. Mean S/N ratio for each level of the four influential parameters are summarized in Table 6. The main effects plot for S/N ratio of control factors is also given in Fig. 2. It is clear that all control parameters have significant effect on response characteristic. It appears that the process temperature of the seeds was the most influential parameter on the yield of jojoba oil while residual discharge opening (process pressure) had the least effect. The second and the third influencing parameters were size of seeds and seed humidity level, respectively. The best response based on the highest S/N ratio was at level 2 (half seed) for seed size, at level1 (humid) for seed humidity level, at again level 1 (22°C) for seed temperature and finally at level 3 (full open) for residual discharge opening.

Table 6. Mean S/N ratio of control parameters and levels

Control Factors		Level 1	Level 2	Level 3	Δ	Rank
A	Seed size	27.05	29.99*	29.95	2.94	2
B	Seed humidity level	30.43*	29.05	27.51	2.91	3
C	Seed temperature (°C)	30.72*	28.66	27.61	3.11	1
D	Residual discharge opening	29.16	28.25	29.57*	1.32	4

*The best response level of control parameters

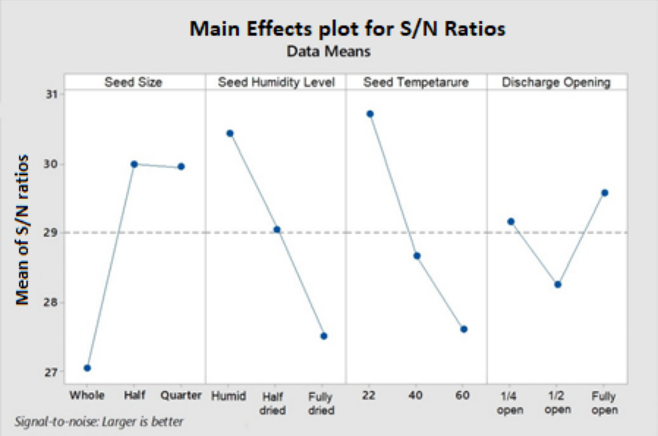

Fig. 2. Main effects plot for S/N ratios of control factors.

It was observed from the ANOVA results that the seed size was the most significant parameter with 35.85% contribution on the jojoba extraction yield. Contribution of seed temperature with 31.57% was close to seed size contribution and followed by seed humidity level with 26.80% contribution. The residual discharge opening was the least influencing process parameter with 5.79% contribution.

ANOVA and S/N ratio analyses showed difference on ranking of influential parameters. While for mean S/N ratio analysis seed temperature was the most influential parameter as depicted in Table 6, for ANOVA seed size had the highest contribution. It must be noted that the influence of size, humidity level and temperature of the seeds on oil yield were close to each other nevertheless, higher than the effect of residual discharge opening.

The optimum levels of control parameters were determined with the aid of Minitab 18 software. Seed size came out to be half (level 2), seed humidity level as humid (level 1), seed temperature as 22°C (level 1) and residual discharge opening as fully open (level 3). The jojoba oil extraction yield was predicted as 41.8% with an S/N ratio of 32.414. The mean yield of confirmation tests was obtained as 41.5% with an S/N ratio of 32.361 closely matching with that of theoretically predicted value.

4. Conclusion

The aim of the current work was to maximize the yield of jojoba oil extraction of the seeds harvested from Mesaoria Plain in a screw expeller without degrading the oil quality. It was determined that the seed size, temperature and humidity level were the dominating control parameters on jojoba oil yield but residual discharge opening which was directly related to process pressure during oil extraction had almost negligible significance. The viscosity of the jojoba oil extracted was not influenced under the experimental conditions and the lubricity remained within the limits of the standards.

The maximum jojoba oil recovery was attained when the seeds were sectioned into half, not dried but kept at room temperature (22°C) and the residual discharge opening of the expeller was held at fully opened position. Hence, the yield could be maximized to 41.5% which was 12.4% above the average (29.1%) of the experiments conducted. First experiment was very close to the case of oil extraction from jojoba seeds without execution of any pre-treatment, i.e. as harvested. Considering that the process pressure had negligible effect, optimum conditions could be attained by just halving the seeds which would increase the jojoba oil yield by approximately 25%.

It appears that all the optimum parameters except halving the seeds could be utilized to reduce the cost of oil extraction. However, halving increased the yield significantly. The oil remaining in the solid press cake obtained from the residual discharge opening can further be extracted by a second screw expelling or by solvent extraction and kept as a future work. It is also recommended to investigate the jojoba agriculture and its oil in terms of the local economy of Mesaoria Plain.

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