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Determination of Critical Conditions for Puncturing Almonds Using Coupled Response Surface Methodology and Genetic Algorithm

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Summary

In this study, the effect of seed moisture content, probe diameter and loading velocity (puncture conditions) on some mechanical properties of almond kernel and peeled almond kernel is considered to model a relationship between the puncture conditions and rupture energy. Furthermore, distribution of the mechanical properties is determined. The main objective is to determine the critical values of mechanical properties significant for peeling machines. The response surface methodology was used to find the relationship between the input parameters and the output responses, and the fitness function was applied to measure the optimal values using the genetic algorithm. Two-parameter Weibull function was used to describe the distribution of mechanical properties. Based on the Weibull parameter values, *i.e.* shape parameter (β) and scale parameter (η) calculated for each property, the mechanical distribution variations were completely described and it was confirmed that the mechanical properties are rule governed, which makes the Weibull function suitable for estimating their distributions. The energy model estimated using response surface methodology shows that the mechanical properties relate exponentially to the moisture, and polynomially to the loading velocity and probe diameter, which enabled successful estimation of the rupture energy (R^2=0.94). The genetic algorithm calculated the critical values of seed moisture, probe diameter, and loading velocity to be 18.11 % on dry mass basis, 0.79 mm, and 0.15 mm/min, respectively, and optimum rupture energy of $1.97 \cdot 10^{-3}$ J. These conditions were used for comparison with new samples, where the rupture energy was experimentally measured to be 2.68 and $2.21 \cdot 10^{-3}$ J for kernel and peeled kernel, respectively, which was nearly in agreement with our model results.

Key words: almond, genetic algorithm, mechanical properties, modelling, response surface methodology, Weibull distribution

Introduction

Almond (*Amygdalus communis* L.) is one of the most popular tree nuts in the world. It is a perennial plant growing in the Mediterranean and cold climates of Iran. The almond and its kernel play an important role as a source of protein (21.22 g per 100 g) in human diet (*1*). In 2011, Iran with $170 \cdot 10^3$ tonne almond production was the third main producer in the world after the USA and Spain. Some of the most important processing steps after almond harvesting are hulling, shell cracking, wetting the kernels, peeling and drying them. These processing methods are greatly influenced by the physical and mechanical properties of the product. Mechanical properties of agricultural products are most commonly measured with the force-deformation (*F–D*) curve. From this

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*Corresponding author; Phone: ++98 913 381 5761; Fax: ++98 381 442 4428; E-mail: rahim.ebrahimi@gmail.com curve, a number of mechanical properties can be determined such as maximum rupture force (F_{max}; *i.e.* maximum force required to rupture the almond kernel), rupture energy (E_n; *i.e.* the resistance of the fruit to mechanical injuries), elasticity (E), and deformation (D). Puncture test is one of the simplest and most widely used methods for objective measurement of the mechanical properties of many food products, including fruit skins (*2–7*). The results of puncture tests are influenced by different puncture conditions such as probe diameter, loading velocity, cultivar (*2,8,9*), stage of maturity, fruit size (*4,6*), temperature and turgor pressure of juicy fruits (*10*).

Recently the influence of these puncture conditions on mechanical properties has been modelled using different polynomial equations and finite element methods (*6,7,11*). Singh and Sreenivasula Reddy (*6*) modelled puncture force and cutting energy with respect to storage period under ambient and refrigerated conditions. Ghazavi *et al.* (*7*) acquired some models for estimating the physical and mechanical properties of tomato. The models of such research are not only highly inaccurate, but also do not report any critical values of puncture conditions. Therefore, using coupled response surface methodology (RSM) and genetic algorithm (GA), a complete model is built and critical points for puncturing are determined. The RSM is a powerful design tool with many engineering applications. It cannot only save a lot of time, but it can also build models quickly and accurately in an optimisation design. It is very difficult to find a global optimum point using RSM when the response is complex (*12*). The GA is a search algorithm that emulates the adaptive processes of natural biological systems. It has been applied in many complex optimisation and search problems, outperforming traditional optimisation and search methods. Integration of RSM and GA seems to be a good choice for finding the critical values of puncture conditions.

An important factor for modelling a property is its distribution. Most mechanical properties are a function of time, therefore a lifetime distribution such as Weibull can describe their frequencies. The Weibull function is widely used due to its flexibility in modelling reverse-J, skewed, and unimodal shapes (*13,14*), but it is not required for the estimation frequencies because of integration (*1,15*). In this respect, the Weibull function has been used in this study. The research idea behind this study is original and brings novelty because to date, coupled RSM and GA techniques have not been used for rupture energy estimation of fruits, especially of nuts. Therefore, it seems reasonable to undertake studies in order to test the method and its usefulness in this field.

The objectives of this study are: (*i*) to describe the effect of seed moisture content, loading velocity and probe diameter on F_{max}, E_n, D and E values of almond kernel and peeled almond kernel, (*ii*) to determine the properties suitable for making a model, (*iii*) to utilise the two-parameter Weibull distribution function for considering the distributions of mechanical properties, and (*iv*) to make a new model by supplementing RSM and GA for the estimation of E_n and determination of critical values of puncture conditions.

Materials and Methods

Mechanical properties

Almonds were taken from Almond Research Center of Shahrekord, Shahrekord, Iran, during the spring season in 2009 and then cracked and peeled. The puncture test was used to evaluate the mechanical properties of kernel and peeled kernel (hereafter seed). First, the effects of seed moisture content, puncture loading velocity and probe diameter (puncture conditions) were tested. The loading velocities were 0.1, 0.75, 1.25, 2.5 and 5 mm/min and probe diameters were 0.4, 0.8, 1.2, 1.6 and 1.8 mm. The seed moisture on dry mass basis at initial hour of harvesting (M_1) was 24.97 %, three hours after harvesting (M_2) it was 18.11 %, six hours after harvesting (M_3) 9.98 %, and nine hours after harvesting (M_4) 2.77 %. Each combination of puncture conditions was replicated five times. The initial moisture content of the samples was determined by oven drying at (105±1) °C for 24 h and calculated on dry mass basis. The seed samples of the desired moisture levels were prepared by soaking them in distilled water and then sealing in separate polyethylene bags. The samples were kept at 278 °K in a refrigerator for 7 days for the moisture to distribute uniformly throughout the sample. This method was used by Altuntas and Yildiz (*11*) to obtain faba bean (*Vicia faba* L.) grains of the desired moisture content for their experiments. Before starting a test, the required quantities of seeds were warmed up to room temperature (*9, 16*).

A normal force of 0.04 N was imposed on the seeds to establish contact. The seeds were then compressed by the probes at a constant loading velocity using a designed apparatus with a driving unit and a data acquisition system (loadcell with precision of 0.001 N, a laptop and software), as illustrated in Fig. 1. An *F–D* curve, shown in Fig. 2, was obtained for each puncture test. From the curve, mechanical properties of F_{max}, D, and E_n (area under *F–D* curve) were determined. The *F–D* curves had different forms depending on different puncture conditions.

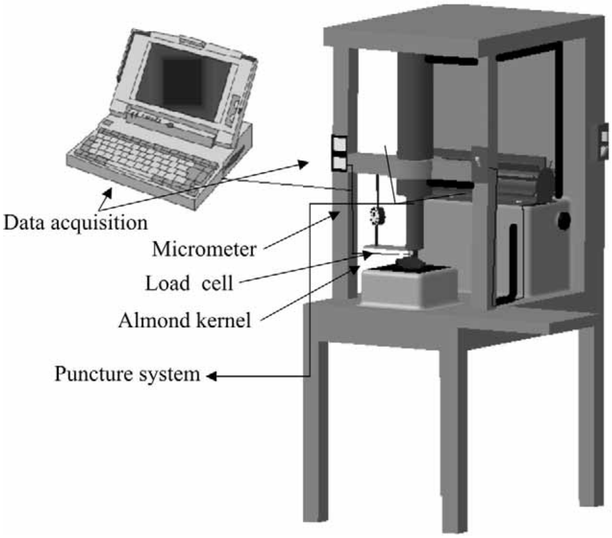

Fig. 1. The apparatus designed for puncture tests

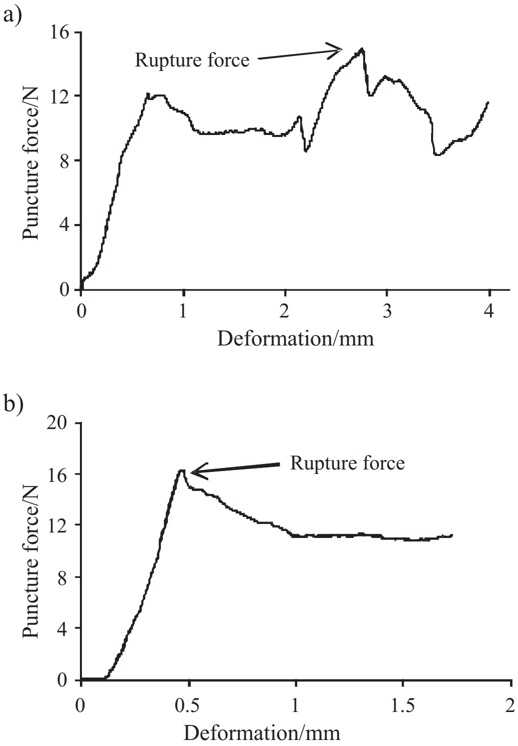

Fig. 2. Force–deformation curves for the samples of almond seeds: a) loading velocity was higher than 3.5 mm/min, and b) loading velocity was lower than 3.5 mm/min

An important mechanical property of agricultural materials is their modulus of elasticity (*E*). It is an intrinsic property of a material reflecting the strength of bonding at the atomic level. If the average value of *E* of a sample is higher, then it behaves more like a spring against impact loads (*7*). This was obtained for the seeds by application of the Hertz's theory (*5,16*). To obtain this goal, the seeds were compressed with probes of five different diameters, and the $F_{\max}$ and *D* were recorded and used to calculate the *E*:

$$E=\frac{F_{\max}\cdot(1-\nu^2)}{d\cdot D} \qquad /1/$$

where *d* is the probe diameter and ν is Poisson's ratio of 0.45 based on the fact that ν for most fruits and vegetables varies between 0.45 and 0.5 (*7,17*).

Distribution of mechanical properties

After the calculation of mechanical properties of seeds, their differences can be considered by probability density function (PDF). Mechanical properties usually change with time, therefore a lifetime distribution such as Weibull can be used to determine the PDF of mechanical properties (*18*). It is a versatile distribution that can take on the characteristics of other types of distributions, based on the value of the shape parameter, β. The primary form of its PDF has three parameters given by:

$$f(X)=\frac{\beta}{\eta}\left(\frac{X-\gamma}{\eta}\right)^{\beta-1}\cdot e^{-\left(\frac{X-\gamma}{\eta}\right)^{\beta}} \quad f(X)\geq 0,\ X\geq 0 \text{ or } \qquad /2/$$
$$\gamma,\ \beta>0,\ \eta>0,\ -\infty<\gamma<\infty$$

where β, η and γ are shape parameter, scale parameter, and location parameter, respectively.

Although the ambient conditions affect the mechanical properties of almond seeds, these conditions were assumed stable in this research, therefore the seeds were independent of the location, and parameter of γ (parameter of location in Weibull distribution function (Eq. 2)) was supposed to be zero (*1*); hence the PDF of the two-parameter Weibull is obtained using Eq. 3, and its cumulative density function (CDF) is calculated by Eq. 4:

$$f(X)=\frac{\beta}{\eta}\left(\frac{X}{\eta}\right)^{\beta-1}\cdot e^{-\left(\frac{X}{\eta}\right)^{\beta}} \qquad /3/$$

$$F(X)=1-e^{-\left(\frac{X}{\eta}\right)^{\beta}} \quad \eta\geq 0,\ \beta\geq 0 \qquad /4/$$

The *X* is an independent variable representing either *F*, *D*, E_n or *E* of seeds. Parameters η and β of the distribution are estimated from the observations. The method usually employed for the estimation of these parameters is linear regression (*19,20*). According to literature (*18*), it can be seen that the shape of the Weibull PDF can take on a variety of forms based on the value of β. When $\beta<2.6$, the Weibull PDF is positively skewed (has a right tail), and when $2.6<\beta<3.7$, its coefficient of skewness approaches zero (no tail). Consequently, it may approximate the normal PDF, and when $\beta>3.7$, it is negatively skewed (left tail). If η is increased while β is kept the same, the distribution gets stretched out to the right and its height decreases, and if η is decreased while β is kept the same, the distribution gets pushed towards the left, and its height increases (*14,19,20*).

To determine the Weibull parameters, Eq. 4 was written in linear form by taking the logarithm twice, the parameters were estimated by applying the linear regression using the least squares procedure, and thus Eqs. 5 and 6 were acquired:

$$\ln[1-F(X)]=-\left(\frac{X}{\eta}\right)^{\beta} \Rightarrow \ln\{-\ln[1-F(X)]\}=$$
$$=\beta\ln\left(\frac{X}{\eta}\right)=-\beta\ln(\eta)+\beta\ln(X) \qquad /5/$$
$$y=a+bx$$

$$y=\ln\{-\ln[1-F(X_i)]\} \Rightarrow a=-\beta\ln(\eta)$$
$$\text{and } b=\beta \qquad /6/$$
$$x=F(X_i)$$

Eqs. 3 and 4 were then replaced by these equations and the Weibull CDF and PDF values for each class of seed mechanical properties were derived.

Effect of puncture conditions on the mechanical properties

Four sets of puncture tests were completed. First, the effect of seed moisture and puncture probe diameter on $F_{\max}$ and E_n was tested. Secondly, the effect of loading velocity and probe diameter on $F_{\max}$ and E_n was considered. Then the combined effect of seed moisture and puncture conditions on E_n was considered and a function between the E_n and the puncture conditions was found. Finally the effect of seed moisture and probe diameter on E was determined. To determine the E, it was necessary to use a low loading velocity. When the velocity was high, the F–D curve had an initial peak that made it difficult to carefully calculate the $F_{\max}$ and E (Fig. 2a).

Genetic algorithms

In this study, an efficient optimisation method by combining RSM and GA is introduced to find critical puncture conditions for predicting the minimum E_n of almond seeds. A predictive model for the puncture conditions and rupture energy was created using RSM and then used with an effective GA to find critical puncture conditions. In GA, a candidate solution to a specific problem is called an individual or a chromosome and consists of a linear list of genes. Each individual represents a point in the search space, and hence a possible solution to the problem. A population consists of a finite number of individuals. Each individual is decided by an evaluation mechanism to obtain its fitness value. Based on this fitness value and undergoing genetic operators, a new population is generated iteratively with each successive population referred to as a generation.

The roulette wheel method was used for the chromosome selection. The crossover operator was applied to create a pair of offspring chromosomes. For each selected pair, a two-point crossover operation was used to generate an offspring with the crossover probability (*12*). The one-gene mutation operation with a preset mutation probability was applied to generate new chromosomes. The MATLAB v. 7.12 software (Math Works, Inc., Natick, MA, USA) was used to develop the algorithms.

Results and Discussion

Mechanical property distributions

The results showed that Eq. 3 provides a good description of D, E and E_n distributions of seeds, but it does not give a good description of $F_{\max}$ distributions. Histogram of frequency distribution (Fig. 3) for the mean values of E_n, D and E showed a trend towards a Weibull distribution and only slight deviation of the average coefficient of determination from the unity was shown. After considering the root mean square error (RMSE) of the

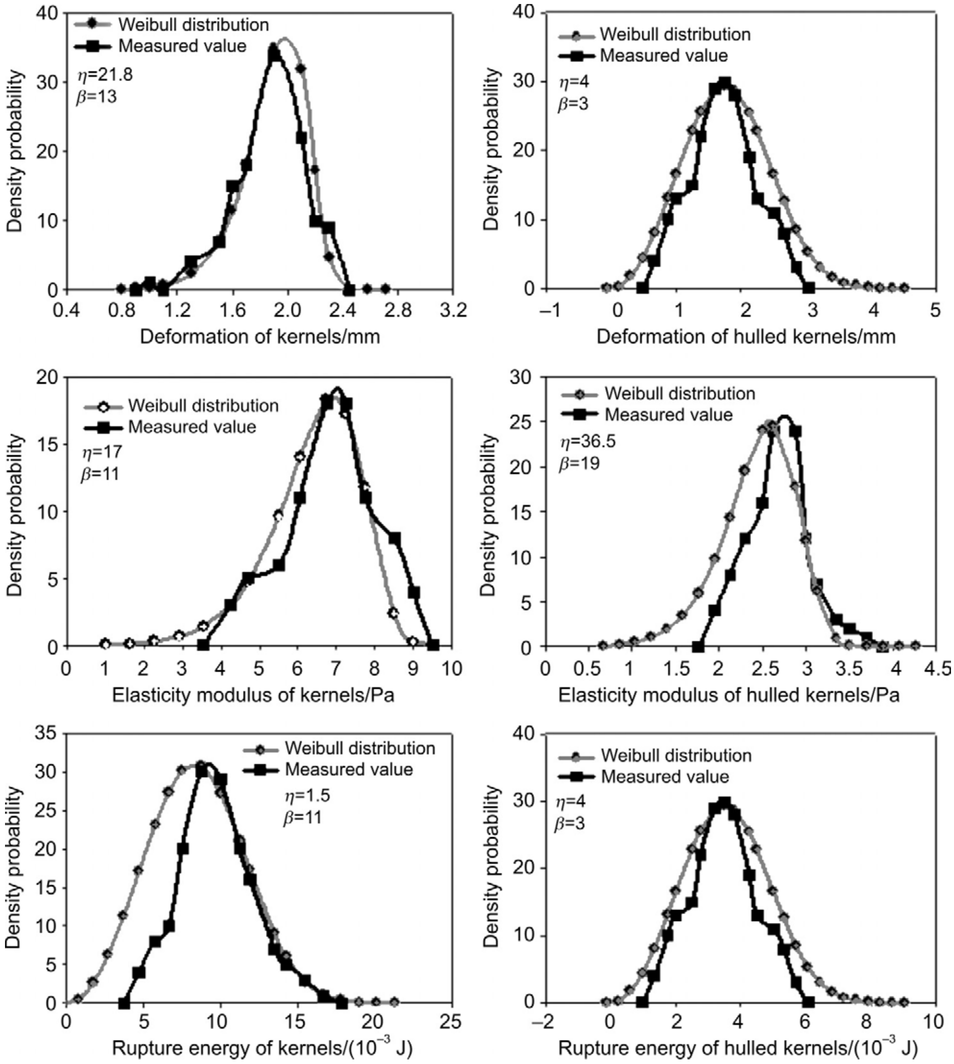

Fig. 3. The measured values and the estimated densities using Weibull function for deformation, elasticity modulus and rupture energy of almond seeds at M_3 moisture content

Weibull distribution, the function for these properties was less than 0.06 and R^2 was above 0.87 (Table 1).

Table 1. The estimated values of Weibull parameters and the statistical parameters derived between the measured values and the estimated values

Sample	Moisture	Property	η	β	RMSE	R^2
kernel	M_1	D	4.0	3	0.055	0.97
		E_n	21.8	13	0.045	0.97
		E	34.0	23	0.041	0.90
		F_{max}	14.6	21	0.138	0.70
	M_4	D	13.5	2	0.055	0.90
		E_n	13.5	5	0.019	0.87
		E	29.0	5	0.014	0.90
		F_{max}	10.5	7	0.150	0.74
peeled kernel	M_1	D	4.4	3	0.045	0.93
		E_n	23.1	15	0.042	0.98
		E	37.9	19	0.036	0.97
		F_{max}	17.4	11	0.144	0.69
	M_4	D	1.9	7	0.049	0.92
		E_n	13.3	15	0.042	0.95
		E	27.5	15	0.043	0.97
		F_{max}	11.9	5	0.095	0.78

Moisture on dry mass basis: M_1=24.97 and M_4=2.77 %

The η is expressed in the same units as X (Eq. 4). Seed parameters β and η varied from 2 to 23 and 0.08 to 37.9, respectively. The β values of kernel distributions were higher than of the peeled kernel distributions, while the η of the peeled kernel distributions was higher than of the kernel distributions. The η values of E distributions were the highest among the mechanical properties, while the η and β values of D distributions were the lowest among the mechanical parameters of seeds. Furthermore, the η values of the mechanical property distributions at moisture M_1 were the highest. The D distributions of seeds nearly approached the normal PDF because β was mostly between 2.6 and 3.7, and E_n, F_{max} and E distributions of seeds were negatively skewed (β>3.7) (Table 1), while only distributions of D and F_{max} of seeds at moisture M_2 were positively skewed (β<2.6). For example, in Fig. 3 distributions of D and E_n of the peeled kernel seed at moisture M_3 approached the normal distribution, while other distributions were negatively skewed Weibull PDF.

Effect of puncture conditions

Comparison of average values of the F_{max} and E_n of seeds for all probe diameters with different moisture contents showed that the kernel was firmer than the peeled kernel (Table 2). The F_{max} and E_n of the kernel at M_4 were 1.4 times higher than those of the peeled kernel. The F_{max} and E_n tended to decrease significantly as the seed moisture decreased; the differences were significant (Table 2). The effect of moisture content on the F_{max} of peeled kernel was higher than of kernel, as with the decrease of moisture content from M_1 to M_4, the F_{max} of kernel decreased 19 % and of peeled kernel 39 %. Table 2 shows that the seeds have a positive firmness–moisture coefficient because of the increase of F_{max} of seeds with the increase of the moisture content. The same results were reported by Bourne (*3*), Lustig and Bernstein (*10*), and Pal *et al.* (*21*) that the firmness–temperature coefficient varied from commodity to commodity, from cultivar to cultivar, and from year to year.

As it is shown in Table 2, the probe diameter had a greater effect on the F_{max} than on the moisture content. Regarding the kernel, increasing the probe diameter from 0.4 to 1.8 mm increased the mean F_{max} up to 8 times, while decreasing the moisture content from M_1 to M_4 decreased the mean F_{max} up to 1.2 times. The F_{max} values ranged from 1.50 N with moisture content of M_4 and probe diameter of 0.4 to 17.75 N with moisture content of M_1 and probe diameter of 1.8. These results were determined for peeled kernel too (increasing the probe diameter from 0.4 to 1.8 increased the F_{max} more than 10 times). After considering the energy, it was found that the effects of moisture and probe diameter on E_n were more highlighted than on F_{max}. When decreasing the moisture content from M_1 to M_4, the E_n decreased exponentially up to 3 times, while with the increase of the probe diameter from 0.4 to 1.8, the E_n increased polynomially more than 13 times. Under different puncture conditions, the E_n values ranged from 0.50 to $40.19\cdot10^{-3}$ J for the kernel and 0.51 to $22.87\cdot10^{-3}$ J for peeled kernel (Table 2) (similar ranges were shown for F_{max}).

The F–D curve had a different form depending on the loading velocity. As illustrated in Fig. 2a, the F–D curve shows an initial peak at loading velocity above 3.5 mm/min. Based on Hertz's theory, this may be due to the failure caused by excessive internal shear stress which can detach the skin and internal layer of the fruit. Analysis of variance (ANOVA) showed that the loading velocity had a significant effect on F_{max} and E_n for the two cultivars (p<0.01) (Table 3). In most tests, an increase in the loading velocity from 0.1 to 5.0 mm/min linearly increased the F_{max} slightly and E_n up to 1.5 times for the seeds. As it is shown in Table 3, most values of F_{max} and E_n were determined with the puncture probe of 1.8 mm in diameter and loading velocity of 5 mm/min, while the lowest values were determined with the probe of 0.4 mm in diameter and loading velocity of 0.1 mm/min.

There was a significant difference in the E calculated using different probes. As probe diameter increased, the E value increased (diameter was 0.8) at first and then decreased significantly (Table 2). The inconsistent results may be attributed to the fact that the fundamental assumptions such as elasticity, homogeneity, and a semi-infinite body were not met (*22*). For the semi-infinite body assumption, the diameter of the probe must be small compared to the diameter of the fruit. In the original work by Hertz, the ratio of the circle of pressure to the radius of the spherical body under load was considered less than 1/10 (*22*). Thus, a probe with diameter of 0.4 mm was the best selection for the almond seeds to determine the E value. Under these conditions the almond seeds can be considered to be semi-infinite bodies. Also, it must be accepted that the assumption of homogeneity for an almond seed is not true. However, one cannot speak of a completely true E for an almond seed. The

Table 2. Effect of moisture content and probe diameter on maximum rupture force (F_{max}), rupture energy (E_n) and elasticity modulus (E) of almond seeds

Sample	Probe diameter	M_1			M_2			M_3			M_4			Average		
	mm	F_{max}/N	E_n/10^{-3} J	E/MPa	F_{max}/N	E_n/10^{-3} J	E/MPa	F_{max}/N	E_n/10^{-3} J	E/MPa	F_{max}/N	E_n/10^{-3} J	E/MPa	F_{max}/N	E_n/10^{-3} J	E/MPa
kernel	0.4	2.15	1.33	18.00	2.11	1.01	16.21	1.76	0.99	13.88	1.50	0.50	10.43	1.88	0.96	13.50
	0.8	4.90	4.73	27.78	4.71	3.88	18.91	4.52	2.51	17.32	4.18	1.42	14.31	4.58	3.13	19.58
	1.2	9.23	8.14	20.30	8.53	6.91	18.31	8.00	6.00	14.90	7.39	4.06	8.54	8.31	6.28	15.51
	1.6	14.54	34.69	15.48	13.92	8.07	12.22	12.95	7.05	10.21	12.66	7.44	7.62	13.51	21.07	11.38
	1.8	17.75	40.19	12.28	16.10	10.02	11.32	14.01	9.33	7.31	13.62	9.01	5.35	15.37	14.39	9.06
	average	9.71^{b}	17.82^{c}	18.96^{c}	9.07^{a,b}	5.98$^{\mathbf{b}}$	15.39^{b}	8.24^{a,b}	5.18$^{\mathbf{b}}$	12.72^{a,b}	7.87^{a}	4.49^{a}	9.25^{a}	8.72	8.36	13.80
peeled kernel	0.4	2.00	1.05	13.55	1.31	1.00	9.00	0.75	0.65	3.16	0.58	0.51	7.84	0.64	0.74	5.50
	0.8	4.10	3.68	20.18	3.06	2.33	13.22	2.15	1.43	2.94	2.21	1.46	6.65	2.82	2.19	12.46
	1.2	8.13	6.58	10.45	7.15	5.18	10.02	4.61	3.64	2.64	5.42	3.16	6.71	6.32	4.64	6.60
	1.6	19.11	34.83	10.03	8.54	5.71	7.65	7.92	5.99	2.75	8.77	4.85	8.28	11.06	12.84	7.18
	1.8	22.87	39.348	13.19	10.60	6.69	1.55	10.77	6.88	1.58	10.84	5.86	6.53	13.77	14.69	5.71
	average	11.24^{b}	17.09^{b}	13.48^{c}	6.13^{a,b}	4.18^{a}	8.28^{a,b}	5.24^{a}	3.72^{a}	2.62$^{\mathbf{a}}$	5.56^{a}	3.17^{a}	7.20^{b}	7.05	7.04	7.90

In each row, average values with the same letter have no significant difference at the 1 % level.
Moisture on dry mass basis at different harvest times: M_1=24.97 %, M_2=18.11 %, M_3=9.98 % and M_4=2.77 %

Table 3. Effect of loading velocity and probe diameter on maximum rupture force (F_{max}) and rupture energy (E_n) of almond seeds

Sample	Probe diameter	Loading velocity/(mm/min)											
		0.1		0.75		1.25		2.5		5		Average	
	mm	F_{max}/N	E_n/10^{-3} J	F_{max}/N	E_n/10^{-3} J	F_{max}/N	E_n/10^{-3} J	F_{max}/N	E_n/10^{-3} J	F_{max}/N	E_n/10^{-3} J	F_{max}/N	E_n/10^{-3} J
kernel	0.4	2.10	0.71	2.12	0.99	2.15	1.13	2.16	1.34	2.20	1.52	2.15	1.14
	0.8	6.46	2.25	7.57	3.81	4.90	4.48	5.98	5.02	7.20	6.09	6.42	4.33
	1.2	8.88	3.63	9.00	5.01	9.23	7.53	11.43	10.24	11.67	11.15	10.04	7.51
	1.6	13.62	24.78	14.00	27.93	14.55	32.05	14.84	30.65	14.09	51.30	14.22	33.34
	1.8	15.91	26.38	15.68	41.05	17.76	39.99	18.94	42.78	20.06	50.74	17.67	40.19
	average	9.40^{c}	11.55^{d}	9.67^{c}	15.76^{c}	9.72^{b}	17.04^{b,c}	10.67^{a,b}	18.01^{b}	11.04^{a}	24.16^{a}	10.10	17.30
peeled kernel	0.4	1.87	0.65	2.03	0.73	2.10	0.82	2.12	0.94	2.15	1.05	2.05	0.84
	0.8	5.00	2.41	5.03	2.83	4.10	3.01	4.38	4.26	5.14	4.96	4.73	3.49
	1.2	6.13	2.98	7.12	4.07	8.13	7.30	8.18	7.23	8.83	8.819	7.68	6.08
	1.6	13.02	24.44	15.22	26.09	19.11	33.99	19.26	35.51	24.10	34.98	18.14	31.00
	1.8	15.92	34.11	17.83	35.47	22.87	37.90	18.99	40.76	23.72	43.49	19.87	38.34
	average	8.39^{c}	12.92^{c}	9.45^{b,c}	13.84^{c}	11.26^{b}	16.60^{b}	10.59^{a,b}	17.74^{a,b}	12.79^{a}	18.66$^{\mathbf{a}}$	10.50	15.95

In each row, average values with the same letter have no significant difference at the 1 % level modulus calculated with Eq. 1 can, at best, be termed the apparent *E*. The *E* of the seeds decreased with decreasing seed moisture significantly (Table 2 and Fig. 4). The results showed that there was a significant difference between the *E* of the seeds at all moisture contents ($p<0.01$). The kernel *E* was more than the peeled kernel *E*. For example, when using the probe with diameter of 0.8 mm, the mean *E* value of kernel was 1.57 times higher than of peeled kernel.

Determination of critical puncture conditions

The relationship between the E_n and the puncture conditions was considered separately (Tables 2 and 3). Some researchers have reported that the E_n related to different puncture conditions linearly (*8,9,11,16*), while we found from the experiments that the E_n related to moisture content exponentially, to loading velocity linearly and to probe diameter squarely (Eqs. 7–9). These relationships were determined by using the interpolation with MATLAB v. 7.12 software. After comparison of the

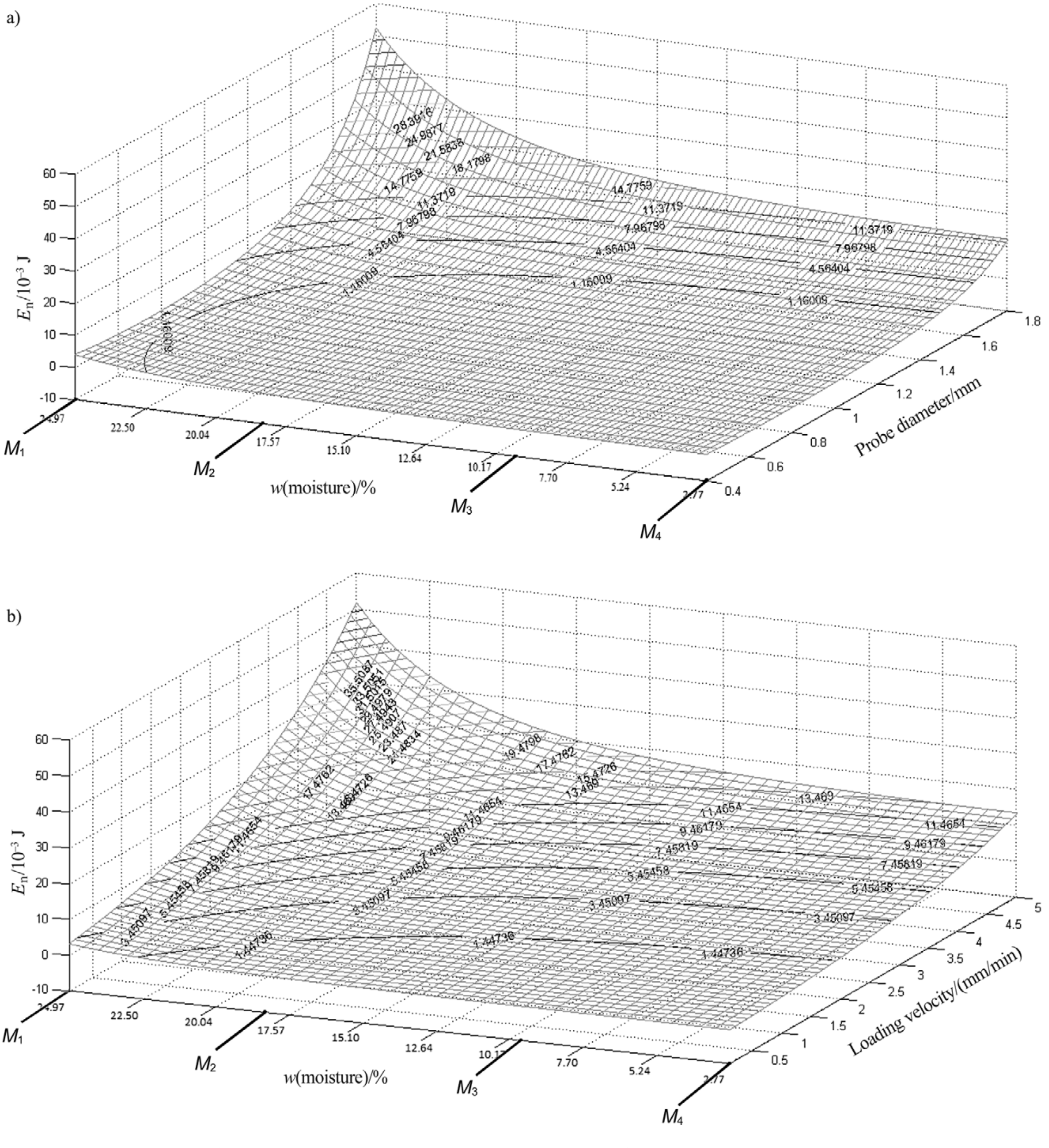

Fig. 4. 3D contour graph of the rupture energy (E_n) *vs.*: a) moisture content of almond seeds and probe diameter, and b) moisture content of almond seeds and loading velocity. Moisture on dry mass basis at different harvest times: M_1=24.97 %, M_2=18.11 %, M_3=9.98 % and M_4=2.77 %

models with the models used in other research, ours were more accurate, for example the accuracy of the models of Altuntas and Yildiz (*11*) in the estimation of E_n from moisture content was not very precise (R=0.86):

$$X_1=E_n=4\exp(-0.39M) \qquad /7/$$

$$X_2=E_n=26.74d^2-29.80d+9.39 \qquad /8/$$

$$X_3=E_n=0.48V+3 \qquad /9/$$

where M, d and V are the moisture content, probe diameter, and loading velocity, respectively. High accuracies between the E_n estimated from these three equations (Eqs. 7–9) and the E_n measured in the experiments (0.92, 0.97 and 0.97, respectively) showed good predictive power using a mixed dataset of these puncture conditions in a new model. The final modified cubic model was described by the RSM from X_1, X_2 and X_3 using Eq. 10:

$$E_n=13.82-18.81X_1-3.77X_2+8.77X_3+ \\ +1.12X_1X_3+1.42X_2X_3-0.85X_3^2 \qquad /10/$$

This equation was selected among different considered models because of the highest accuracy. This model checked hierarchically, *i.e.* (any higher order terms of the model could appear only in the presence of their parent (lower order) terms). The terms X_1X_3 and X_2X_3 are significant, so the model should also include the parent terms of X_1, X_2 and X_3 to have the hierarchical model.

The 3D-contour graph of E_n can be shown first *vs.* moisture content and probe diameter and then *vs.* the moisture content and loading velocity, while the other factor remained at zero level constantly (Fig. 4). The surface response plot is an *n*-dimensional surface in the (*n*+1)-dimensional space. Usually, a two-dimensional representation of a three-dimensional plot can be drawn. Thus, if there are three or more variables, the plot visualisation is possible only if one or more variables are set to a constant value (*12*).

The final model (Eq. 10) was selected because the high R^2 (0.94) and low RMSE (3.35) are in reasonable agreement with the adjusted R^2 of 0.93 based on the RSM, indicating the model is significant (Fig. 5). This fitness function (Eq. 10) was then used to measure the fitness value for each chromosome in the GA procedure. The adjustable parameters in GA are the size of the population, mutation rate, number of generations (*i.e.* iterations) *etc.*, which were employed as an individual or a population of chromosomes (20), initial population size (200), crossover probability (0.85), mutation rate (0.15), and the number of iterations (2000). The optimal values (in fact are the critical values for a peeling machine) of seed moisture content, probe diameter, and loading velocity (determined using GA) were 18.11 % on dry mass basis determined 3 hours after harvesting, 0.79 mm, and 0.15 mm/min, respectively, and the critical energy or minimum energy for rupturing calculated using these three conditions was $1.97\cdot10^{-3}$ J. After considering the E_n in Tables 2 and 3, the experimental results were in agreement with our model. These critical puncture conditions for the peeling machine are necessary to avoid breaking the kernels during the peeling.

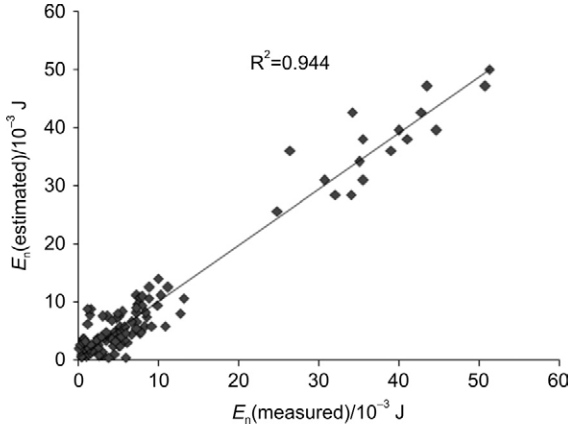

Fig. 5. Comparison of the measured rupture energy and the estimated rupture energy using the final model

For comparison of the calculated critical conditions with the experimental results, some seeds were soaked again in distilled water according to the reported method to obtain the critical moisture content, then critical loading velocity (0.15) and probe diameter (the probe diameter of 0.8 mm was used because of the limitations of puncture apparatus) of the puncture apparatus were adjusted. The average values of the final E_n for almond kernel and peeled kernel calculated using *F–D* curve areas were determined to be 2.68 and $2.21\cdot10^{-3}$ J, respectively, which is nearly in agreement with our results.

It can be concluded that coupled RSM and GA could produce a mathematical model for determination of the E_n depending on the puncturing conditions, as well as the critical values of these conditions. Indeed, coupled RSM and GA is a superior, cheaper and faster optimisation technique for finding appropriate and critical puncture conditions for the processing machines when compared to the experimental methods. Therefore, the integrated RSM and GA approach is an appropriate research method which can reduce the computational cost and help the researchers and factories.

Conclusion

The moisture content, probe diameter, and loading velocity (puncture conditions) had significant effects on F_{max}, E_n, D and E (mechanical properties). As each puncture condition increased, both F_{max} and E_n increased. Their distributions nearly approached the normal PDF for D and were negatively skewed for E_n, F_{max} and E distributions, only the distribution of D and F_{max} of seeds with moisture content of M_2 was positively skewed. The distributions show that the mechanical properties can be accurately modelled. Therefore, coupled RSM and GA approach used for the determination of the minimum E_n ($1.97\cdot10^{-3}$ J) and critical values of moisture content, probe diameter, and loading velocity (18.11 % on dry mass basis, 0.79 mm and 0.15 mm/min, respectively) showed good agreement with experimental results (2.68 and 2.21 $\cdot10^{-3}$ J for almond kernel and peeled kernel, respectively), which indicates that this approach can be a useful tool to find the critical puncture conditions for the determination of appropriate conditions of peeling machine to reach the optimal efficiency of peeling the almond kernel, which is considered as a very tedious and time-consuming task.

Nomenclature

F	force (N)	RSM	response surface methodology
D	deformation (mm)	M_1	moisture at initial hour of harvesting
E	elasticity modulus (Pa)	M_2	moisture three hours after harvesting
$F_{\max}$	rupture force (N)	M_3	moisture six hours after harvesting
E_n	rupture energy (10^{-3} J)	M_4	moisture nine hours after harvesting
B	shape parameter	PDF	probability density function
η	scale parameter	CDF	cumulative density function
γ	location parameter	RMSE	root mean square error
GA	genetic algorithm		

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