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TIP CUTTING, OSMOTIC PRETREATMENT AND TWO-STAGE LOW-TEMPERATURE HELIO-CONVECTIVE DRYING FOR WHOLE-KERNEL SHELL OPENING OF PUMPKIN (CUCURBITA MAXIMA DUCH.) SEEDS: DEVICE DESIGN AND RESPONSE-SURFACE OPTIMIZATION

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Abstract. Pumpkin seed kernels are rich in protein (≈30 g/100 g), unsaturated lipids and minerals, but conventional processing relies on drying at 50–80 °C, roasting at 160–180 °C and mechanical cracking of the whole seed, which breaks the kernel and degrades heat-sensitive compounds.

Objective. To develop and optimize a low-temperature route in which the seed shell is opened from the inside: the pointed tip of the seed is cut off, the seed is soaked in a 10 % NaCl or sucrose solution, and it is dried in two helio-convective stages at 38–40 °C.

Methods. Seeds of the cultivar ‘Ispanka-73’ were treated at 30–50 °C with NaCl and sucrose solutions of 5–20 % in full 5 × 4 factorial designs (100 seeds per run). The second drying stage was studied at 30–50 °C. The data were analysed by two-way ANOVA, Tukey’s test, second-order regression and the Box–Wilson procedure (2^2 design with centre point, face-centred composite design, canonical analysis). A drum-type tip-cutting device was designed for mechanizing the cutting step.

Results. Temperature and concentration had significant effects on the shell opening degree (NaCl: $F_T = 24.00$, $F_C = 8.91$; sucrose: $F_T = 40.47$, $F_C = 38.91$; $p \leq 0.002$). Opening reached a plateau of 91.6 % (NaCl) and 93 % (sucrose) at 40 °C and 10 %; raising the concentration from 10 to 20 % gave no significant gain. Second-order models described the data with $R^2 = 0.917$ and 0.933 (full designs) and 0.990 and 0.978 (face-centred designs). The best second-stage drying regime was 40 °C to 5–6 % residual moisture (91.6 %). In production trials (19.2 t/year), whole-kernel yield rose from 50.0 % to 57.5 %, broken kernels fell from 8 % to 3 %, and specific electricity use fell from 0.620 to 0.312 kWh/kg. The designed drum cutter (D = 200 mm, 44 pockets, 30 rpm) has a calculated capacity of ≈18.7 seeds/s at 0.13 kW.

Keywords: pumpkin seed; shell opening; tip cutting; osmotic pretreatment; helio-convective drying; response surface methodology; Box–Wilson method

1. Introduction

Pumpkin (Cucurbita spp.) seeds are a valuable by-product of pumpkin processing. Dried kernels contain about 30 g protein, 49 g fat, 592 mg magnesium, 1233 mg phosphorus and 7.8 mg zinc per 100 g [1], and their oil is dominated by linoleic and oleic acids [2,3]. These properties make the

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kernels attractive for functional foods and nutraceuticals [3,4]. Uzbekistan grows large-fruited pumpkin cultivars such as ‘Ispanka-73’, but most of the seed is either sold unshelled or cracked by hand.

The seed coat (shell) is a lignocellulosic layer 0.3–0.6 mm thick that encloses the kernel tightly. Its rupture force and the energy it absorbs depend strongly on moisture content [5–7]. When the shell is cracked by impact or compression, the kernel often splits in two and sticks to the shell. This lowers whole-kernel yield and raises losses. Existing processes also use high temperatures. Pumpkin seed is commonly dried at 50–80 °C [8,9], and in one patented flour process seeds are dried at 60–65 °C and roasted at 160–180 °C after crushing with the shell [10]. Such temperatures accelerate the degradation of tocopherols, carotenoids and other heat-sensitive compounds.

Two ideas from food engineering suggest a gentler route. First, osmotic treatment with salt or sugar solutions changes the water distribution in plant tissue and enhances mass transfer [11,12]. Second, a pressure difference between the inside and outside of a closed capsule can open it without mechanical impact, as in instant controlled pressure drop processes [13]. For a seed, internal pressure builds up only if the shell has an opening for the solution to enter and if the seed is heated after soaking. Cutting off the pointed tip of the seed provides this opening.

Solar and helio-convective dryers reduce energy consumption in agricultural drying [14,15], and thin-layer drying of hull-less pumpkin seed has been modelled [8,21]. However, we found no study that combines tip cutting, osmotic loading and low-temperature drying to open pumpkin seed shells, nor a statistical optimization of such a route. The process was protected by Uzbek patent UZ IAP 07182 [16]; a helio-convective implementation was described in our earlier work [17].

The aims of this study were: (i) to quantify the effects of treatment temperature and solution type and concentration on the shell opening degree; (ii) to find the optimal regime by ANOVA, regression and the Box–Wilson method; (iii) to determine the second-stage drying regime; (iv) to design a device that mechanizes tip cutting; and (v) to verify the process under production conditions.

2. Materials and methods

2.1. Raw material

Seeds of the large-fruited pumpkin cultivar ‘Ispanka-73’ (Cucurbita maxima Duch.) grown in Bukhara region, Uzbekistan, were used. The cultivar is late-ripening (117–130 days), with fruit mass 3.3–4.4 kg. Seeds were separated from the pulp, cleared of fibrous tissue and empty seeds, washed in water at 25–28 °C and sorted by size. Mean seed dimensions were about 19.9 × 11.3 × 3.2 mm (length × width × thickness). Moisture content was determined by the air-oven method at 105 °C to constant mass (GOST 10856-96).

2.2. Process route and helio-convective drying

The process route is shown in Fig. 1. All thermal steps were carried out at 38–40 °C in a helio-convective dryer, where air heated in a solar collector was circulated through the drying chamber by a fan and the chamber temperature was held at the set point. In the first stage, washed seeds were dried

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to 12–14 % residual moisture. After tip cutting and osmotic treatment, the semi-finished product was dried in the second stage to 5–6 %. The shells were then separated, and the product (opened seeds or kernels) was vacuum-packed to exclude moisture and oxygen.

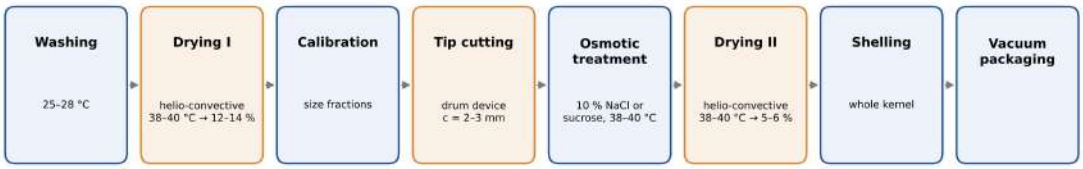


Fig. 1. Process route for whole-kernel shell opening of pumpkin seeds. Orange boxes: steps studied in this paper.

To select the second-stage regime, five combinations of air temperature (30–50 °C), air velocity (1.35–3.75 m/s) and final moisture (3–8 %) were tested (Table 2). In this series the three variables were changed together, so it was analysed as a single-factor series in temperature.

2.3. Osmotic treatment

Tips (2–3 mm) were cut off the seeds before treatment. In the experiments reported here this was done with a manual blade fixture with a fixed stop; the device in Section 2.4 was designed to mechanize this step. The cut seeds were treated with aqueous NaCl or sucrose solutions of 5, 10, 15 and 20 % (w/w) at 30, 35, 40, 45 and 50 °C, then heated and dried. The ideal osmotic pressure of the solutions was estimated from the van ’t Hoff equation:

$$\pi = i\, c\, R\, T \qquad (1)$$

where i is the van ’t Hoff factor (2 for NaCl, 1 for sucrose), c the molar concentration (mol/m³), R = 8.314 J/(mol·K) and T the absolute temperature. For 10 % solutions at 40 °C, $\pi \approx 9.5$ MPa for NaCl (c = 1.83 mol/L) and ≈ 0.8 MPa for sucrose (c = 0.30 mol/L). These are ideal-solution values; activity corrections lower the value for NaCl.

2.4. Design of the drum-type tip-cutting device

The device (Fig. 2) consists of a vibrating hopper (1, 2), a brush (3) that leaves one correctly oriented seed per pocket, a drum (4) with 44 axial pockets on its circumference, a fixed knife (5) set parallel to the drum side face, a tip chute (6), an ejector (7), a container for cut seeds (8) and a gear motor with frequency control (9). A seed lies in a pocket with its blunt end against an adjustable stop, so its pointed tip projects beyond the drum face by the cut length c. As the drum rotates, the tip enters the knife edge and is sheared between the knife and a hardened side ring (scissor principle). The main design data are given in Table 1.

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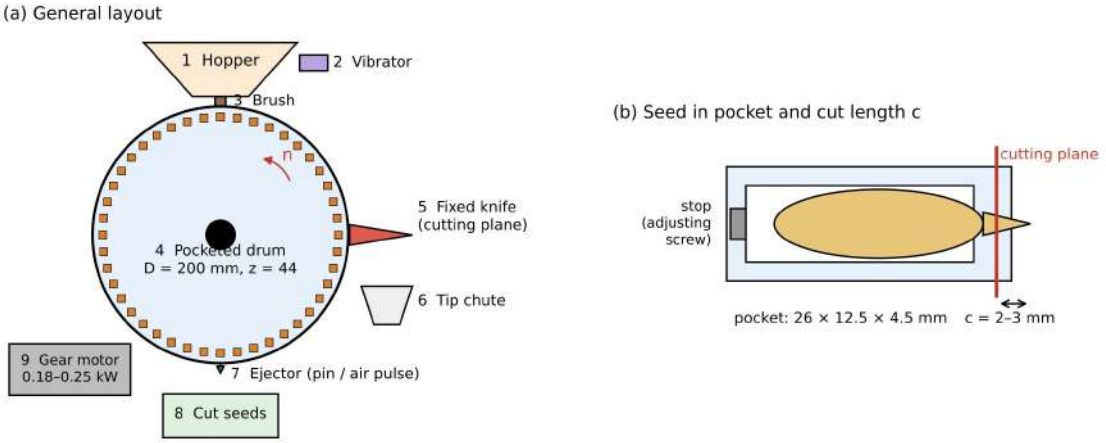


Fig. 2. Drum-type tip-cutting device: (a) general layout; (b) position of the seed in the pocket and cut length c.

Table 1. Main design parameters of the tip-cutting device

Parameter	**Value**
Drum diameter D / width	200 mm / 60 mm
Number of pockets z / pitch	44 / 14.3 mm
Pocket size (axial × tangential × radial)	26 × 12.5 × 4.5 mm (±0.1 mm)
Cut length c (adjustable stop)	2–3 mm (screw pitch 0.5 mm)
Knife: wedge angle / clearance angle / gap to ring	20–25° / 8–10° / 0.05–0.10 mm
Knife and ring material	tool steel X12MF (56–60 HRC) or 40X13; ring ≥ 45 HRC
Drum speed n	15–50 rpm (design 30 rpm)
Shaft diameter / bearings	25 mm / 6205-2RS (2 pcs)
Gear motor	0.18–0.25 kW, ratio ≈ 45–50, frequency converter

The capacity of the device, the circumferential speed and the ratio of centrifugal to gravitational acceleration were calculated as:

$$Q=\frac{z\,n\,\varphi}{60},\qquad v=\frac{\pi D n}{60},\qquad K=\frac{\omega^2 R}{g},\quad \omega=\frac{\pi n}{30} \qquad (2)$$

where φ is the pocket filling coefficient (taken as 0.85) and R = D/2. The drive power and shaft diameter were found from

$$P=\frac{T_c\,\omega}{\eta},\qquad d\geq\sqrt[3]{\frac{16\,T_c}{\pi\,[\tau]}} \qquad (3)$$

with design torque T_c = 25 N·m, drive efficiency η = 0.6 and allowable shear stress [τ] = 25 MPa.

2.5. Experimental design and statistical analysis

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The response was the shell opening degree, $Y = n_o/N \cdot 100$ %, where n_o is the number of seeds with an open shell and N = 100 is the number of seeds per run. Full 5 × 4 factorial designs (T = 30–50 °C; C = 5–20 %) were run separately for NaCl and sucrose. The binomial standard error of Y at p = 0.92 and N = 100 is $\sqrt{(p(1-p)/N)} = 2.7$ percentage points.

Because each combination was run once, effects were tested by two-way ANOVA without replication, with the residual mean square as error. Concentration means were compared by Tukey's HSD test ($\alpha = 0.05$). Second-order polynomial models were fitted by least squares:

$$\hat{Y}=b_0+b_1x_1+b_2x_2+b_{12}x_1x_2+b_{11}x_1^2+b_{22}x_2^2 \qquad (4)$$

For the full designs, $x_1 = (T - 40)/10$ and $x_2 = (C - 12.5)/7.5$. Model quality was assessed by R^2, adjusted R^2, Fisher's F, RMSE, MAPE and leave-one-out cross-validation (Q^2). Coefficients were tested by Student's t ($\alpha = 0.05$), and residual normality by the Shapiro–Wilk test.

The Box–Wilson procedure [18–20] was applied in three steps: (1) a 2^2 design (T = 35/45 °C; C = 5/15 %) with a centre point (40 °C; 10 %) to fit a first-order model and test for curvature; (2) a face-centred composite design ($3^2 = 9$ runs; $x_1 = (T - 40)/5$, $x_2 = (C - 10)/5$) to fit a second-order model; (3) canonical analysis to locate and classify the stationary point. All calculations were done in Python 3 (NumPy, SciPy).

2.6. Production trial

The process was tested in the fruit and seed processing shop of "Greenic" LLC (Uzbekistan) from 20 November 2024 to 20 November 2025, in one shift with 19,200 kg of raw seed per year. It was compared with the conventional process (electric dryer at 55–60 °C and manual cracking).

3. Results

3.1. Second-stage drying regime

The shell opening degree depended strongly on the second-stage drying regime (Table 2, Fig. 3). At 30 °C and 3–4 % final moisture only 58 % of the shells opened. The maximum, 91.6 %, was reached at 40 °C, 5–6 % moisture and 2.55 m/s air velocity. At 45–50 °C the opening degree (89–91 %) did not increase further. A quadratic fit in temperature gave $Y = -0.1663T^2 + 14.723T - 231.8$ ($R^2 = 0.933$).

Table 2. Effect of the second-stage drying regime on the shell opening degree

Final moisture, %	Air temperature, °C	Air velocity, m/s	Shell opening degree Y, %
3–4	30	1.35	58.0
4–5	35	1.70	84.0
5–6	40	2.55	91.6
6–7	45	3.40	89.0
7–8	50	3.75	91.0

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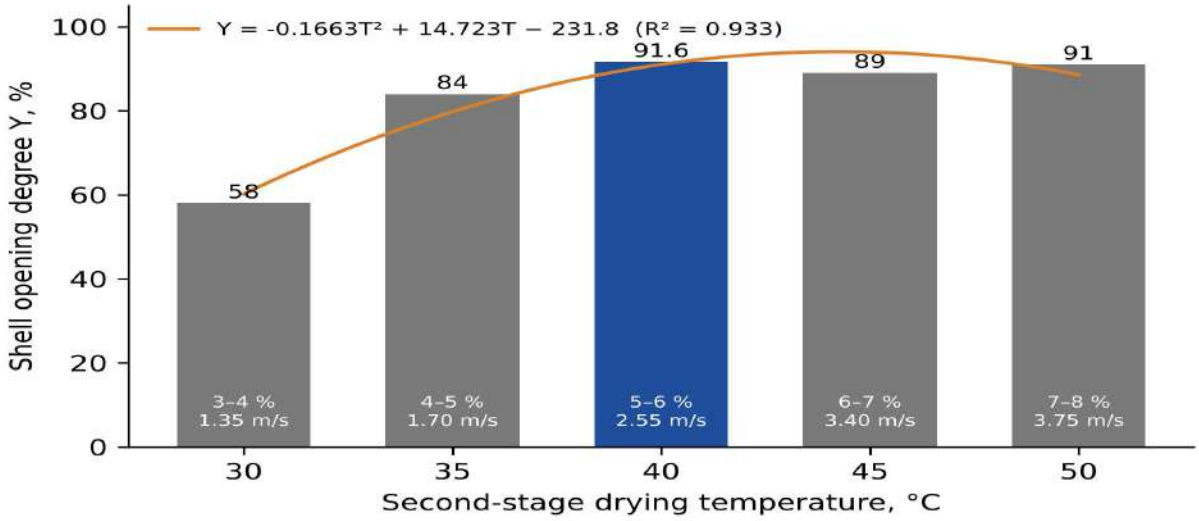


Fig. 3. Effect of the second-stage drying regime on the shell opening degree (labels in bars: final moisture and air velocity).

3.2. Effects of temperature and solution concentration

The opening degree rose with temperature and concentration in both solutions and levelled off at 40 °C and 10 % (Fig. 4). With NaCl it reached 91.5–91.6 % at T ≥ 40 °C and C ≥ 10 %; with sucrose it reached 92–93 %. At 30 °C the values were 64–82 %, and with 5 % solutions they stayed at 78–82 % even at 40 °C.

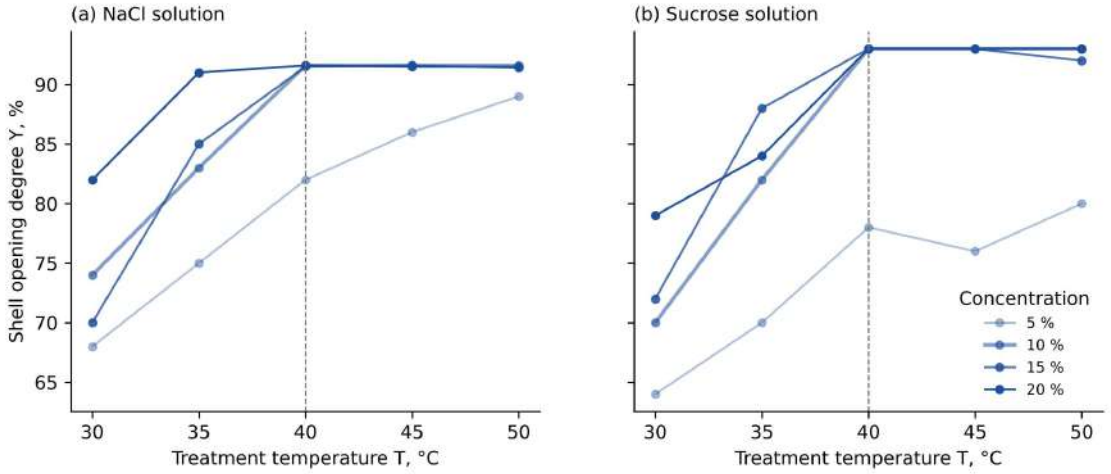


Fig. 4. Shell opening degree versus treatment temperature at four solution concentrations: (a) NaCl; (b) sucrose (100 seeds per point).

Both factors were significant in both solutions (Table 3). Temperature explained most of the variance with NaCl (η^2 = 0.71). With sucrose, temperature and concentration contributed about equally (η^2 = 0.56 and 0.40). Tukey's HSD for concentration means was 5.6 (NaCl) and 4.7 (sucrose) percentage points. Increasing the concentration from 5 to 10 % raised the mean opening degree

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significantly (NaCl: 80.0 → 86.4 %; sucrose: 73.6 → 86.2 %). A further increase from 10 to 20 % did not (+3.2 and +2.2 points). Thus 10 % is the lowest concentration that gives the full effect.

Table 3. Two-way ANOVA of the shell opening degree (without replication, α = 0.05)

Solution	Source	SS	df	MS	F	$F_{0.05}$	p	η^2
NaCl	Temperature	848.95	4	212.24	24.00	3.26	< 0.001	0.712
	Concentration	236.49	3	78.83	8.91	3.49	0.002	0.198
	Residual	106.11	12	8.84				
Sucrose	Temperature	1007.70	4	251.93	40.47	3.26	< 0.001	0.557
	Concentration	726.55	3	242.18	38.91	3.49	< 0.001	0.402
	Residual	74.70	12	6.23				

Pearson correlation of Y with temperature was r = 0.759 (p < 0.001) for NaCl and r = 0.658 (p = 0.002) for sucrose. Correlation with concentration was significant for sucrose (r = 0.538, p = 0.014) but not for NaCl (r = 0.407, p = 0.075), because with NaCl the response saturated at 10 %. The responses in the two solutions were strongly correlated (r = 0.92), which indicates a common opening mechanism.

3.3. Regression models

The second-order models fitted to the full designs are summarized in Table 4. In natural variables (T in °C, C in %):

$$Y_{NaCl} = -80.20 + 6.623T + 2.765C - 0.0380TC - 0.0665T^2 - 0.0274C^2 \quad (5)$$

$$Y_{suc} = -99.11 + 7.074T + 4.106C - 0.0060TC - 0.0764T^2 - 0.1180C^2 \quad (6)$$

Table 4. Coefficients of the second-order models (coded variables) and model statistics, n = 20

Term	NaCl: b	p	Sucrose: b	p
b_0	89.63	< 0.001	91.46	< 0.001
b_1 (T)	8.29	< 0.001	8.85	< 0.001
b_2 (C)	4.22	< 0.001	6.87	< 0.001
b_{12}	−2.85	0.024	−0.45	0.724
b_{11}	−6.65	< 0.001	−7.64	< 0.001
b_{22}	−1.54	0.268	−6.64	< 0.001
R^2 / adjusted R^2	0.917 / 0.888		0.933 / 0.909	
F ($F_{0.05}$ = 2.96)	31.06	< 0.001	38.82	< 0.001
RMSE / MAPE, %	2.65 / 2.06		2.95 / 2.42	
Q^2 (leave-one-out)	0.825		0.844	

The negative quadratic terms show that both responses have a maximum inside the studied region. The RMSE values (2.65–2.95 %) are close to the binomial standard error of a single run (2.7 points), so the models fit to within the experimental precision (Fig. 6).

3.4. Box–Wilson optimization

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In the first step, the centre point (40 °C; 10 %) gave a response 7.2 (NaCl) and 11.25 (sucrose) points higher than the mean of the four factorial points (Table 5). Curvature was significant for sucrose ($p = 0.002$) and borderline for NaCl ($p = 0.051$). The optimum therefore lies inside the region, and a second-order design was used instead of a steepest-ascent search.

Table 5. Box–Wilson procedure: first-order step and second-order (face-centred composite) models

Statistic	**NaCl**	**Sucrose**
First-order model b_0; b_1; b_2; b_{12}	84.40; 4.40; 3.90; −1.10	81.75; 2.75; 8.75; −0.25
Curvature at centre, points (F; p)	7.20 (4.69; 0.051)	11.25 (16.27; 0.002)
Second-order model R^2 / adjusted R^2	0.990 / 0.974	0.978 / 0.943
F ($F_{0.05} = 9.01$); p	60.18; 0.003	27.29; 0.011
RMSE / MAPE, %	0.94 / 0.52	2.12 / 1.28
Eigenvalues λ_1; λ_2	−3.89; −2.66	−6.34; −4.33
Stationary point (T; C)	43.2 °C; 12.5 %	42.0 °C; 13.2 %
Predicted Y at stationary point	93.2 %	95.7 %
Predicted Y at 40 °C, 10 % (± 95 % prediction interval)	90.7 ± 3.7 %	92.2 ± 8.4 %
Observed Y at 40 °C, 10 %	91.6 %	93.0 %

The second-order models of the face-centred designs were:

$$Y_{NaCl} = 90.73 + 4.37x_1 + 4.18x_2 - 1.10x_1x_2 - 3.00x_1^2 - 3.55x_2^2 \quad (7)$$

$$Y_{suc} = 92.22 + 3.67x_1 + 8.33x_2 - 0.25x_1x_2 - 4.33x_1^2 - 6.33x_2^2 \quad (8)$$

Both eigenvalues were negative in both models, so the stationary points are maxima (Fig. 5). They lie at 42–43 °C and 12.5–13.2 %. The observed responses in this zone, however, were no higher than at 40 °C and 10 % (for NaCl, 91.6 % at both 40 °C/10 % and 45 °C/15 %). The predicted gain at the stationary point is within the prediction interval. We therefore chose the lowest-temperature, lowest-concentration point of the plateau, 40 °C and 10 %, which saves energy and reagent and keeps the temperature within the 38–40 °C limit of the process.

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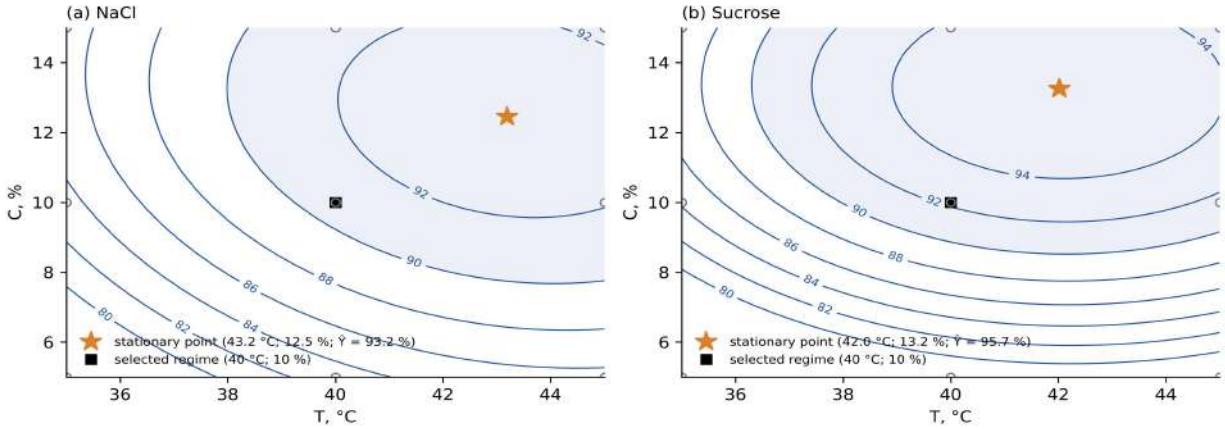


Fig. 5. Contour plots of the face-centred composite models with stationary points and the selected regime: (a) NaCl; (b) sucrose. Shaded: $\hat{Y} \geq 90$ %.

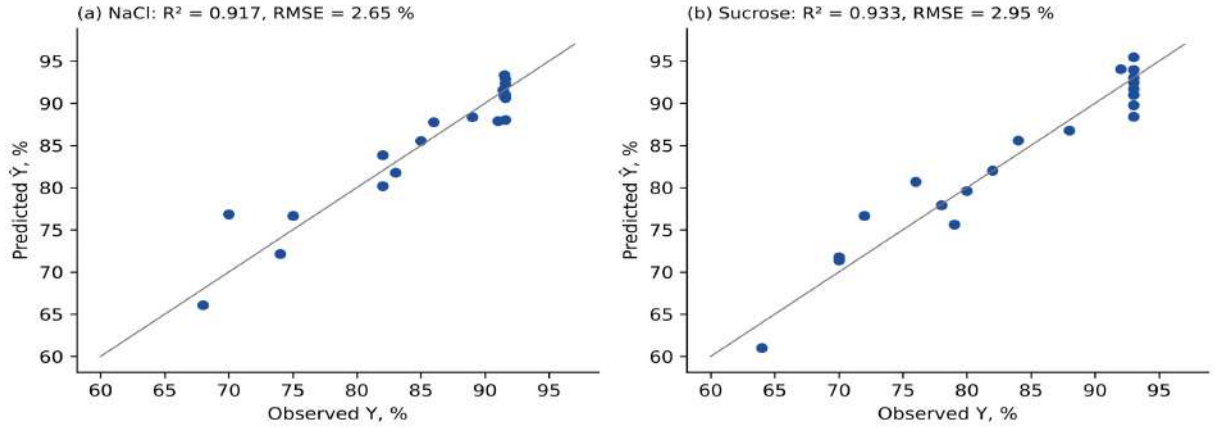


Fig. 6. Predicted versus observed shell opening degree (full 5 × 4 designs): (a) NaCl; (b) sucrose.

3.5. Calculated performance of the tip-cutting device

By Eq. (2), at the design speed of 30 rpm the circumferential speed is 0.31 m/s and the capacity is $Q = 44 \cdot 30 \cdot 0.85 / 60 \approx 18.7$ seeds/s (9.4–31.2 seeds/s over 15–50 rpm). The centrifugal ratio is K = 0.10 at 30 rpm and 0.28 at 50 rpm, well below 1 (K = 1 at 94.6 rpm). Seeds therefore stay in the pockets through the upper half of the rotation. By Eq. (3), the drive power is $P = 25 \cdot 3.14 / 0.6 \approx 131$ W, so a 0.18–0.25 kW gear motor is sufficient, and the minimum shaft diameter is 17.2 mm (25 mm chosen). With unit seed masses of 0.20–0.29 g reported for pumpkin and squash seeds [5,6], 18.7 seeds/s corresponds to roughly 13–20 kg/h. This value is an estimate and must be confirmed with the mass of ‘Ispanka-73’ seeds.

4. Discussion

Opening mechanism. The results support an internal-pressure mechanism. Cutting the tip opens a path into the seed. During osmotic treatment the solution enters the space between the shell and the kernel and the shell itself. On heating, water vapour forms inside the shell faster than it can escape

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through the small opening, and the pressure difference produces a tensile hoop stress in the shell, $\sigma = \Delta p \cdot r/t$. Because the stress is generated from inside, the shell splits along its natural seam instead of being crushed, and the kernel does not stick to it. The strong correlation between the NaCl and sucrose responses ($r = 0.92$) indicates that the type of solute matters less than the presence of solution under the shell. NaCl reached the plateau at lower concentration, which is consistent with its higher osmotic pressure (≈9.5 versus 0.8 MPa).

Role of temperature. Below 35 °C the vapour pressure of water (5.6 kPa at 35 °C versus 7.4 kPa at 40 °C) is too low to open most shells, which explains the 58–84 % values. Above 40 °C no further gain was observed, while the rate of thermal degradation keeps rising. For an activation energy of 60–100 kJ/mol, the Arrhenius equation predicts degradation rates 3.6–8.6 times higher at 57.5 °C (conventional drying) than at 39 °C. This is a calculated estimate; direct measurement of tocopherols and carotenoids in the kernels is planned.

Comparison with other methods. Conventional cracking breaks the kernel because the shell's rupture force (tens of newtons, decreasing with moisture [5–7]) has to be applied from outside, through the kernel. Roasting-based processes [10] add a step at 160–180 °C. In the proposed route the highest temperature is 40 °C, and the energy for drying comes partly from the sun [14,15], which explains the halving of electricity use. The helio-convective drying regime found here (40 °C) is lower than the 50–80 °C range used for pumpkin seed and slices [8,9].

Limitations. Each design point was run once with 100 seeds, so the residual mean square, not pure error, was used to test effects; replicated runs would allow a lack-of-fit test. In the drying series, temperature, air velocity and final moisture were varied together, so their separate effects cannot be distinguished. The drum cutter is presented at the design stage; its capacity and cutting quality are calculated values that must be confirmed experimentally. Nutrient retention was estimated, not measured.

5. Conclusions

Cutting 2–3 mm off the seed tip, treating with 10 % NaCl or sucrose solution and drying in two helio-convective stages at 38–40 °C opens 90–93 % of pumpkin seed shells without roasting.

Treatment temperature and solution concentration both have significant effects ($p \leq 0.002$). Concentrations above 10 % give no significant gain (Tukey's test).

Second-order models describe the process with $R^2 = 0.917–0.990$ and errors at the level of the experimental precision. The Box–Wilson procedure places the maximum at 42–43 °C, but the response plateau begins at 40 °C and 10 %, which was selected as the optimal regime.

The best second-stage drying regime is 40 °C to 5–6 % residual moisture (91.6 % opening).

A drum-type device with 44 pockets was designed for tip cutting; its calculated capacity is ≈18.7 seeds/s at 30 rpm with a drive power of about 0.13 kW.

In production, the process raised whole-kernel yield from 50.0 to 57.5 %, cut broken kernels from 8 to 3 %, and halved specific electricity use.

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