Separation efficiency and energy consumption of oil expression using a screw-press: The case of Jatropha curcas L. seeds

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A B S T R A C T

The performance of oil expression from *Jatropha curcas* L. (*Jatropha*) seeds using a pilot scale continuous screw press was studied. The influence of seed pre-treatment, i.e. whole, crushed and deshelled seeds, screw-press operational settings (shaft rotational speed and press cake outlet section) was investigated. For each experiment, the material flows (seeds, press cake and crude oil) were measured and analysed for their oil, water and solids contents. The behaviour of oil expression was very sensitive to seeds preparation. It was shown that for whole seeds, a good reproducibility was obtained, whereas for crushed or deshelled seeds, heterogeneity of the feed led to unsteady pressing conditions and important discrepancies in the performance. The presence of seed shells contributes to build a porous solid matrix which favours oil flow through the press cake. For whole seeds, a correlation between oil recovery and seed throughput was proposed. The mass balance consistency was carefully analysed and oil yield was determined using a direct and an indirect method. A good linear correlation between seed and press cake throughputs was observed: the seed throughput is always divided in a stream of crude oil and a stream of press cake in the same proportion. This important result shows that the residual oil in press cake and the amount of solids carried by the oil are directly related and determine the efficacy of the separation. Thus, for a given screw press and feed material, the oil sediment content can be predicted knowing the oil recovery. The energy consumption during pressing was measured and modelled as a function of oil recovery and seeds oil content. The specific mechanical energy for oil expression was less than 5% of the energy content of the oil and a minimum mechanical energy requirement was generally observed at oil recoveries between 70% and 80%.

1. Introduction

Screw pressing, also called oil expression, is the most widespread technique for extracting vegetable oils from dry oilseeds in small and medium-sized plants (Khan and Hanna, 1983). Nowadays, most vegetable oil in the food industry is produced in large-scale industrial plant using solvent extraction, and screw-presses are mainly used for prepressing seeds with high oil contents (Matthäus, 2012). Screw-presses are also widely used for high value vegetable oils (virgin), for small-scale processing in developing countries and for the production of straight vegetable oil (SVO) for fuel purposes. The latter application is the main scope of this study and more specifically the production of SVO from *Jatropha curcas* L. (*Jatropha*) seeds.

A screw-press is composed of a barrel made of narrow spaced bars, in which a conical screw (worm shaft) rotates and presses the seeds (see Fig. 1). The pressure increases along the screw due to reduced volume, and squeezes the oil through the seed mixture, termed cake, and out of the barrel through the spaces between the bars. The de-oiled press cake is discharged at the end of the screw. A mobile conical part, called choke, allows the adjustment of the outlet section of press cake. The mechanical strains inside the barrel are high, up to 50–100 MPa (Bredeson, 1977; Mrema and McNulty, 1985), and friction phenomena increase the temperature of the cake. The temperature build-up is crucial in the process since it lowers the oil viscosity and enables it to flow more readily through the pores of the cake (Khan and Hanna, 1983).

Prior to pressing, the seeds can undergo several preparation steps to facilitate oil expression and increase oil recovery. The most common pre-treatment operations are drying, dehulling,

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Nomenclature

E	mechanical energy spent per mass unit (Wh kg^{-1})
$FOOT$	foots mass fraction in crude oil
m	mass (kg)
$\dot{m}$	mass flowrate or throughput (kg h^{-1})
M	moisture content on wet basis
N	shaft rotational speed (rpm)
O	oil mass fraction on wet basis
s	shell mass fraction of seeds
SED	sediment mass fraction in crude oil
SED_{vol}	sediment concentration in crude oil after foots removal (mg L^{-1})
TS	total solids fraction in crude oil
η	oil recovery
ρ	density (kg m^{-3})

Subscripts

batch	seed batch
co	crude oil
foot	foots in crude oil (solids larger than 0.8 mm)
ker	seed kernels
po	pure oil
pc	press cake
s	seeds
sed	sediment in crude oil (solids between 1 μm and 0.8 mm diameter)
shell	seed shells
vap	water evaporated during pressing

Superscripts

D	direct calculation method
I	indirect calculation method

flaking, crushing and cooking. Thermal treatment (cooking) improves oil expression by thermally breaking oil cell walls but it results in higher contents of phospholipids and in some cases, higher contents of free fatty acids in the oil (Matthäus, 2012; Veldsink et al., 1999). If such pre-treatments are applied for SVO production, the oil will have to undergo purification treatments such as neutralisation and degumming to comply with quality needs for use as fuel in Diesel engines (Blin et al., 2013). That is why cold pressing is usually preferred for SVO production, especially in small-sized installations.

Although screw expellers have been used for decades in the vegetable oil industry, no satisfactory mathematical models are available as is the case for most solid–liquid separation processes. The development and implementation of screw expellers are essentially based on the experience and know-how of manufacturers and operators. Several modelling attempts are reported in the scientific literature, most of them dating back to the 1980s and 1990s. If batch hydraulic oil expression can be satisfactorily simulated using Shirato-type models – based on soil consolidation theory (Willems et al., 2008), it is not the case for continuous expression using screw-presses. Vadke et al. (1988) applied Shirato models to screw expeller with relatively good prediction results of seed throughput and press cake residual oil with a lab-scale equipment but only on a narrow range of processing conditions. Willems et al. (2009) improved Vadke's model and applied it to gas assisted mechanical expression (GAME), but the influence of temperature on pressure and residual oil was not satisfactorily predicted. Moreover, these models could not determine the presence of solid impurities in the oil, or the energy requirements. A theoretical model, based on the cellular structures of oilseeds, was developed by Lanoisellé et al. (1996) but was not applied to continuous oil expression (Lanoisellé et al., 1996).

Only few data are available in the scientific literature on the performance of screw-pressing for *Jatropha* oil expression and even fewer concerning energy requirements of vegetable oil expression in general. Karaj and Müller (2011) presented experimental results and analysed the links between oil recovery and energy consumption for *Jatropha* oil expression using a lab-scale cylinder-hole type screw-press. This type of press is commonly used for farm-scale oil production, but on industrial scale strainer presses are far more common. Thus, the work presented in this paper aims to bridge the gap by providing experimental results, including oil expression performance and energy requirements for a pilot scale strainer-type screw-press.

We present an experimental methodology to investigate the performances of continuous oil expression using screw expellers. The present case study deals with the pressing of *Jatropha* seeds but the methodology could be applied to any type of oilseeds. The main objectives are (i) to investigate the influence of seed preparation on the behaviour and performance of oil expression; (ii) to establish a mass balance of oil, solids and water and (iii) to identify useful relations between oil recovery, specific energy consumption and material throughput.

A series of experiments was conducted on a pilot scale screw press. The parameters studied included seed preparation, i.e. whole, crushed and deshelled seeds, as well as screw-press operational settings, i.e. screw rotational speed and press cake outlet section. For each experimental setting, the mechanical energy consumption was measured and material flows (seeds, press cake and crude oil) were measured and analysed for oil, water and solids contents. The analysis of the results started with a thorough assessment of oil, solids and water mass balance over the press, including the reconciliation of measurement data, which constitutes the basis for determining the separation efficiency. Then, from the mass balance analysis, a systematic correlation between residual oil in the press cake and solids content of expressed oil will be proposed. Finally, the specific energy consumption will be studied with respect to separation efficiency.

2. Materials and methods

2.1. Input materials

The experiments were carried out in the fall of 2012 at the pilot oil plant of CREOL in Bordeaux, France. The seeds used originated from Jakarta, they had been harvested in 2008 and stored in France for 4 years. For these experiments, all seeds were dried in a hot air dryer to reduce the moisture content from 9.5% to about 6% wb. Then five batches were prepared: whole seeds, crushed seeds and deshelled seeds, including three different deshelling levels.

For crushing, an industrial cracking mill was used (200 kg h^{-1}, Damman-Croes S. A. International, Belgium), made of two couples of corrugated cylinders with a spacing of 3 mm. For deshelling, the seeds first passed through the same cracking mill, but with a larger spacing between the rolls (5 mm) to break the shells. Large shell parts were removed by passing through an air grader (D50, Ets Denis S. A., France) and a specific gravity separator (Kipp Kelly, ArrowCorp Inc., Canada) allowed finer sorting of kernels. The specific gravity separator had 5 outputs with gradual shell mass fractions that were used to prepare deshelled seeds batches.

Whole seeds had an average shell mass fraction of 45%. Three levels of deshelling were used in the experiment, termed "deshelled – low", "deshelled – medium" and "deshelled – high" corresponding to shell mass fractions of 39%, 33% and 26%, respectively (see Section 3.1 for the calculation of shell mass fractions).

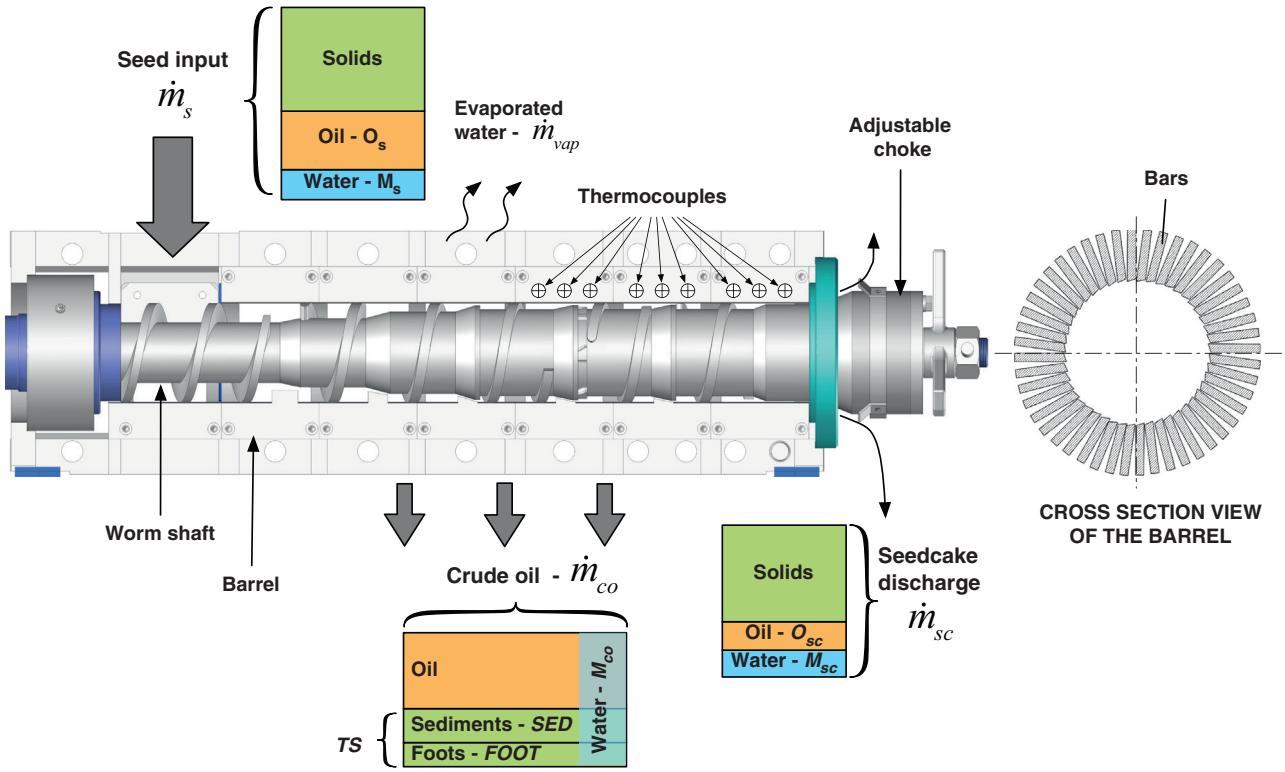

Fig. 1. Side view of an oilseed screw-press and mass balance assessment terms.
With authorisation of La Mécanique Moderne.

2.2. Microwave continuous heating tunnel

For some experimental settings, the seeds were preheated to a temperature of 35 °C using a microwave continuous heating tunnel. This equipment is a prototype specially developed for oilseed materials, constituted of microwave applicators and a conveyor belt. It is similar to the one described in Methlouthi et al. (2010) and made by MES International Ltd., United Kingdom.

2.3. Instrumented screw-press

The experiments were conducted on a 101 mm diameter screw-press with a nominal throughput of 120 kg h^{-1} (MBU20, La Mécanique Moderne S. A., France). The electrical motor of 7.5 kW was powered through a frequency converter set in a closed regulation loop with an RPM feedback from an incremental coder. This configuration allowed for torque, speed and power acquisition (2 Hz) from the frequency converter (Altivar 71, Schneider Electric S. A., France) with an accuracy of 5%. For temperature measurements, 9 K-type thermocouples of 1.5 mm diameter (Inconel 600® sheath ref. 405-050, TC Ltd., United Kingdom) were inserted in 25 mm depth holes in the 5 cm thick steel bars along the barrel. They were connected to a temperature display. The seeds were fed by gravity through the hopper and a vat allowed for oil collection below the barrel.

2.4. Analytical methods

2.4.1. Oil content analysis using pulsed NMR spectroscopy

All measurements of oil contents in solid materials (seeds, press cake, kernels and shells) were made in triplicate using a pulsed nuclear magnetic resonance spectrometer (Minispeq MQ20/10, Bruker Corp., United States) following the standard method NF EN ISO 10565. Prior to measurements, the spectrometer had to be calibrated with *Jatropha* materials of known oil contents. This was done using two reference samples, one of seeds and one of press cake, that were previously analysed for oil contents using the Soxhlet extraction method NF V03-908. This method provides a measurement of pure oil mass fraction, excluding moisture, with a precision of about ±0.1% (m/m) (Krygsman et al., 2004).

2.4.2. Seeds and press cake moisture content measurements

The moisture content of seeds and press cake was determined by weighing samples before and after drying in an oven at 103 °C for 24 h, following the standard method NF V03-909. This method provides a precision of about ±0.2% (m/m).

2.4.3. Oil properties analyses

The water content of crude vegetable oil was measured using the Karl-Fischer titration method described by standard ISO 8534, with a precision of approximately ±0.1% (m/m).

Foots are gross solid particles contained in crude oil, larger than 0.8 mm. They are assumed to be free of oil and content moisture. The method to measure this solid content consisted in passing the crude oil through a 0.8 mm sieve, and weighing it before and after the operation. This gives the mass of foots impregnated with oil, m_{foot}. Then, the mass fraction of foots free of oil, termed *FOOT* was deduced using Eq. (1), assuming they had an average oil content of 50% (O_{foot} = 0.5) (Beerens, 2007).

$$FOOT = \frac{m_{foot} \cdot (1 - O_{foot})}{m_{co}} \quad (1)$$

The sediment content of crude oil was analysed after foot removal, by gravimetry following the standard NF E 48-652. This measurement provided a sediment mass concentration, termed SED_{vol} expressed in mg L^{-1}, that was further converted to a mass

fraction *SED*, relative to crude oil mass, using Eq. (2). Sediments were assumed to be free of oil but they contain moisture.

$$SED = \frac{SED_{vol} \times 10^{-3}}{\rho_{co}} \cdot \frac{m_{co} - m_{foot}}{m_{co}} \quad (2)$$

where $\rho_{co} = 920\ \mathrm{kg\,m^{-3}}$ (Akintayo, 2004).

In further calculations, foots and sediments will be grouped in a single term *TS*, for total solids expressed as $TS = SED + FOOT$.

2.5. Experiments

2.5.1. Experimental settings

The influence of four independent variables was investigated: screw rotational speed at 9, 18 and 26 rpm (when it was technically achievable), choke ring adjustment (i.e. open, medium and tight), seed crushing and seed deshelling. Due to the seed preparation process, deshelled seeds were necessarily coarsely crushed. By combining different values of these independent variables, 19 experimental settings were defined, out of which three were in triplicate, giving 25 experiments. Two settings appeared technically undoable (see Section 4.1.1), three other settings were added, and finally giving 26 experiments completed (see Table 1).

2.5.2. Experimental protocol

A complete measurement was made for each operational setting. Prior to pressing, three samples of 150 g were taken from the seed batch for oil and moisture content measurement, so that for each experiment, the oil and moisture contents of input material were known. Then the press was gradually brought to a stable operating regime. The process was considered in steady state when cage temperatures and electric power values were stable for 5 min.

Once the steady state was achieved, the measurements were taken on a 15 min run. At $t = 0$, the oil and press cake containers were set in place and the acquisition of mechanical power measurement was triggered. The 9 temperature values from thermocouples were recorded twice during the experiment.

After 15 min, produced press cake and crude oil were weighed. About 200 g of press cake were sampled for oil and moisture content analyses. The collected oil was passed through a 0.8 mm sieve to remove the foots. Afterward, 200 mL of oil was sampled and sent to laboratory for sediment and moisture content analyses.

Crushed and deshelled seeds were slightly preheated to a temperature between 30 °C and 35 °C prior to pressing using a microwave continuous heating tunnel. This was necessary to achieve a proper temperature and pressure build-up during pressing (see Section 4.1.1). Crushed and deshelled seeds are indeed more difficult to process and moreover the room temperature had dropped from 20 °C to about 14 °C between the period when the experiments with whole seeds were conducted and the period when crushed and deshelled seeds were processed. Table 1 gives the measurement results for each experimental setting.

3. Calculations

3.1. Calculation of shell mass fraction

As mentioned above, the effect of seeds deshelling on the expression performance was investigated in the experiments. Therefore, the shell mass fraction of deshelled seeds batches had to be characterised. It was calculated from the oil content measurement of the seed batch, assuming that kernels and shells had constant oil contents. Reference values of oil contents in kernels and shells were determined by manually deshelling 20 entire seeds and measuring separately kernels and shells oil contents by pulsed NMR spectrometry (see Section 2.4.1). Average oil contents of kernels and shells were 55.3% and 1.4% on wet basis (at 6% moisture content) respectively.

Eq. (3), established from the oil mass balance in a seed, allowed to calculate the shell mass fraction *s* of a given seed batch, provided its oil content was known.

$$s = \frac{O_{ker} - O_{batch}}{O_{ker} - O_{shell}} \quad (3)$$

with $O_{ker} = 0.553$ and $O_{shell} = 0.014$.

3.2. Mass balance calculations

The calculation of mass balance was crucial for determining the separation efficiency of the process and it was also helpful in appreciating the quality of the measurements.

The different variables used for mass balance calculation are presented in Fig. 1.

The following assumptions were made:

- Crude oil (co) is the mass flowrate coming directly from the press, which contains solids and water.
- Pure oil (po) is a fictive oil mass flowrate free of solids and water, as if the crude oil had undergone a perfect separation of solids and water.
- Crude oil moisture content is measured on supernatant oil and we assume it is representative of crude oil water content, including solids, as shown in Fig. 1.

Four equations of mass conservation can be written, corresponding to overall matter, oil, water and solids, presented in Eqs. (4)–(7) respectively.

The *overall mass balance* is expressed as:

$$\dot{m}_s = \dot{m}_{co} + \dot{m}_{pc} + \dot{m}_{vap} \quad (4)$$

The *water mass balance* is given by:

$$\dot{m}_s \cdot M_s = \dot{m}_{co} \cdot M_{co} + \dot{m}_{pc} \cdot M_{pc} + \dot{m}_{vap} \quad (5)$$

The *oil mass balance* comes as:

$$\dot{m}_s \cdot O_s = \dot{m}_{co} \cdot (1 - TS) \cdot (1 - M_{co}) + \dot{m}_{pc} \cdot O_{pc} \quad (6)$$

that can also be written as: $\dot{m}_s \cdot O_s = \dot{m}_{po} + \dot{m}_{pc} \cdot O_{pc}$, where $\dot{m}_{po}$ is the pure oil mass flowrate.

Eventually, the solids mass balance is expressed as:

$$\dot{m}_s \cdot (1 - O_s - M_s) = \dot{m}_{pc} \cdot (1 - O_{pc} - M_{pc}) + \dot{m}_{co} \cdot TS \cdot (1 - M_{co}) \quad (7)$$

The *seed throughput* is calculated from Eqs. (4) and (5). As the evaporated water mass flowrate is not measured, the calculation has to be iterated in order to converge to seed throughput and water mass flowrate values that verify both Eqs. (4) and (5).

3.3. Pure oil mass flowrate determination

The pure oil mass flowrate may be derived from the following equation (direct calculation):

$$\dot{m}^D_{po} = \dot{m}_{co} \cdot (1 - TS) \cdot (1 - M_{co}) \quad (8)$$

Following oil mass balance equations, pure oil mass flowrate may also be determined indirectly:

$$\dot{m}^I_{po} = \dot{m}_s \cdot O_s - \dot{m}_{pc} \cdot O_{pc} \quad (9)$$

Important uncertainties arise from measurements with both methods of calculation. Among the quantities involved, i.e. seeds, raw oil and press cake mass flowrate, residual oil in press cake, water, foots and sediment content, sediment content appears as the most prone to measurement errors. Even if the analytical method is standardised, experience shows that the results are difficult to reproduce,

Table 1
Detailed results for all experiments. (*Abbreviations*: indir.: indirect calculation method; dir. corr.: direct calculation method corrected with coefficient α, see Sections 3.3, 3.4 and 4.2.1 for details.).

Settings	N (rpm)	Choke	Seed preparation	M_s	O_{sc}	$\dot{m}_s$ (kg h^{-1})	$\dot{m}_{co}$ (kg h^{-1})	M_{co}	TS'	$\dot{m}_{po}$ (indir.) (kg h^{-1})	$\dot{m}_{po}$ (dir. corr.) (kg h^{-1})	$\dot{m}_{sc}$ (kg h^{-1})	O_{sc}	M_{sc}	$\dot{m}_{wap}$ (kg h^{-1})	η (indir.)	η (dir. corr.)	E_s (Wh kg^{-1})
1.1	9	Open	Whole	0.062	0.31	59.4	16.8	0.0040	0.13	14.31	14.57	41.8	0.10	0.068	0.786	0.77	0.79	56.4
1.2	26	Open	Whole	0.062	0.31	161.5	33.7	0.0075	0.28	24.97	24.15	126.6	0.20	0.067	1.217	0.50	0.48	47.3
1.3	9	Tight	Whole	0.062	0.31	57.0	16.2	0.0035	0.14	15.13	13.88	39.8	0.07	0.062	1.030	0.85	0.78	66.8
1.4	26	Tight	Whole	0.062	0.31	173.3	45.2	0.0075	0.24	35.15	33.89	125.9	0.15	0.065	2.253	0.65	0.63	51.7
1.5	9	Open	Crushed	0.056	0.32	68.1	21.0	0.0060	0.20	18.62	16.56	46.1	0.07	0.059	0.973	0.86	0.76	53.9
1.6	16	Open	Crushed	0.054	0.31	122.3	40.2	0.0065	0.25	32.35	29.94	80.3	0.06	0.057	1.765	0.86	0.80	51.4
1.7	9	Tight	Crushed	0.056	0.32	67.4	21.1	0.0050	0.18	19.05	17.16	45.1	0.06	0.053	1.257	0.88	0.80	66.0
1.8	16	Tight	Crushed	0.054	0.31	123.8	40.7	0.0070	0.25	33.10	30.20	80.4	0.06	0.047	2.645	0.87	0.80	64.0
1.9	18	Medium	Whole	0.059	0.32	115.8	35.1	0.0075	0.18	30.25	28.44	79.2	0.09	0.064	1.528	0.81	0.77	55.1
1.A	18	Medium	Whole	0.062	0.31	119.5	36.4	0.0055	0.19	30.09	29.46	81.1	0.09	0.063	2.075	0.81	0.79	53.0
1.B	18	Medium	Whole	0.062	0.31	121.0	37.0	0.0060	0.19	29.63	29.73	81.7	0.10	0.062	2.248	0.79	0.79	51.5
1.C	18	Medium	Crushed	0.056	0.32	139.5	42.2	0.0085	0.31	23.07	29.06	95.7	0.23	0.060	1.686	0.52	0.65	30.7
1.D	18	Medium	Crushed	0.055	0.31	144.0	46.3	0.0085	0.30	29.78	32.33	96.1	0.16	0.062	1.587	0.66	0.72	38.9
1.E	18	Medium	Crushed	0.054	0.31	143.2	46.0	0.0065	0.24	37.20	34.63	94.4	0.07	0.050	2.730	0.85	0.79	58.7
2.1	9	Open	Deshell. – L	0.058	0.34	73.4	26.0	0.0045	0.16	22.73	21.66	46.5	0.05	0.070	0.863	0.90	0.86	53.5
2.2	18	Open	Deshell. – L	0.058	0.34	136.4	48.9	0.0095	0.23	36.28	37.30	86.6	0.12	0.075	0.913	0.77	0.80	33.8
2.3	9	Tight	Deshell. – L	0.058	0.34	66.8	24.8	0.0085	0.27	18.26	17.94	41.2	0.11	0.072	0.674	0.80	0.78	44.3
2.4	18	Tight	Deshell. – L	0.058	0.34	135.4	50.3	0.0065	0.20	38.18	39.77	83.4	0.10	0.070	1.649	0.82	0.85	42.6
2.5	5	Open	Deshell. – H	0.056	0.42	43.0	16.5	0.0065	0.24	11.77	12.48	26.0	0.24	0.070	0.492	0.65	0.69	23.5
2.7	4	Tight	Deshell. – H	0.056	0.41	34.2	14.2	0.0055	0.22	11.85	10.99	19.6	0.12	0.073	0.404	0.84	0.78	35.1
2.9	13	Medium	Deshell. – M	0.057	0.37	99.1	32.1	0.0080	0.27	21.16	23.06	66.3	0.24	0.069	0.843	0.57	0.62	25.7
2.A	13	Medium	Deshell. – M	0.057	0.37	103.3	38.0	0.0065	0.24	26.81	28.65	64.3	0.18	0.073	0.948	0.70	0.74	28.5
2.B	13	Medium	Deshell. – M	0.057	0.37	98.6	36.1	0.0060	0.18	29.23	29.32	61.2	0.12	0.067	1.308	0.79	0.80	31.5
3.1	11	Open	Whole	0.059	0.32	76.0	24.3	0.0050	0.14	21.40	20.73	50.5	0.06	0.064	1.127	0.88	0.85	57.9
3.2	9	Medium	Deshell. – L	0.058	0.34	73.1	26.3	0.0080	0.22	19.00	20.34	46.2	0.13	0.075	0.569	0.76	0.81	37.5
3.3	18	Medium	Deshell. – L	0.058	0.34	135.8	43.8	0.0110	0.32	28.82	29.42	91.5	0.20	0.075	0.572	0.62	0.63	28.4

especially for high sediment contents (Chirat, 1996). Therefore, the indirect calculation equation was assumed more reliable and taken as a reference.

3.4. Performance indicators

The main indicator of separation efficiency is the oil recovery defined as the ratio of pure oil expressed to seeds oil content, which can be calculated either from directly or indirectly calculated pure oil mass flowrate, presented respectively in Eqs. (10) and (11).

$$\eta^D = \frac{\dot{m}^D_{po}}{\dot{m}_s \cdot O_s} \tag{10}$$

$$\eta^I = \frac{\dot{m}^I_{po}}{\dot{m}_s \cdot O_s} \tag{11}$$

All calculation results are available in Table 1.

4. Results and discussions

In this section, the efficacy and reproducibility of oil expression using a screw-press is described in regard of operational parameters. Then, the consistency of the mass balance is thoroughly analysed and a relation between press cake residual oil content and solids content of crude oil is presented. Finally, a model linking the specific energy consumption of the process to the oil recovery is proposed.

4.1. Influence of operational settings on process performance and behaviour

4.1.1. Description of process operation and difficulties

During the experiment, it was observed that temperature and pressure build-up were closely linked and crucial in obtaining proper oil expression. While the press was gradually brought to a steady operation regime, the barrel temperature raised together with the mechanical power delivered by the motor. Maximum barrel temperatures varied between 75 °C and 120 °C, depending on the experimental setting. Below 75 °C, no proper oil expression occurred. The choke adjustment appeared to have no significant effect on operating conditions and process performance.

Several difficulties were encountered when pressing crushed and deshelled seeds. Instead of clean oil, a thick mixture of oil and fine solids was extracted. With deshelled seeds, it was difficult to obtain proper pressure and temperature build up, so that the seeds were merely extruded and no oil was expressed. This phenomenon is known to occur when pressing seed materials with an insufficient structure to allow a proper pressure build up, such as deshelled or over-cooked seeds (Boeck, 2011). To overcome these issues, it was decided to preheat the seeds to a temperature close to 35 °C, using a microwave continuous heating tunnel, to facilitate temperature build-up, which proved to be quite effective. However, even with this precaution, pressing 50% deshelled seeds was impossible at a shaft speed higher than 4 or 5 rpm.

The difficulty of pressing deshelled oilseeds was previously reported in literature by several authors. Zheng et al. (2003) observed that the screw pressing of dehulled flaxseed presented lower oil yields than whole seeds and required a special configuration of the worm shaft because of the softness of dehulled seeds. A Japanese research group reported the same observation for sunflower seeds and developed a twin-screw press for the oil extraction from dehulled seeds (Isobe et al., 1992). Finally, Xiao et al. (2005) compared the permeability of dehulled and undehulled rapeseeds under various pressures and found greater permeability in undehulled material. Thus, the difficulties in pressing deshelled

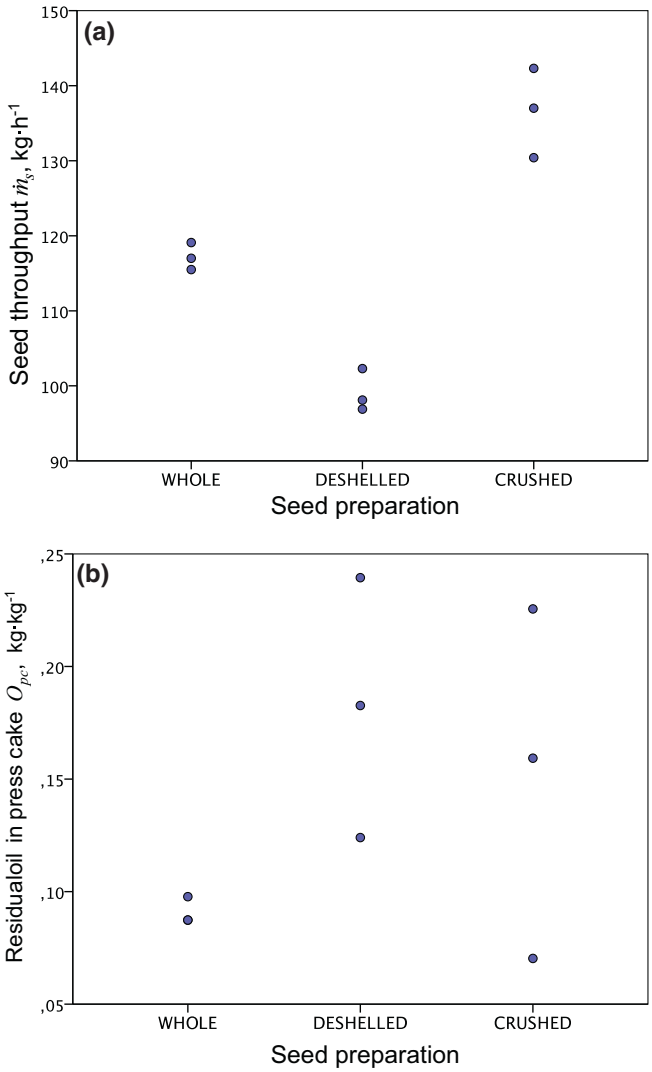

Fig. 2. Graphical illustration of the results for triplicate experimental settings with respect to seed preparation. (a) Seed throughput; (b) residual oil in press cake.

Jatropha seeds might be explained by the reduction of permeability and the lack of solid structure caused by the deshelling.

Then, it was observed during the pressing of crushed and deshelled seeds that the process is never totally in steady state, especially at high rotational speed. In particular, large fluctuations of mechanical power and temperature are observed. This is attributed to the lack of homogeneity of input material: shells and fines always tend to separate from kernel parts. At the best, a quasi-periodicity is observed and the regime is self-maintained.

In some other cases, the regime is not steady and starts drifting: either the temperature and power increase until the worm shaft gets stuck, or the temperature and power drop and oil expression turns to seed extrusion.

Thus, operation at 26 rpm was only possible with whole seeds. With deshelled seeds, such high speed systematically prevented pressure build up and with crushed seeds, pressure and temperature build up was too high and the shaft got stuck.

4.1.2. Reproducibility of the results

The reproducibility of the experiment is appreciated by analysing the results of triplicated experimental settings. Fig. 2 shows the results of these three settings in terms of seed throughput and residual oil in press cake. The graph shows that seed

throughput results are fairly reproduced with any type of seeds, the worst case being with crushed seeds with less than ±10% gap around average. In terms of residual oil in press cake, the results are well reproduced only with whole seeds. It is much more difficult to reproduce the performances when pressing crushed or deshelled seeds. This is attributed to the unsteady state phenomena described in Section 4.1.1.

The lack of reproducibility observed reflects that, in some cases, the control of operational parameters (rotational speed, choke ring adjustment) of the present experimental apparatus is not sufficient to govern the process conditions. Parameters such as feed material homogeneity, cake porosity and temperature cannot be controlled. Consequently, the variable results of triplicated settings with deshelled and crushed seeds correspond to different process conditions, but under no circumstances are linked to measurement errors.

This means that any analysis of the links between controlled parameters and residual oil will present high uncertainty for crushed and deshelled seeds. However, the lack of reproducibility does not impede the analysis of the mass balance for each experiment and the relations between separation efficiency and energy consumption.

4.1.3. Relation between oil recovery and material throughput

Fig. 3a presents the relation between oil recovery and seed throughput with respect to seed preparation: the oil recovery tends to decrease with increasing material throughput. This is physically meaningful, since the increase of material throughput corresponds to a lower residence time and thus a lower oil extraction. Moreover, it can be shown from the results presented in Table 1 that the material throughput is strictly proportional to the screw rotational speed for a given seeds preparation.

Although the residence time is a crucial factor influencing oil recovery, the influence of processing conditions such as temperature and pressure cannot be ignored. Yet, we had observed and explained previously that the processing conditions cannot be reproduced for crushed and deshelled seeds with the present experimental apparatus. Then, no model regression can be made on these data, apart for whole seeds results, which are fairly reproducible.

A non-linear regression was performed on whole seeds, following an asymptotic model defined as:

$$\eta = k_1 + k_2 \cdot \exp(k_3 \cdot \dot{m}_s) \tag{12}$$

The regression gives an $R^2 = 0.68$ and the curve corresponding to the model is presented in Fig. 3b. The values of the coefficient k_1, k_2 and k_3 are respectively 0.88, −0.01 and 0.02. Additional experiments with whole seeds at different screw rotational speeds would be required to improve this correlation. The same model was published by Karaj and Müller (2011), but with an $R^2 = 0.78$.

4.2. Mass balance assessment

4.2.1. Interpretation of results and data reconciliation

According to Eqs. (8) and (9), the direct and indirect calculation methods of the pure oil mass flowrate should give similar results. Fig. 4a illustrates the indirect versus direct calculation of pure oil mass flowrate. Results from both methods are very close, but with random variations and a systematic error revealed by the linear regression that slightly deviates from equality. Indeed, the direct calculation method provides a result significantly higher than the indirect method at $p << 0.05$ (t-test).

The random variations can be attributed to unavoidable measurement and sampling errors. The systematic deviation is attributed to crude oil sampling for sediment content measurement. The mass flowrate calculated indirectly, taken as the reference (see Section 3.3), is systematically lower than with the direct method, which means that the sediment content is always under-estimated. The under-estimation of sediment content measurement may be explained by the sampling method. For each experiment, 5–15 kg of raw oil is extracted, from which a raw oil sample of 200 mL is retrieved from the top of the bucket using a beaker while manually agitating the mixture. Thus, even with manual agitation, the sediment content of the sample is certainly lower than the overall sediment content.

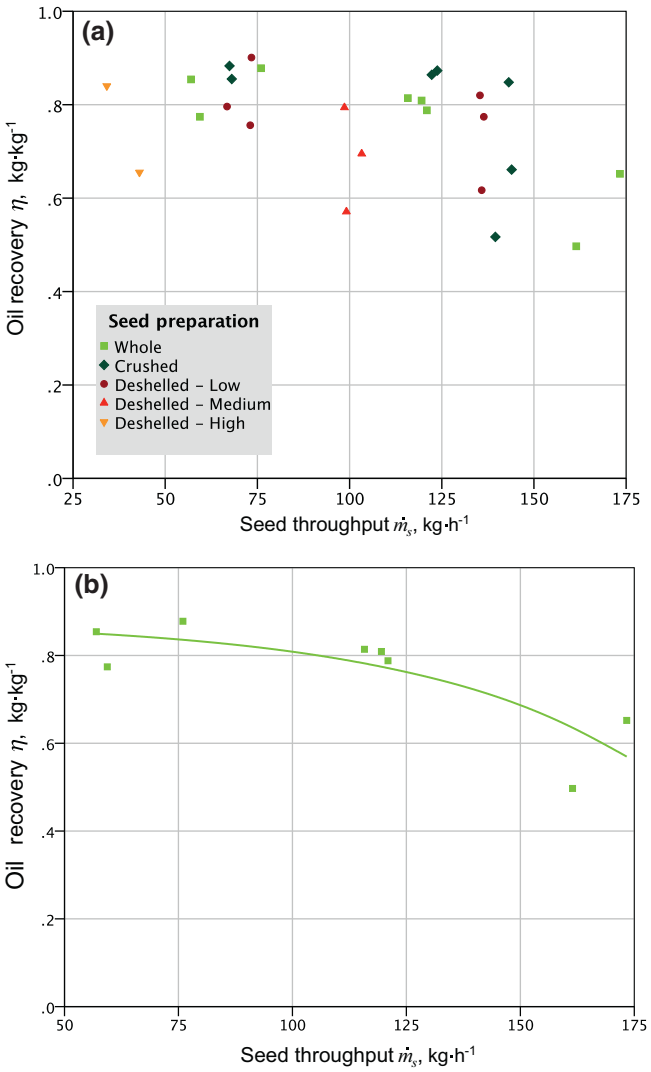

Fig. 3. Relation between oil recovery and seed throughput. (a) All seed preparation; (b) whole seeds only, line is the regression model (Eq. (12)).

This systematic error is corrected by applying a coefficient to the total solids content of crude oil, which is provided by the linear regression ($\alpha = 0.9324$).

$$\dot{m}_{po}^{I} = \alpha \cdot \dot{m}_{po}^{D} = \alpha \cdot \dot{m}_{co} \cdot (1 - TS) \cdot (1 - M_{co}) \tag{13}$$

We introduce a corrected value of total solids TS_α, such as: $1 - TS_\alpha = \alpha \cdot (1 - TS)$.

This corrected value of total contamination content is set as reference for further analyses and the direct calculation of pure oil mass flowrate becomes:

$$\dot{m}_{po}^{D} = \dot{m}_{co} \cdot (1 - TS_\alpha) \cdot (1 - M_{co}) \tag{14}$$

The determination of oil recovery is crucial for appreciating the efficiency of the solid–liquid separation and directly depends on pure oil mass flowrate. Thus, two values can be calculated using

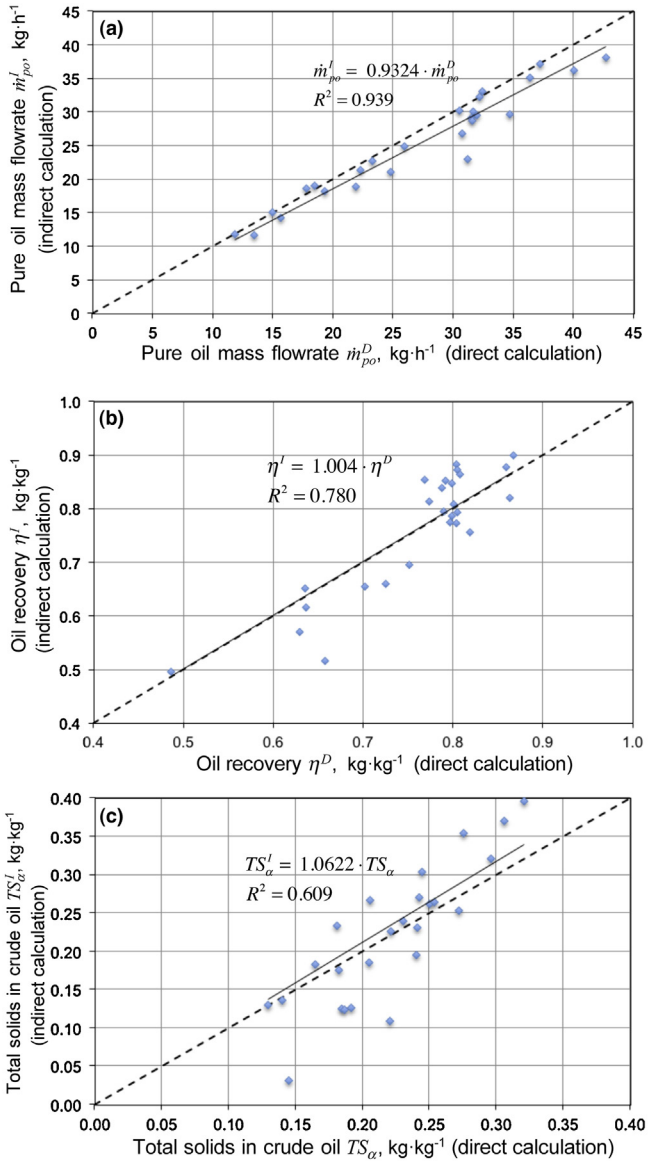

Fig. 4. Validation graphs for the consistency direct and indirect calculation methods of pure oil mass flowrate (a), oil recovery (b) and total solids (c).

direct and indirect pure oil mass flowrate calculation methods (see Eqs. (10) and (11)). Fig. 4b illustrates the matching between both methods. It is clear that the random error is exacerbated when pure oil mass flowrate is divided by input oil. However, the linear least squares regression exhibits a fair $R^2 = 0.78$ and the regression coefficient is very close to 1 (interception was forced to 0).

4.2.2. Correlation between seed, press cake and crude oil mass flowrates

A very well-correlated linear relation is observed between seed throughput and press cake output. The press cake throughput is always strictly proportional to the seed input. This result can also be observed in the results published by Karaj and Müller (2011) on *Jatropha* oil expression experiments but was not highlighted by the authors. We call β the linear regression coefficient relating press cake throughput to seed throughput, as showed in Eq. (15). Fig. 5 shows linear regressions between seeds and press cake throughput

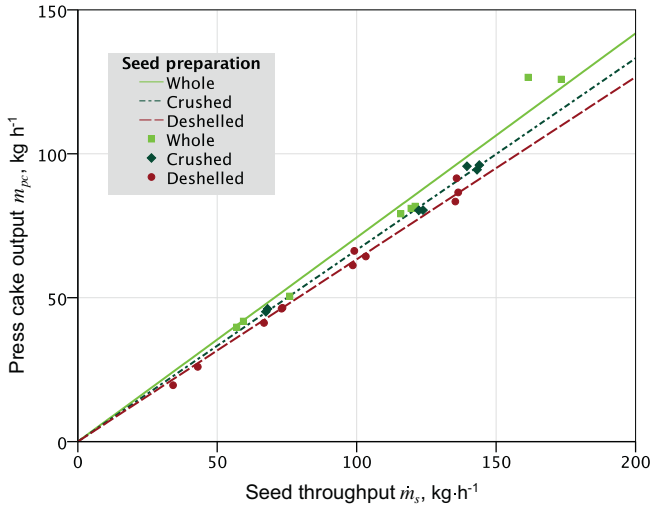

Fig. 5. Relations between seed and press cake throughput with respect to seed preparation. Lines are linear least squares regression for each modality of seed preparation.

Table 2
Values of coefficient β (linear regression coefficient relating seedcake to seed throughput in Eq. (15)) and square residues of linear regressions.

Seed preparation	β	R^2
All types	0.674	0.968
Whole	0.717	0.975
Crushed	0.666	0.995
Deshelled	0.637	0.990
Karaj and Müller (2011) (whole seeds)	0.762	0.969

with respect to seed preparation grouped as entire seeds, crushed seeds and deshelled seeds.

$$\dot{m}_{pc} = \beta \cdot \dot{m}_s \tag{15}$$

The value of the coefficient β is mostly related to the design of the press, especially the volume generated by the profile of the worm shaft, which is the same for all experiments. However, it also depends on the seeds characteristics, in particular bulk density and oil content, which will influence the input mass flowrate conveyed by the screw and the proportion in which the material is divided between press cake and oil outlets. Indeed, β can be precisely evaluated with respect to seed preparation as shown in Fig. 5. Table 2 summarises the value of β for each seed preparation and for Karaj and Müller (2011) data. These values are specific to *Jatropha* seeds, and to the pressing equipment used in these experiments.

Crushed and entire seeds have approximately the same oil content; deshelled seeds have higher oil content and are only coarsely crushed compared to crushed seeds. The highest value of β relates to whole seeds. For crushed seeds, the β value is slightly lower, which can be explained by a higher bulk density. Then the even lower β value for deshelled seeds might be explained by higher oil content, resulting in less press cake and more oil.

This important result shows that, whatever the operational parameters, the seed throughput is always divided in a stream of crude oil and a stream of press cake in the same proportion (β) for a given input material. Then, the residual oil in press cake and the amount of solids carried by the oil are directly related and determine the efficacy of the separation, i.e. the oil recovery. When the oil recovery is high, the press cake oil content is low, as well as the solids in crude oil, and conversely. This means that the separation efficacy of screw-pressing cannot be evaluated only by measuring crude oil mass flowrate, the knowledge of solids content or residual oil in press cake is required. This result allows writing the relations

between oil recovery, press cake oil content and solids in crude oil using the coefficient β and the mass balance equations. This information could be very useful for choosing the screw-press design best suited to the type of seeds to process, especially given their oil contents.

4.2.3. Total solids prediction from oil recovery

Using β, oil recovery can be expressed as a simple function of seeds and press cake oil content:

$$\eta = 1 - \beta \cdot \frac{O_{pc}}{O_s} \tag{16}$$

Then, in the perspective of process modelling, provided that the value of β is known, the total solids in the extracted crude oil can be predicted. Combining Eq. (16) with the oil mass balance Eq. (6), total solids contamination can be expressed as a function of oil recovery as:

$$TS_{\alpha}^{l} = 1 - \frac{\eta \cdot O_s}{(1-\beta)\cdot(1-M_{co})}$$

Fig. 4c illustrates the calculated solids content versus the measured one. Of course, here the random errors are strongly increased by the several ratios and multiplications.

In practice, the equation for total solids calculation can be simplified by ignoring oil moisture content. The water content of oil is indeed very low: in this case the maximum measured value is 1.1% and the average 0.7%. However, these moisture contents are actually high compared to usual values for vegetable oils, because this oil is degraded (high free fatty acid 9%) due to the poor storage conditions and the age of the seeds. Normally, even after being washed with water, vegetable oil has moisture content up to 0.5% (w/w) after phase separation (Lusas et al., 2012). In comparison, following the standard DIN 51605, the moisture level required for using vegetable oil as a fuel is 0.075% maximum.

4.3. Relation between oil recovery and specific energy consumption

The oil expression is a solid–liquid separation process and as such, the specific energy consumption should be linked to the efficiency of the separation. This intuition is confirmed by observing Fig. 6a, which shows a scatterplot of seed-specific energy consumption versus press cake residual oil content.

Using an exploratory data analysis methodology as described in NIST/SEMATECH (2013), a model for seed-specific energy consumption was built stepwise. The basic procedure consists in identifying and fitting a first model including only the main explanatory variable – press cake residual oil in this case. The form of the equation should be determined according to the physics of the process. Then, the residues of this model are plotted against other potential explanatory variables and if there is a strong correlation, the variable is integrated in the model – seeds oil content in this case. In order to ensure that the model describes the data well enough and that there is no missing term, the residues were tested for normality using Shapiro–Wilk test (NIST/SEMATECH, 2013).

The final model is presented in Eq. (17); it explains 87% of seed-specific energy consumption variations – $R^2 = 0.87$. It includes two explanatory variables, oil recovery and seeds oil content and only three parameters, β_1, β_2 and β_3 – press cake residual oil was replaced with oil recovery using Eq. (16). The values of β_1, β_2 and β_3 are 1.075, −11.813 and −4.294 respectively. These parameters values are valid for *Jatropha* seeds and the pressing equipment used in these experiments. Additional experiments would be required, with other type of seeds and machinery to check if the same correlation is suitable to describe the process and to adapt the parameters values.

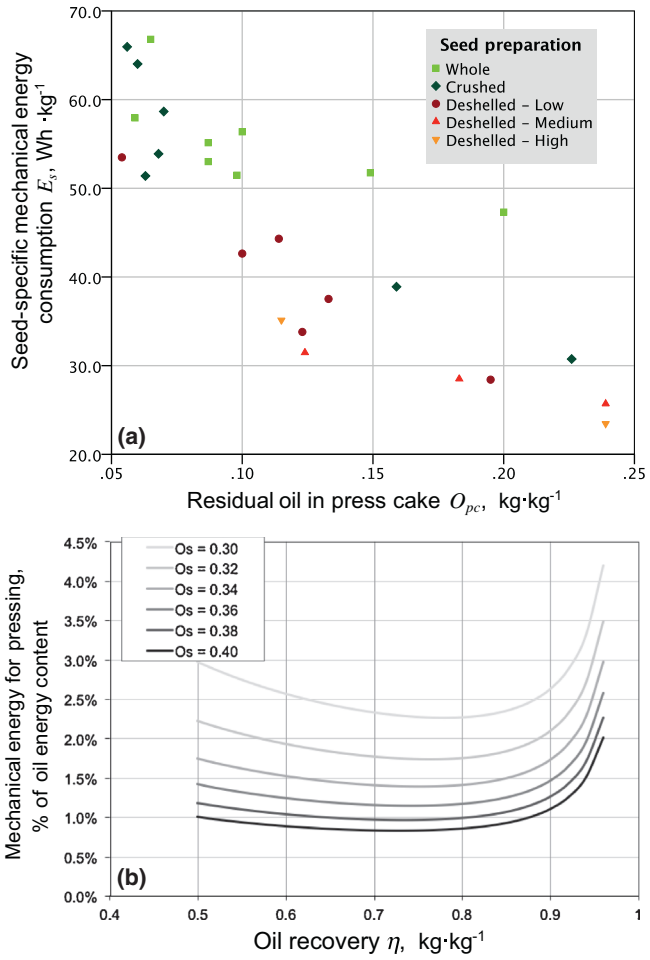

Fig. 6. (a) Scatterplot of seed-specific energy consumption versus press cake residual oil content, with respect to seed preparation. (b) Graphical representation of the proposed energy model. Mechanical energy requirement for pressing, expressed as percentage of oil heating value, versus oil recovery, for different values of seeds oil content.

$$E_s = \frac{\beta_1}{O_s \cdot (1-\eta)} + \frac{\beta_2}{1+\beta_3 \cdot O_s} \tag{17}$$

Then, it is useful to observe oil-specific energy consumption, given by Eq. (18).

$$E_{po} = \frac{E_s}{\eta \cdot O_s} \tag{18}$$

This is also very well-correlated to experimental data with an $R^2 = 0.86$.

It is relevant to compare the energy required to extract vegetable oil from the seeds with the oil heating value. Assuming an average heating value of 38.8 MJ kg (Blin et al., 2013), we calculated the embodied energy of oil as a percentage of its energy content. This value is plotted against oil recovery in Fig. 6b, for several values of seeds oil contents. The energy spent for oil expression is small (<5%) compared to the heating value of the oil, which makes it an energy efficient separation process. Of course, the production of the mechanical energy and the energy required for seeds preparation, transport and production should also be estimated for a complete determination of the overall embodied primary energy.

The specific energy consumption is strongly sensitive to seeds oil content, especially at low oil content. A minimum energy requirement is generally observed at oil recoveries between 70%

and 80%. Karaj and Müller (2011) presented similar results for cylinder-hole type screw-press but with significantly higher energy consumption levels, up to 400 Wh kg^{-1} of seeds. This shows that strainer-type screw-press is much more energy efficient than cylinder-hole type.

The relation of energy efficiency to oil recovery is an important consideration for optimising the processing strategy of oilseeds, depending on the final uses of the products, their economic values and energy prices. For instance, if the oil and the press cake are used for energy purposes, it might be beneficial to limit the oil recovery in order to minimise the oil expression cost and increase the energy value of the press cake. In this context, the approach applied in this work is particularly relevant and should be validated for other types of seeds and pressing equipment. Additional experiments would be necessary to determine if the correlation in Eq. (17) can be generalised to any type of mechanical oil expression process.

5. Conclusion

The oil expression from crushed and deshelled seeds appeared to be unstable due to a lack of homogeneity in input material, resulting in important discrepancies in the pressing efficiency. A high fraction of shells in the feed allows to build a solid permeable matrix which favours oil flow through the press cake. For a given feed material, the press cake mass flowrate is strictly proportional to the seed throughput, which enables to establish a direct relation between oil recovery and solids content in crude oil. A correlation between oil recovery and specific energy consumption was proposed.

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