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Physical parameters kinetics during the drying process of quarters and halves cut tomatoes

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Abstract. Tomato drying is a time-consuming industrial process. Moreover, the prolonged use of high temperatures decreases the quality of tomatoes and increases the environmental footprint of the process. In most cases, drying is performed on halved tomatoes. Alternatively, the use of quarter tomatoes could guarantee a drying times reduction without compromising the final product quality. This work aimed at modelling changes in physical characteristics of half and quarter tomatoes. The drying tests were conducted at 50 and 60 °C. The kinetics of weight loss, colour change, and volume reduction were determined. Colour change was monitored through image analysis, while volume reduction using RGB-D reconstructions. Based on the results, an increase in the drying temperature and the use of quartered tomatoes allow a significant reduction in drying times. The loss of water kinetic allowed the determination of critical moisture. Between initial and critical moisture, loss of water occurred at constant rate (zero-order kinetic), while after that the rate decreased exponentially (first-order kinetic). The colour kinetics showed an initial constant rate followed by a linear increase for brown pixels. The variation of red pixels did not have a clear trend. Increasing the temperature there was no significant reduction in colour quality while quarter tomatoes showed a greater loss of redness than halved tomatoes. Furthermore, the temperature increase does not affect the volume reduction of the tomatoes. Increasing the temperature and the use of quartered tomatoes are simple solutions to reduce drying times. However, quartered tomatoes are less visually appreciable than halved tomatoes.

Key words: modelling, artificial vision, sustainability, food quality, process optimization.

INTRODUCTION

Tomato drying is a widely used process in the food industry, allowing to increase the shelf life of the products by removing water up to a threshold that inhibits microbial activity (Abano et al., 2011). Other benefits are related to a reduction in the volume of the material, guaranteeing lower transport costs, and improving handling Lewicki, 2006; (Kumar et al., 2022). The drying process could be conducted using various drying techniques. However, the most widespread in the food sector is hot-air drying in dryers. Tomatoes exposed to heat treatment are subject to the progressive loss of water contained in their tissues causing irreversible repercussions on the structural, chemical, and physical characteristics of the product (Cernîşev, 2010).

The loss of water during dehydration causes the progressive loss of the shape and structure of the tomato. Excessive volumetric shrinkage of the material could have negative consequences on the quality of the final product as well as on consumer satisfaction (Mayor & Sereno, 2004).

Prolonged exposure of tomato tissue to high temperatures and oxygen causes the loss of important nutritional characteristics, in particularly of the antioxidant properties of tomatoes (Gümüşay et al., 2015). The drying process affects the carotenoid content, in terms of β-carotene and lycopene which, in addition to influencing the nutritional properties of the product, determines the red colour of the tomato Muratore et al., 2008; Coelho et al., 2013; Demiray et al., 2013; (Abano et al., 2014).

Colour is among the physical parameters most influenced by the hot air-drying process. It plays a key role influencing the appreciation of consumers. The high temperatures cause a darkening of the tomato tissues and a loss of brightness. This is due to the combined action of various factors such as the hydrolysis of sugars, the onset of non-enzymatic browning processes such as the Maillard reaction, the loss of pigments (e.g., the isomerization of lycopene from *trans* form to *cis* form) Zanoni et al., 1999; Cernîşev, 2010; Coelho et al., 2013; Jorge et al., 2018).

Both temperature and drying time affect the colour of the final product (Zalewska et al., 2022). An increase in the drying temperature causes a greater browning of the tomatoes as well as a greater loss of antioxidants including lycopene (Ashebir et al., 2009; Abano et al., 2014; Zalewska et al., 2022). Using lower temperatures could help to reduce thermal damage (Zalewska et al., 2022). However, even prolonged exposure of tomatoes to low temperatures can cause a significant reduction in colour due to prolonged contact with atmospheric oxygen (Goula & Adamopoulos, 2010; Kaur et al., 2020). Furthermore, low temperatures significantly increase drying times, slowing down the operations of companies. From an energy point of view, the drying process is among the industrial processes that consume the greatest amount of energy (Xiao & Mujumdar, 2020). EL-Mesery (2022) and Motevali et al. (2011) shown how the use of low temperatures for prolonged periods of time determines a significant increase in energy consumption and consequently in the cost of the process.

Several parameters influence the drying process and the quality of the final product. These can be linked to the type of drying (e.g., solar drying or hot air drying) and the pre-treatments carried out (e.g., the addition of salt) as well as the characteristics of the tomato itself such as maturity, variety and above all shape Zanoni et al., 1999; (Bhatkar et al., 2021). Tomatoes can be cut into slices, halves, or quarters. Half tomatoes are the most common choice in the food industry. Alternatively, the use of tomatoes cut into quarters could guarantee a significant reduction in drying times (Brooks et al., 2008; Karaaslan et al., 2019). As the size of the material subjected to drying decreases, the cutting surface in contact with the hot air flow increases, guaranteeing a more rapid loss of water (Brooks et al., 2008). Few studies in the literature have investigated how the drying kinetics of tomatoes change when cut into quarters or halves (Brooks et al., 2008; Karaaslan et al., 2019), focusing mainly on the drying rate and without modelling the colour and volume change during the process.

The aim of this work was to model the changes in the physical characteristics of half and quarter tomatoes, also comparing their quality and operating conditions. The drying tests were conducted at 50 °C and 60 °C. The kinetics of weight loss, colour change, and volume reduction were determined. The colour change was monitored through image analysis, while volume reduction using RGB-depth reconstructions.

MATERIALS AND METHODS

Sample preparation and tomato drying process

The tomatoes used for the drying test belong to the H 1015 variety. Tomatoes were selected based on their red color according to the USDA Color Scheme Categorization since more than 90% of their surface was red. Tomatoes were cut in halves through a longitudinal cut and into quarters. For each drying test, three replicates of about 1,000 g were used. The tests were conducted in a laboratory-scale convection hot air cabinet dryer (air flow rate of 0.1 m s^{-1}) at two different temperatures (50 and 60 °C) until the target moisture was reached (25% w.b.). This value was established in agreement with the standards of a local dry tomato producer (Coelsanus Industria Conserve S.p.A., Sossano, Vicenza, Italy). For simplifying the calculation, the target humidity was shifted to dry basis (X). To monitor the weight loss, at predetermined intervals, the samples were weighed using a digital scale balance RadWag ®PS. 6000/C/2, with a sensitivity of 0.01 g, until the target moisture value (0.33 d.b.) was reached. The final moisture value reached after drying was checked using the procedure described in the next paragraph.

Moisture content determination

An oven drier (model Binder® FD115) was used for determining the initial moisture content of the tomatoes before the drying process and for verifying when the tomatoes achieved the target moisture at the end of the process. The tomatoes were placed in trays and dried at 105 °C for 24 h. The following formula was used to calculate the moisture content *(M%)*:

$$M(\%) = \frac{w_0 - w_F}{w_0} \times 100 \tag{1}$$

where W_0 – initial sample weight, W_F – final sample weight. Based on this, the dry matter value DM(%) of the tomatoes was calculated using:

$$DM(\%) = 100 - M \tag{2}$$

The sample humidity was expressed in dry basis using the formula:

$$X = \frac{M(\%)}{DM(\%)} \tag{3}$$

Colour analysis

For monitoring the colour change during the dying process a Nikon® Coolpix W300 camera (resolution = 16 M-pixels) was used. In order to avoid external environment light interference, the tomatoes were placed in a controlled light chamber with a black background. The camera was placed on the chamber top at 40 cm of focal distance. A Colour Checker with 24 coloured squares with known RGB values was used for the calibration. The GNU Image Manipulation Program (GIMP)® software was used for removing the black background from each image before proceeding with the colour analysis. Moreover, the images were cropped to leave only the tomatoes on the picture and the dark background was subtracted by applying a threshold. The colour analysis was performed using the method described by Pulcini et al. (2021). The three-dimensional coordinates in RGB space were obtained from each pixel of the image, and the RGB space was following divided into 8 equal zones. Based on the RGB values of each pixel they were assigned to one of the 8 zones. Finally, the frequencies were calculated as the ratio between the pixels present in each RGB zone and the total number of pixels.

RStudio® software was used for the colour analysis.

Volume determination

Using a Microsoft Kinect™ RGB-depth camera the tomato volume was determined. The Kinect is a low-cost sensor able to acquire the volume of different objectives with good accuracy Quintino Ferreira et al., 2014; (Marinello et al., 2015). The sensor is equipped with an RGB camera, an infrared camera (IR) and an infrared laser emitter (Marinello et al., 2015; Andújar et al., 2016). For the acquisition of depth, data is used the IR camera. The IR light emitted hit the surface of the objects and once reflected is detected again by the camera. Based on the time taken by the beam, it is possible to calculate the distance of the object from the camera, thus determining its depth (Andújar et al., 2016). The camera was installed in support at a constant height and placed on a worktable. The tomatoes were arranged alternately with the cut surface up and down under the camera. Before proceeding with the volumetric estimation of the tomatoes, the Kinect sensor was calibrated using polystyrene hemispheres placed on a flat surface which, in terms of size and curvatures of the surfaces, are similar to the analysed tomatoes Quintino Ferreira et al., 2014; (Marinello et al., 2017). The hemispheres used had regular and known dimensions between 50 mm (32.7 cm^3) and 120 mm (452.3 cm^3). To determine the tomato volume the Scanning Probe Image Processor™ software was used.

Statistical analysis

In order to verify the differences between the means of the parameters analysed at the end of the drying processes a *one-way ANOVA* (95% confidence interval) and a post-hoc *Tukey's Honestly Significant Difference* (HSD) test were performed. Moreover, in order to determine the effects of the cut type, temperature, and their interaction (cut type x temperature) on the color and volume a *two-way analysis of variance* (*ANOVA*) (95% confidence interval) was performed. The analyses were conducted using RStudio® software.

RESULTS AND DISCUSSION

Weight loss kinetics

The measured drying curves are reported in Fig 1 where moisture (X) is expressed in terms of the mass of water on dry basis. Increasing the temperature from 50 °C to 60 °C, the drying process becomes significantly faster both for halved (-42%) and quartered (-42%) tomatoes (Table 1). Moreover, at the same temperature, the use of quartered tomatoes guarantees a further reduction in drying times (-19%). No significant difference was found in the interaction between drying temperature and cut of tomatoes. Cutting into quarters allows for a greater contact surface with the hot air, guaranteeing greater removal of the water present on the surface of the tomato, and speeding up the process. The use of higher temperatures is the most important factor affecting the drying speed, followed by the sample size and the air velocity (Krokida et al., 2003; Abano et al., 2011, 2014; EL-Mesery, 2022).

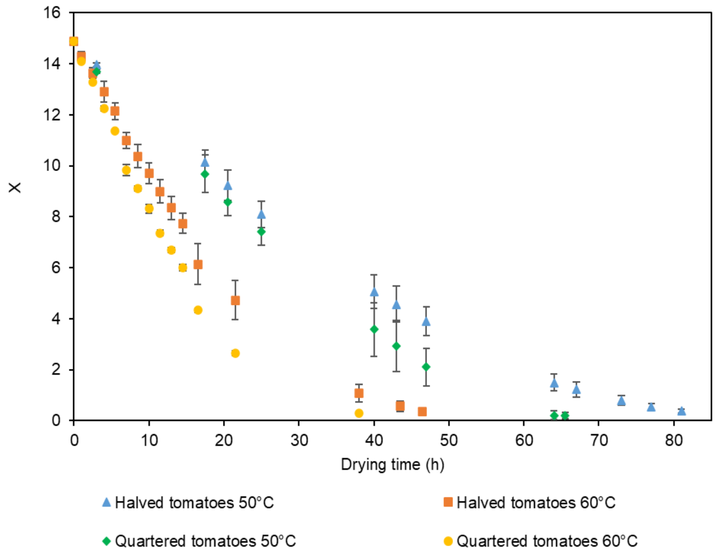

Figure 1. Moisture changes of tomatoes during the drying process at 50 and 60 °C for both quartered and halved tomatoes. The standard deviation is represented by the error bars.

Table 1. Mean values and standard deviations in brackets of the qualitative parameters of halved and quartered tomatoes dried at 50 and 60 °C

Tomato type	Drying times (h)	Final brown content	Final red content	Final mean volume (cm^3)
50 °C				
Halves	81	0.11 (0.01) [a]	0.74 (0.01) [b]	130.26 (11.85) [b]
Quarters	64	0.13 (0.03) [a]	0.67 (0.04) [a]	83.91 (12.89) [a]
60 °C				
Halves	46.5	0.13 (0.04) [a]	0.71 (0.00) [a, b]	133.65 (9.28) [b]
Quarters	38	0.15 (0.02) [a]	0.66 (0.01) [a]	80.94 (1.17) [a]

[a, b] Mean values having the same letter were not significantly different at Tukey HSD post hoc test ($P > 0.05$).

The drying kinetics, both for halved and quartered tomatoes, are divided into two distinct stages. In the first stage, the loss of water and the drying speed remain constant (rate constant - RC). Therefore, a zero-order kinetic occurs until the critical moisture value (Xc) is reached. This represents the transition point between the two phases and the time required for achieving depends on sample shape (quarters or halves) and drying conditions (e.g., temperature) (Aguilera & Stanley, 1999; Brooks et al., 2008). Once this threshold is exceeded, there is a change in kinetics. The loss of water becomes exponential, the speed of dehydration is higher initially and then gradually decreases as the available water decreases. For X values lower than Xc, a first-order kinetics occurs.

For the determination of the critical moisture value (Xc) an iterative approach was used until obtaining the value that determines the smallest distance between the linear model (zero-order) and the exponential model (first order). The Xc value determined during the tests was 3.21 ± 0.93 kg_{H2O} kg_{dw}^{-1} (dw = dry weight). No significant difference in Xc was found, neither related to temperature nor to tomato cut. Values higher than this threshold make up the straight line where the moisture content decreases linearly, while values higher than Xc make up the exponential section. The kinetics coefficients were reported in Table 2. For the zero-order stage, the R^2 of the model was 0.99 with a residual standard error (RSE) of 0.47 kg_{H2O} kg_{dw}^{-1} while for the first-order stage the R^2 was 0.87 and the RSE = 0.32 kg_{H2O} kg_{dw}^{-1}.

$$X = \begin{cases} X_0 e^{-kt}, & X < 3.21 \\ I + at, & X \geq 3.21 \end{cases}$$

Table 2. Model coefficients of the linear and exponential stages of the drying kinetics. For each model, the residual standard error was reported in brackets

		Linear coefficients		Exponential coefficients	
Temperature	Cut type	I (kg_{H2O} kg_{dw}^{-1})	RC (h^{-1})	ln(X_0)(kg_{H2O} kg_{dw}^{-1})	k (h^{-1})
50 °C	Halves	14.45 (0.2)	0.233 (0.01)	12.55 (0.7)	0.045 (0.01)
60 °C	Halves	14.72 (0.2)	0.489 (0.01)	12.94 (1.0)	0.078 (0.02)
50 °C	Quarters	14.48 (0.2)	0.265 (0.01)	13.44 (0.9)	0.126 (0.01)
60 °C	Quarters	14.61 (0.3)	0.595 (0.02)	11.58 (1.4)	0.155 (0.03)

Colour kinetics

During the drying process, the frequency of brown and red pixels in tomatoes changed. For the brown pixels, it was possible to observe a first initial constant phase (Fig. 2).

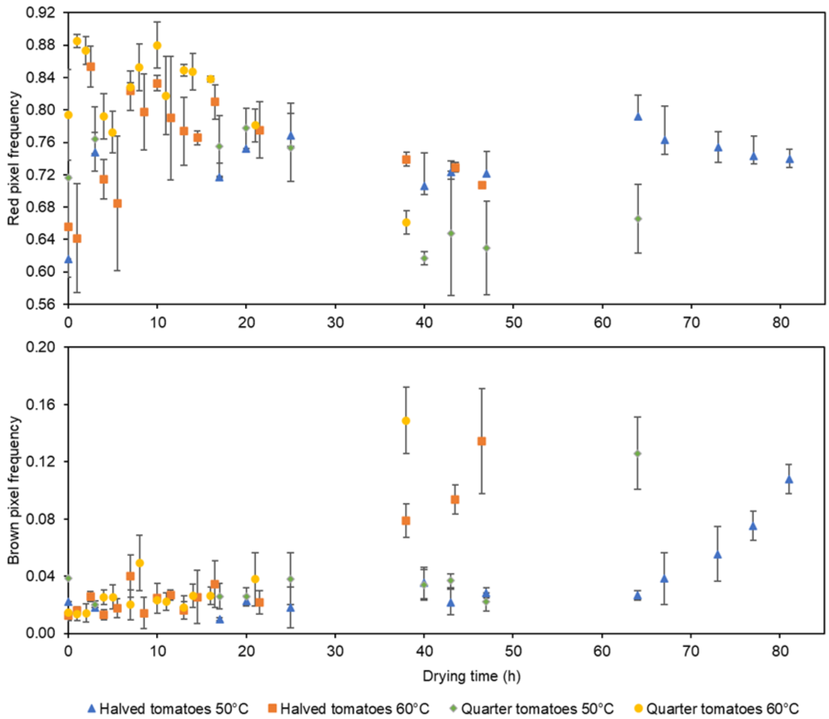

Figure 2. Red and brown pixel frequency changes of tomatoes during the drying process at 50 and 60 °C for both quartered and halved tomatoes. The standard deviation is represented by the error bars.

The duration of this phase varies according to the drying temperature and the type of cut made on the tomato. After the first constant phase, the frequency of brown pixels increases linearly. In this phase, due to the lower availability of water on the surface of the tomato, the greatest thermal damage occurs leading to a deterioration in the quality of the tomato (Kumar et al., 2014). The rate of brown pixel formation increases as tomato water loss progresses during the drying process, with a slightly higher incidence in tomatoes dried at higher temperatures (Abano et al., 2011; Cernîşev, 2010). The use of the highest temperature (60 °C) and the cutting of the tomatoes into quarters determine a reduction of the constant phase, anticipating the growing phase. As regards the red color variation, it was not possible to observe a clear trend. In halved tomatoes, as the drying process progresses, a slight increase in redness in the tomato tissues is observed at both 50 °C and 60 °C. On the contrary, in tomatoes cut into quarters an initial phase is observed in which the red content increases followed by a progressive loss. The final values are lower than the starting values.

In terms of brown pixel frequency, despite the tomatoes dried at 60 °C tending to have slightly higher values than tomatoes dried at 50 °C, no significant differences were observed (Table 1). While, regarding red pixel frequency, an increase in temperature led to a slightly lower value. This agrees with what was observed by Abano et al. (2011), increasing the temperature the tomatoes become darker.

Table 3. Results of two-way ANOVA test for brown pixel frequency

Source	D.f.	Sum of squares	Mean square	F-Ratio	P-Value
A: Cut type	1	0.0008	0.0008	1.21	0.30 $^{n.s.}$
B: Temperature	1	0.0018	0.0018	2.79	0.13 $^{n.s.}$
Interactions					
Cut type x Temperature	1	0.0000	0.0000	0.02	0.91 $^{n.s.}$
Residual	8	0.0052	0.0007		

Note: *** (0 < P< 0.001); ** (0.001 < P< 0.01); * (0.01 < P< 0.05); $^{n.s}$ (not significant, P > 0.05).

Regarding the effects of the cutting on colour changes, no significant effect of the type of cut was found for brown pixel frequency (Table 3). Conversely, quartered tomatoes show a significantly lower red content than halved tomatoes (P < 0.05) (Table 4). Finally, the interaction between the type of cut and the temperature did not determine a statistically significant effect (P > 0.05) on the frequency of brown pixels and red pixels.

Table 4. Results of two-way ANOVA test for red pixel frequency

Source	D.f.	Sum of squares	Mean square	F-Ratio	P-Value
A: Cut type	1	0.0108	0.0108	19.83	0.00 **
B: Temperature	1	0.0010	0.0010	1.89	0.21 $^{n.s.}$
Interactions					
Cut type x Temperature	1	0.0006	0.0006	1.03	0.34 $^{n.s.}$
Residual	8	0.0043	0.0005		

Note: *** (0 < P< 0.001); ** (0.001 < P< 0.01); * (0.01 < P< 0.05); $^{n.s}$ (not significant, P > 0.05).

Volume kinetics

During the drying process, the volume decreases linearly both in tests at 50 °C and 60 °C and when using tomato halves or quarters (Fig. 3). During the drying process volumetric shrinkage occurs in all directions leading to a progressive reduction of the tomato volume. The humidity gradient that occurs during tomato dehydration causes the progressive migration of water from the protoplasm of the cells towards the outside causing the loss of the cellular structure (Aguilera & Stanley, 1999; Dianda et al., 2015). This can lead to contractions which determine the shrinkage and collapse of the product, causing a change of shape and in some cases even damage to the tissues (e.g. cracking) Mayor & Sereno, 2004; (An et al., 2013).

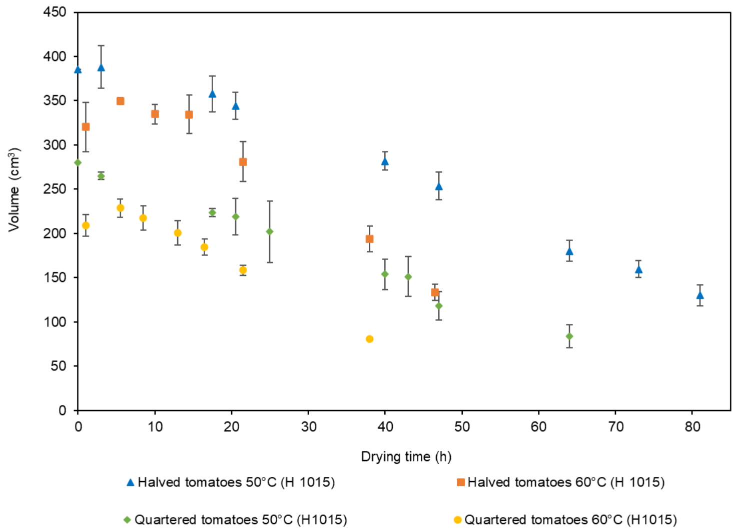

Figure 3. Volume loss of tomatoes during the drying process at 50 and 60 °C for both quartered and halved tomatoes. The standard deviation is represented by the error bars.

The volume decreases linearly both at 50 and 60 °C and for halved and quartered tomatoes. The linear model had a R^2 of 0.94 and RSE of 29.5 cm^3. The coefficients of the model were reported in Table 5.

Obviously, the cut type determines a significant effect on final volume ($P < 0.05$) (Table 6). On the contrary, the temperature did not have a significant effect on volume decrease ($P > 0.05$). This agrees with Dianda et al. (2015), that tomato shrinkage is more affected by air velocity than temperature. Also, the interaction between the type of cut and the temperature did not determine a statistically significant effect ($P > 0.05$).

Table 5. Coefficients of the linear model for volume loss. For each term of the model the RSE was reported in brackets

Temperature	Cut type	Intercept (cm^3)	Slope (cm^3 h^{-1})
50 °C	Halves	408 (11)	3.34 (0.22)
60 °C	Halves	370 (15)	4.61 (0.46)
50 °C	Quarters	278 (11)	3.09 (0.26)
60 °C	Quarters	280 (15)	4.18 (0.54)

Table 6. Results of two-way ANOVA test for volume

Source	Sum of squares	D.f.	Mean square	F-Ratio	P-Value
A: Cut type	7326.02	1	7326.02	74.18	0.00 ***
B: Temperature	0.24	1	0.24	0.00	0.96 $^{n.s.}$
Interactions					
Cut type x Temperature	28.52	1	28.52	0.29	0.61 $^{n.s.}$
Residual	790.11	8	98.76		

Note: *** (0 < *P*< 0.001), ** (0.001 < *P*< 0.01), * (0.01 < *P*< 0.05), $^{n.s}$ (not significant, *P* > 0.05).

CONCLUSIONS

In this study, the kinetics of physical parameters (moisture, colour and volume) during the drying process at 50 °C and 60 °C using halved and quartered tomatoes were modelled.

The kinetics of moisture loss showed an initial zero-order trend where the water loss remains steady until the critical moisture of roughly 3 on a dry basis was reached. Once this threshold was exceeded, the loss of moisture changed in a first-order kinetic.

Colour kinetics showed a constant initial phase in brown pixel frequency where no large increments occurred. After that, the brown content increased linearly as drying progresses. The variation of red pixels did not show a regular trend.

The volume loss kinetics was characterized by a linear decrease in both temperatures and types of cuts used, while the final volume of tomatoes was not affected by the drying temperature.

An increase in temperature allows a significant reduction in drying times both for tomatoes cut into quarters and halves (-42%). At the same temperature, a decrease in the size of the tomatoes allows a higher drying speed (-19%). Regarding colour, the temperature had no significant effect on brown and red pixel frequency changes ($P > 0.05$) while the cut type affected both the red pixel frequency and volume loss ($P < 0.05$). Interactions between cut type and temperature did not have a significant effect on any of the parameters analysed.

Using quartered or halved tomatoes is both associated with advantages and disadvantages. Quartered tomatoes allow obtaining operational advantages by significantly reducing drying times while using the same temperature. However, compared to tomatoes cut in halves, they present a worsening of the visual qualities of the product due to a greater loss of red content in the tissues. Therefore, based on their necessity, companies will have to choose whether to optimize product quality by using halved tomatoes or to reduce drying times by using quartered tomatoes.

Finally, color determination could be used as a control parameter to optimize the quality and productivity of the process.

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