Effects of Tomato Geometries and Air Temperature on the Drying Behavior of Plum Tomato

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Abstract: The drying behavior of plum tomatoes as affected by drying temperature and tomato pieces geometry was investigated. The tomato was cut into halves, quarters and eighths and dried at temperatures of 55 and 65°C. During drying, the moisture content followed an exponential decay curve with $R^2 > 0.98$. The time required to achieve the critical moisture content for storage (15%) for the tomato halves, quarters and eights were 36, 26 and 20 h and 23, 18 and 13 h, at the temperatures of 55 and 65°C, respectively. The rate of drying also followed exponential decay and was unaffected by the temperature and tomato piece geometries. The specific drying rate was dependent on the drying temperature and was not affected by geometry. The total surface area appeared to have a significant effect on the specific moisture loss than the cut surface area. Cutting the tomato samples into smaller pieces and drying at lower temperatures is recommended to reduce the drying time and maintain quality.

Key words: Air-drying, tomato, geometry, volume, weight, area, temperature, time, moisture ratio, specific moisture loss, drying rate

INTRODUCTION

Tomatoes are an important commercial vegetable having the highest production figures of all the vegetables in the world, apart from the root-vegetables[1]. In 2005, the world-wide production of tomatoes reached 91 million tons. Major producers of tomatoes include the United States, Turkey, Egypt, India and Italy[2]. Tomatoes are popular for their culinary properties and their health benefits. They are a natural source of lycopene, a carotenoid that reduces the risk of cancer and coronary heart disease. Tomatoes and tomato-based products account for more than 85% of the dietary lycopene in North America[3].

Drying is a common form of food preservation. When drying agricultural products, the aim is to reduce the moisture content to a level that allows the food to be stored safely for an extended period. In addition to increasing the shelf-life, drying reduces the weight and volume of the product, thereby reducing packing, storage and transportation costs[4]. Dried tomato products are used for making pizza and various culinary dishes. During the drying process, the moisture content of the dried tomato product is typically reduced to ≤15%[5]. Drying tomatoes in Mediterranean countries has traditionally been carried out using sun-drying techniques which are simple and have low capital costs. In order to improve the quality of dried tomato products, industrial drying methods such as hot-air and solar drying are preferred[6]. However, conventional air drying is considered expensive due to the high moisture content in the tomatoes[7].

Consumers demand that processed products retain many of their original characteristics[8]. For tomatoes, this means maintaining the color, nutritional content and level of antioxidant compounds present in the fresh fruit. These include vitamins A, C, E and carotenoids such as beta-carotene and lycopene[9]. It is, therefore, desirable to minimize the oxidative damage to the tomatoes prior to reaching the consumer, during both the drying process and storage of the dried tomatoes[5]. The oxidation damage during tomato drying has been linked to drying processes occurring at high temperatures over long times in the presence of oxygen. Optimization of tomato drying can be achieved by maximizing the drying rate and minimizing oxidative heat damage. This could be accomplished by reducing the tomato thickness and drying smaller pieces of tomato (e.g., tomato slices, quarters, cubes)[10], which would require shorter times to achieve the same level of moisture removal.

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The aim of this study was to experimentally investigate the air-drying behavior of plum tomatoes using different sample geometries (halves, quarters and eighths) and temperatures (55 and 65°C).

MATERIALS AND METHODS

Raw material: Plum tomatoes were purchased from a local supermarket in Halifax, Nova Scotia. They were selected for uniformity in size and ripeness. The average dimensions of vertical height (h) and horizontal diameter (2r) were 7.75 and 4.63 cm, respectively. The tomatoes had an average weight of 95.23 g. The initial moisture content was determined according to standard procedures[11] and the average value was found to be 93% (wet basis).

Sample preparation: The tomatoes were washed and cut into different geometries: halves, quarters and eighths as shown in Fig. 1. They were then weighed to the nearest 0.01 g using a Mettler balance (PM 4600 Digital Balance, Mettler-Toledo, Mississauga, Ontario). The dimensions of tomato pieces were measured to the nearest 0.01 mm and the following parameters were calculated: volume, total surface area and cut surface area (Table 1).

Drying procedure: Drying experiments were conducted at 55 and 65°C. The pre-cut tomato pieces (halves, quarters, eighths) were placed in pre-weighed trays. The trays were placed in a forced-air oven (Isotemp Oven 630F, Fisher Scientific, Ottawa, Ontario) at the desired temperature. The trays were taken out of the oven at regular time intervals (every 3 h) and weighed. The experiments were carried out in duplicates and the averages were determined.

Table 1: Characteristic dimensions for plum tomato pieces

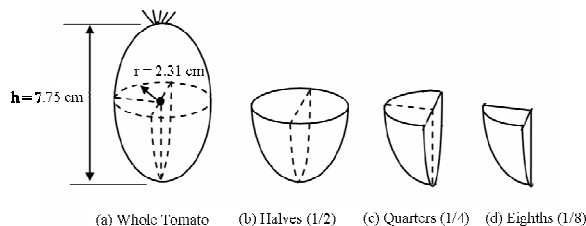| Geometry	Weight (g)	Volume (cm^3)	Total surface area (cm^2)	Cut surface area (cm^2)	Cut surface area (%) [a]
Half (1/2)	47.6	43.5	66.4	16.8	25.3
Quarter (1/4)	23.8	21.8	47.3	22.5	47.6
Eighth (1/8)	11.9	10.9	30.7	18.3	59.6

[a]: Cut area as a percentage of total surface area

Fig. 1: Plum tomato pieces

RESULTS AND DISCUSSION

Moisture content: The effect of drying time on the moisture content of the various tomato pieces is shown in Fig. 2. The moisture content followed an exponential decay curve with an $R^2 > 0.98$. As the initial moisture content of all the tomato pieces was fixed at 93% (wet basis), variations in the drying process, as a result of the geometry of the tomato piece, can be determined by the exponential constants in the drying equation. The exponents indicated that the drying time had a greater effect on the moisture content of smaller tomato pieces due to the larger total surface area per unit weight (1.39, 1.99 and 2.58 cm^2 g^{-1} for halves, quarters and eighths, respectively). Increasing the surface area to weight ratio
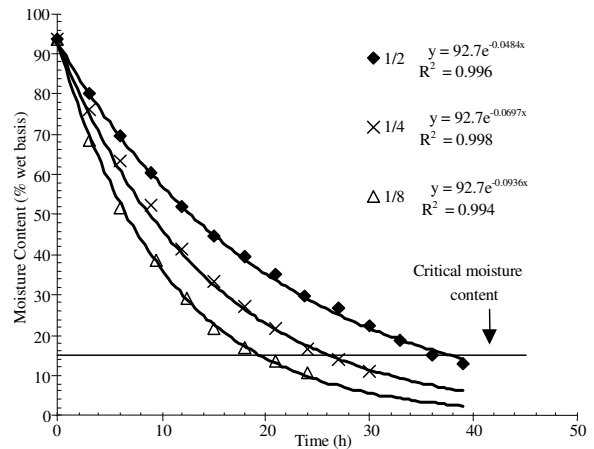
(a) at 55°C
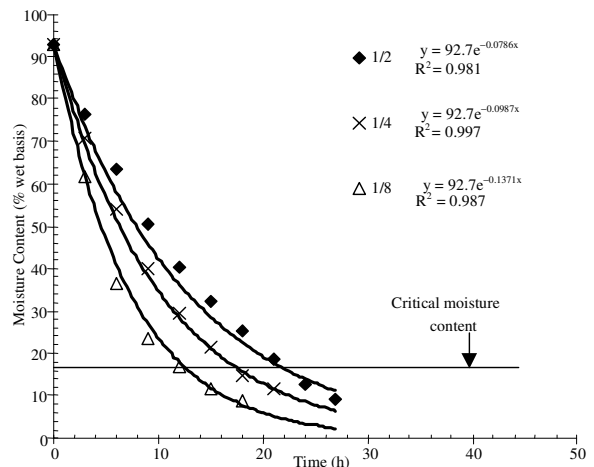
(b) at 65°C

Fig. 2: Effect of drying time on moisture content at different drying temperatures
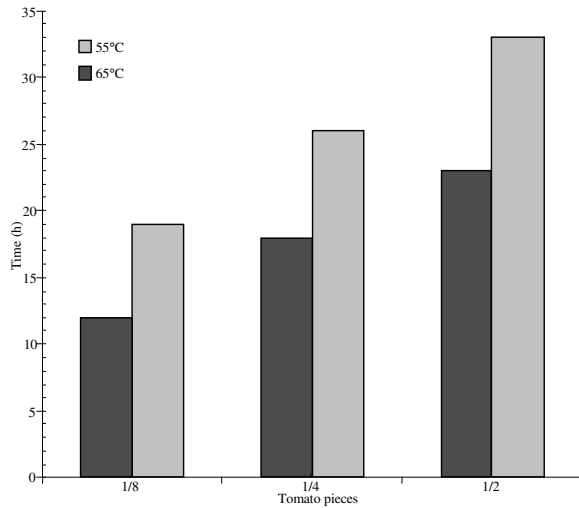
Fig. 3: Time required to reach the critical moisture content (15%) for storage at different drying temperatures

resulted in a faster decrease in moisture content over time. Drying curves exhibiting an exponential decay in moisture content were also reported by Krokida *et al.*[12] who showed that an increase in drying temperature from 65 to 85°C resulted in the acceleration of the drying process for tomatoes as well as other vegetables. Exponential drying curves were observed for hemispherical potatoes in the study by Bon *et al.*[13] who also showed an increase in the rate of moisture loss when the drying temperature increased from 30 to 70°C.

In their study of drying tomato halves, Zanoni *et al.*[5] reported that an initial equilibrium period was observed before the falling rate period, where a sharp decrease in moisture content occurred. They attributed the equilibrium periods of 20 and 30 min (at 110 and 80°C respectively) to the tomato specimen surface coming to equilibrium with the drying air. In the present study, no equilibrium periods were observed. However, it is possible that short equilibrium periods could have occurred within the first 3 h of the experiment, before the first measurements were taken.

Figure 3 summarizes the time required for the tomato pieces to reach the critical moisture content (15%) for storage. At the temperature of 55°C, the times required to achieve the critical moisture content for the tomato halves, quarters and eighths were 36, 26 and 20 h, respectively. However, at the higher temperature of 65°C, the critical moisture content was reached after shorter respective drying periods of 23, 18 and 13 h. Zanoni *et al.*[5] investigated drying of tomato

halves at higher temperatures and reported that drying to a moisture content of around 10% (wet basis) required 7 and 4 h at 80 and 110°C, respectively. Typical drying times of 2 to 10 h, drying temperatures of 60 to 110°C and air flow rates of 0.5 to 2.0 ms^{-1} (using through-flow or cross-flow arrangements) have been reported by several authors[5,7,12,14]. It may, however, be desirable to decrease the drying times while maintaining lower temperatures to reduce energy requirements and maintain a high quality of the dried product. Lower moisture contents have been observed in smaller strawberry pieces (quarters and discs) than whole and halved strawberries, when subjected to the same solar drying conditions[15]. It is, therefore, recommended that the tomato pieces be cut into smaller sizes to reduce drying time and maintain high quality of the dried tomato.

Drying rate: An average rate of drying was calculated over successive 3 h drying time intervals. The changes in the rate of drying over time at different temperatures for various tomato pieces are shown in Fig. 4. The results showed that the rate of drying can also be described by exponential decay curves with an $R^2 > 0.92$. These curves show that for the tomato geometries investigated, different rates of drying occur when the same drying temperature and drying times were used. The exponential equations show that the rate of drying was affected by the initial moisture content at the beginning of each time interval, the geometry of the tomato pieces and the drying temperature. In the study by Zanoni *et al.*[5] the drying rate was shown to be a linear function of the moisture content, with three distinct linear relationships during the falling rate period of drying. The authors observed that the drying rate at 110°C was twice that at 80°C and attributed this to the increased moisture diffusion in the tomato due to the higher temperature within the tomato. Although the higher temperature increased shrinkage of the tomato halves which decreased diffusion, the increased moisture diffusion due to the higher temperature was considered the more dominant factor. The importance of temperature during drying is also illustrated in the study by Krokida *et al.*[12] in which they determined that temperature had a greater effect on the drying rate than air velocity or air humidity.

Moisture ratio: Figure 5 shows the change in moisture ratio of the tomato pieces with time. In this study, the Moisture Ratio (MR) is defined as follows:

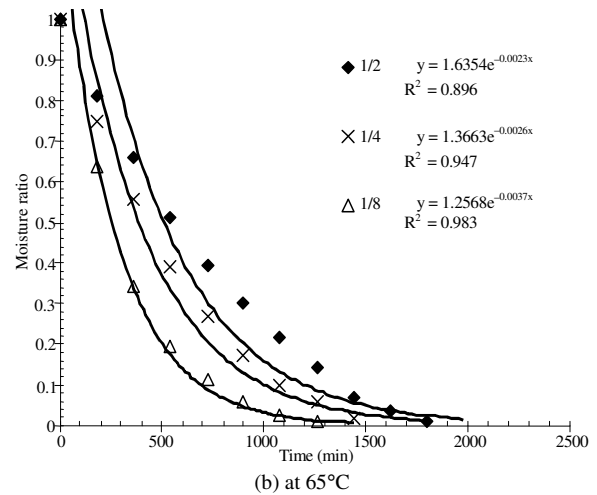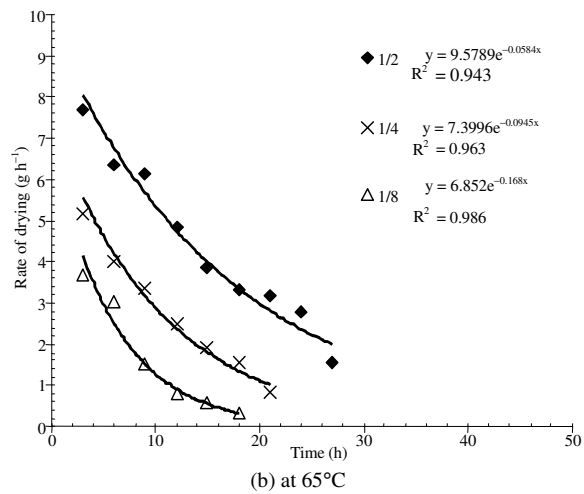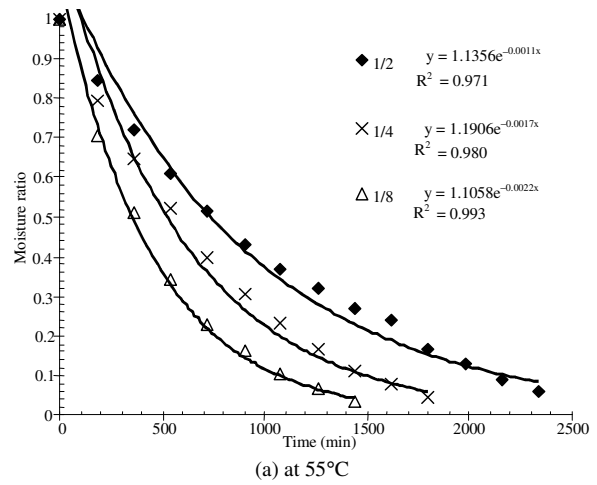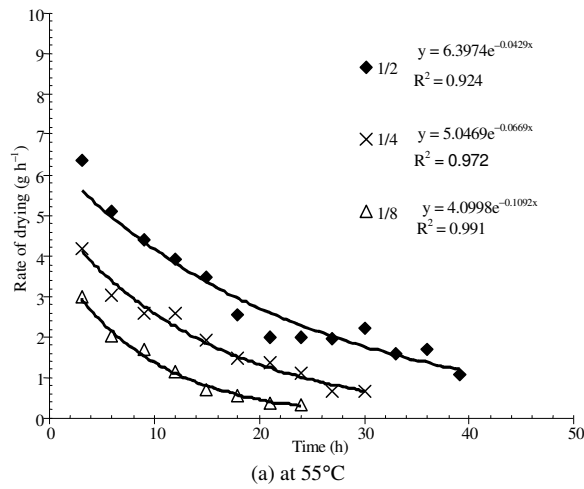$$MR = (M_t - M_e)/(M_o - M_e) \qquad (1)$$

Fig. 4: Change in drying rate as affected by the size of tomato specimen and drying temperature

Fig. 5: Change in moisture ratio over time at different temperatures

where:

M_t = Moisture content of the sample at any time (kg water per kg dry solid)

M_o = Initial moisture content of the sample (kg water per kg dry solid)

M_e = Equilibrium moisture content of the sample (kg water per kg dry solid)

It is evident from the results that the moisture ratio was variant during the whole drying period. The drying of the tomato pieces is controlled by a diffusion mechanism, which is affected by the moisture content at a given time. Henderson and Pabis[16] developed a model for thin-layer drying which has been used to

describe the drying of various agricultural products[17] and the drying of tomato halves[6]. The model can be expressed as follows:

$$MR = ae^{-kt} \qquad (2)$$

where:

a = Drying constant (-)

k = Drying constant (min^{-1})

t = Drying time (min)

A comparison of the data obtained from drying tomato halves in this study with those obtained from Doymaz[6] is shown in Table 2. It can be seen that the

Table 2: Comparison of drying model parameters for tomato halves

Temperature (°C)	Results from present work			Results from Doymaz[6]		
	a	k (min⁻¹)	R²	a	k (min⁻¹)	R²
55	1.1356	0.0011	0.97	1.0575	0.0016	0.99
65	1.6354	0.0023	0.90	1.0538	0.0018	0.99

Table 3: Comparison of drying model parameters for different tomato piece geometries

Tomato geometry	Temperature (°C)	Results from present work		
		a	k (min⁻¹)	R²
Half (1/2)	55	1.1356	0.0011	0.97
	65	1.6354	0.0023	0.9
Quarter (1/4)	55	1.1906	0.0017	0.98
	65	1.3663	0.0026	0.95
Eighth (1/8)	55	1.1058	0.0022	0.99
	65	1.2568	0.0037	0.98

Table 4: Effect of temperature on drying kinetics

Temperature (°C)	Tomato geometry	Critical drying time (h)	Average drying rate[b] (g h⁻¹)	Specific drying rate[c] (g h⁻¹cm⁻²)
55	Half (1/2)	33	1	0.015
	Quarter (1/4)	26	0.7	0.015
	Eighth (1/8)	19	0.5	0.016
65	Half (1/2)	23	1.6	0.024
	Quarter (1/4)	18	1	0.021
	Eighth (1/8)	12	0.8	0.026

[b]: Averaged over the initial to critical moisture content
[c]: Calculated from the average drying rate and total surface area

model parameters obtained from the current study are in reasonable agreement with those of Doymaz[6]. The model was also tested for other tomato pieces used in the current study as shown in Table 3. It is interesting to note that for a given drying temperature, as the total surface area of the tomato piece increases, the model provided a better fit to the experimental data. The results also indicated that the model is a better fit at 55°C than at 65°C for a given surface area.

Temperature: The effects of drying temperature on the drying kinetics are shown in Table 4. At 65°C, the moisture content of the tomato pieces decreased at a greater rate than at 55°C. The higher temperature typically resulted in higher average drying rates. Thus, the critical moisture content was achieved sooner at the higher temperature. Other studies have shown similar effects of temperature on drying rate. Akanbi *et al*.[18] reported an increase in the drying rate with an increase in temperature from 45 to 75°C for pretreated tomato slices. In the study by Doymaz[6], an increase in drying temperature from 55 to 70°C resulted in a marked increase in the drying rate of tomato halves. In addition, it was found that to achieve the final moisture content of around 10% (wet basis), 35 and 27 h were required at
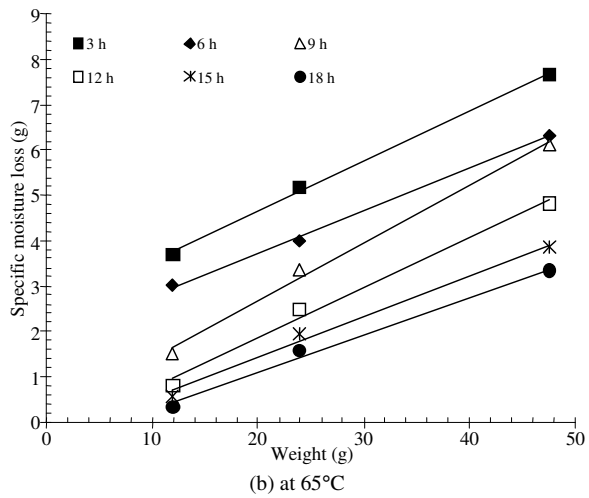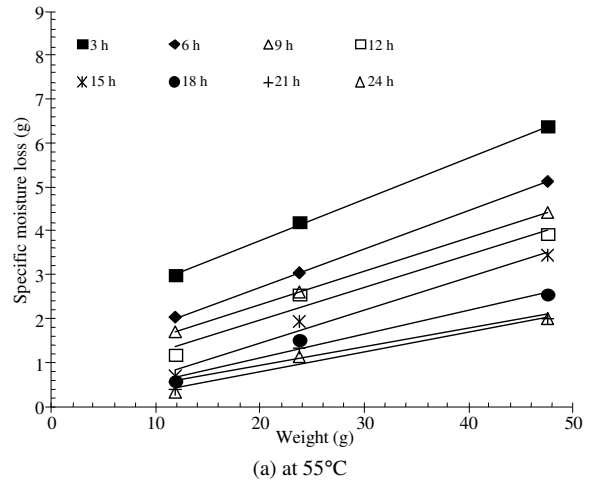

(a) at 55°C

(b) at 65°C

Fig. 6: Effect of tomato specimen weight on specific moisture loss

55 and 65°C. These results are similar to those from the current work. The results from the present study also show that the specific drying rate (g moisture h⁻¹ cm⁻²) was affected by temperature but not the tomato piece geometry. This was due to the increased diffusion per unit surface area as a result of increased temperature.

Tomato geometry: The specific moisture loss (the moisture loss during each 3 hour drying period) was plotted against a characteristic dimension of the tomato piece (Fig. 6-8). Figure 6 shows that the specific moisture loss increased linearly as the mass of the tomato piece increased. Similar trends are shown in Fig. 7 and 8, where the specific moisture loss increased linearly with increases in volume and in the total surface area of the tomato specimen, respectively.
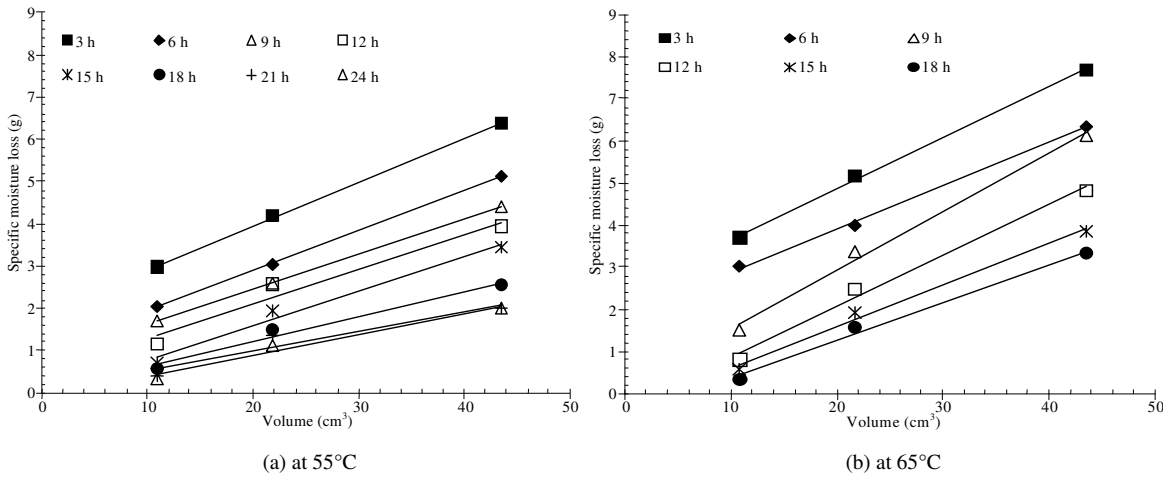
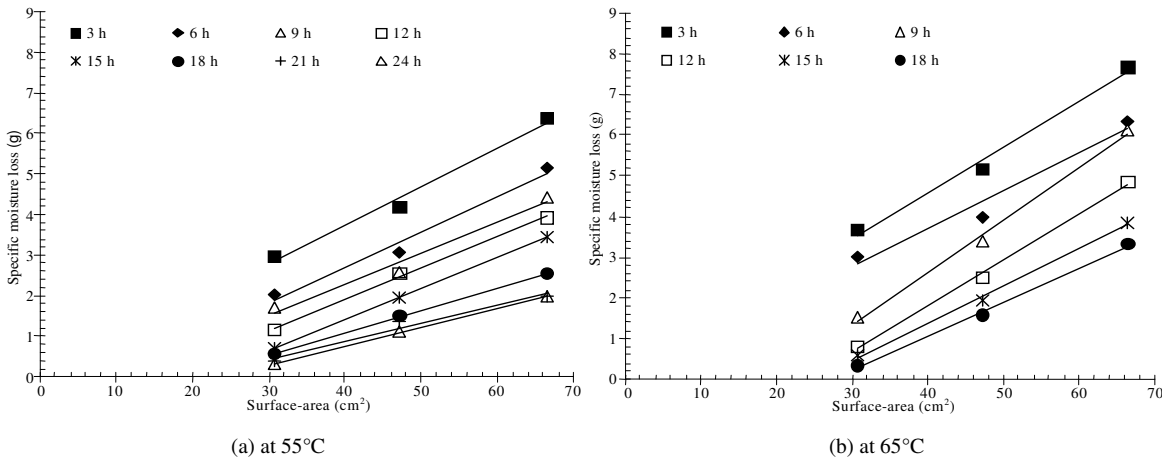Fig. 7: Effect of the tomato specimen volume on specific moisture loss

Fig. 8: Effect of tomato specimen total surface area on specific moisture loss
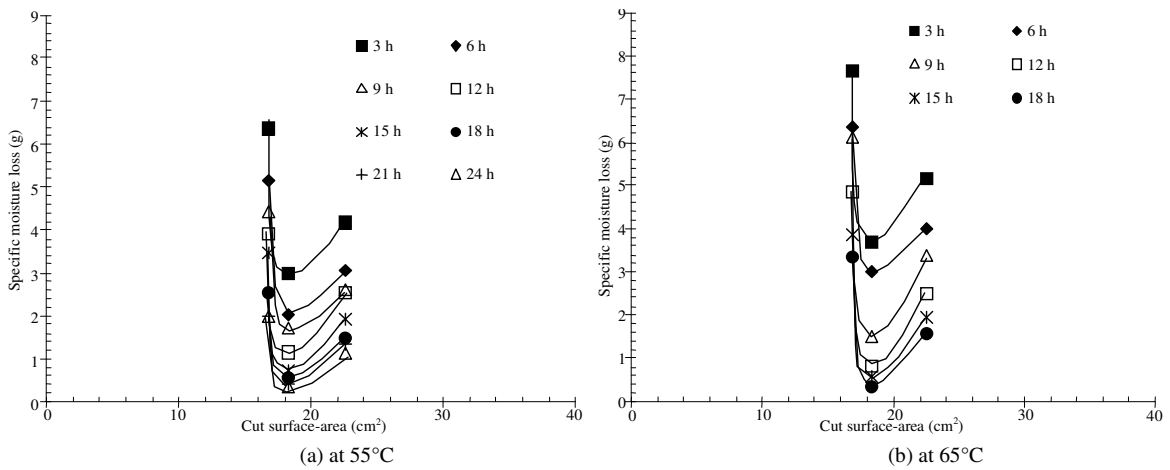
Fig. 9:   Effect of cut surface area on specific moisture loss

However, a non-linear trend was observed when the specific moisture loss was graphed against the cut surface area (the area of cut surfaces) as shown in Fig. 9. Although the evaporation of water from the cut surface area would be faster than that from the non-cut surface area, the results indicated that the total surface area is more important than the cut surface area. Although the halves had the smallest cut surface area (16.8 cm^2), they had the largest total surface area (66.4 cm^2) and therefore the highest specific moisture loss. The eighths had the second largest cut area (18.3 cm^2) but had the lowest specific moisture loss because they had the smallest total surface area (30.7 cm^2).

CONCLUSIONS

During drying, the moisture content followed an exponential decay curve with $R^2 > 0.98$. The time required to achieve the critical moisture content for storage (15%) for the tomato halves, quarters and eighths were 36, 26 and 20 h and 23, 18 and 13 h, at the temperatures of 55 and 65°C, respectively. The rate of drying also followed exponential decay and was unaffected by the temperature and tomato piece geometries. The specific drying rate was dependent on the drying temperature and was not affected by geometry. The total surface area appeared to have a significant effect on the specific moisture loss than the cut surface area. Cutting the tomato samples into smaller pieces and drying at lower temperatures is recommended to reduce the drying time and maintain quality.

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