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COMPARATIVE ANALYSIS OF INFRARED AND FREEZE-DRYING METHODS FOR DIFFERENT STRAWBERRY CULTIVARS

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Abstract. *This study compared the effects of infrared (IR) drying and freeze-drying (lyophilization) on the quality parameters of three strawberry cultivars: Malwina, Portola, and San Andreas. Fresh strawberries were subjected to IR drying at 60°C for 8 hours and freeze-drying at -70°C for 52 hours. Quality parameters including moisture content, vitamin C, total carbohydrates, organic acids, proteins, color (L*a*b*), and antioxidant activity were evaluated. The results showed that freeze-drying preserved significantly higher levels of vitamin C (92.5-94.2%), organic acids (89.2-92.0%), and antioxidants (90.5-93.1%) compared to IR drying (vitamin C: 68.3-72.5%; organic acids: 71.4-75.8%; antioxidants: 70.2-74.6%). However, IR drying required substantially less time (8 hours vs. 52 hours) and consumed less energy. Among cultivars, Malwina showed the best nutrient retention under both drying methods. Infrared drying at 60°C is recommended for rapid, energy-efficient processing, while freeze-drying is preferred when maximum nutrient preservation is required.*

Keywords: *Strawberry; infrared drying; freeze-drying; lyophilization; cultivar comparison; nutrient retention; Malwina; Portola; San Andreas; antioxidant activity.*

Annotatsiya. *Ushbu tadqiqotda uchta qulupnay navi – Malwina, Portola va San Andreasning sifat ko'rsatkichlariga infraqizil (IQ) quritish va sublimatsion quritish (liofilizatsiya) usullarining ta'siri qiyoslandi. Yangi qulupnaylar 60°C haroratda 8 soat davomida IQ quritishga va -70°C haroratda 52 soat davomida sublimatsion quritishga duchor qilindi. Namlik miqdori, S vitamini, umumiy uglevodlar, organik kislotalar, oqsillar, rang (L*a*b*) va antioksidant faollik kabi sifat ko'rsatkichlari baholandi. Natijalar shuni ko'rsatdiki, sublimatsion quritish IQ quritishga nisbatan sezilarli darajada yuqori darajadagi S vitaminini (92.5–94.2%), organik kislotalarni (89.2–92.0%) va antioksidantlarni (90.5–93.1%) saqlab qolgan (IQ quritishda: S vitamini – 68.3–72.5%; organik kislotalar – 71.4–75.8%; antioksidantlar – 70.2–74.6%). Biroq, IQ quritish sezilarli darajada kamroq vaqt (52 soatga nisbatan 8 soat) talab qilgan va kamroq energiya sarflagan. Navlar orasida Malwina ikkala quritish usulida ham eng yaxshi ozuqa moddalarini saqlash ko'rsatkichini namoyish etdi. 60°C haroratdagi infraqizil quritish tez va energiya tejamkor qayta ishlash uchun tavsiya* *etiladi, sublimatsion quritish esa maksimal ozuqa moddalarini saqlash talab etilganda afzal ko'riladi.*

Kalit so'zlar: *qulupnay; infraqizil quritish; sublimatsion quritish; liofilizatsiya; navlarni qiyoslash; ozuqa moddalarini saqlash; Malwina; Portola; San Andreas; antioksidant faollik.*

Аннотация. *В данном исследовании сравнивалось влияние инфракрасной (ИК) сушки и сублимационной сушки (лиофилизации) на качественные показатели трех сортов клубники: Malwina, Portola и San Andreas. Свежая клубника подвергалась ИК-сушке при температуре 60°C в течение 8 часов и сублимационной сушке при температуре -70°C в течение 52 часов. Оценивались такие качественные параметры, как содержание влаги, витамин С, общие углеводы, органические кислоты, белки, цвет (L*a*b*) и антиоксидантная активность. Результаты показали, что сублимационная сушка сохранила значительно более высокие уровни витамина С (92.5–94.2%), органических кислот (89.2–92.0%) и антиоксидантов (90.5–93.1%) по сравнению с ИК-сушкой (витамин С: 68.3–72.5%; органические кислоты: 71.4–75.8%; антиоксиданты: 70.2–74.6%). Однако ИК-сушка требовала существенно меньше времени (8 часов против 52 часов) и потребляла меньше энергии. Среди сортов Malwina показала наилучшее сохранение питательных веществ при обоих методах сушки. Инфракрасная сушка при 60°C рекомендуется для быстрой и энергоэффективной переработки, в то время как сублимационная сушка предпочтительна, когда требуется максимальное сохранение питательных веществ.*

Ключевые слова: *клубника; инфракрасная сушка; сублимационная сушка; лиофилизация; сравнение сортов; сохранение питательных веществ; Malwina; Portola; San Andreas; антиоксидантная активность.*

1. INTRODUCTION

1.1 Background. Strawberry (*Fragaria × ananassa* Duch.) is one of the most widely consumed berries worldwide due to its attractive red color, pleasant aroma, high nutritional value, and various health-promoting properties. Strawberries are rich in essential nutrients including carbohydrates (glucose, fructose, and sucrose), organic acids (citric, malic, and succinic acids), proteins, vitamin C, and numerous phenolic compounds with antioxidant activities (Giampieri et al., 2015; Afrin et al., 2016).

However, fresh strawberries have a very short post-harvest life (10-15 days under refrigeration) due to their high moisture content (88-95%) and soft texture. Therefore, various drying methods have been developed to extend the shelf life of strawberries while preserving their nutritional quality (Kumar & Sharma, 2022).

1.2 Drying Methods for Strawberries. Among the various drying technologies, freeze-drying (lyophilization) is widely recognized as the most advanced method for preserving heat-sensitive fruits. Freeze-drying operates at low temperatures (-70°C to +25°C) under vacuum conditions, which minimizes thermal degradation of nutrients. However, freeze-drying has significant drawbacks: it is expensive, time-consuming (typically 48-72 hours), and has low energy efficiency (Zhao et al., 2017; Abouelenein et al., 2021).

Infrared (IR) drying is an innovative alternative that has gained increasing attention in recent years. Unlike conventional hot air drying, which heats the product surface through convection, infrared radiation penetrates the food material and directly heats its internal layers. This mechanism offers several advantages: shorter drying time (typically 4-12 hours), higher energy efficiency, and better product quality compared to hot air drying (Sun et al., 2024).

1.3 Cultivar Importance. Not all strawberry cultivars respond to drying in the same way. Different cultivars have different initial chemical compositions, which directly affects how well they retain nutrients during processing. Factors such as sugar-to-acid ratio, fiber content, and cell wall structure vary significantly between cultivars and influence drying kinetics and final product quality (Saridas & Paydas Kargi, 2023).

1.4 Problem Statement and Objectives. Despite the availability of individual studies on infrared drying and freeze-drying of strawberries, there is a lack of systematic comparative research that evaluates both methods using the same strawberry cultivars under controlled conditions. In particular, no study has directly compared IR drying and freeze-drying across multiple cultivars using identical quality parameters.

Therefore, the objectives of this study were:

1. To compare the drying kinetics of infrared drying and freeze-drying for three strawberry cultivars (Malwina, Portola, San Andreas).
2. To evaluate and compare the quality parameters (moisture, vitamin C, carbohydrates, organic acids, proteins, color, antioxidant activity) of strawberries dried by both methods.
3. To determine which cultivar performs best under each drying method.
4. To provide recommendations for selecting the appropriate drying method based on specific quality requirements.

2. MATERIALS AND METHODS

2.1 Plant Materials. Three strawberry (*Fragaria* × *ananassa* Duch.) cultivars were used in this study:

I. **Malwina**: Late-fruiting variety, very sweet and fragrant, disease-resistant (Cornell University, 2014)

II. **Portola**: Cross between "Cal 97.93-7" and "Cal 97.209-1", bred in 2001 (Shaw & Larson, 2009)

III. **San Andreas**: Day-neutral variety, very firm, sweet, and aromatic fruits (Saridas & Paydas Kargi, 2023)

The fruits were hand-picked at full ripeness, transported to the laboratory within 2 hours, and stored at 4°C until processing.

2.2 Sample Preparation. Strawberries were washed with distilled water, gently dried with paper towels, and the calyx and stem were removed. The fruits were then sliced into uniform 4 mm thick slices using a stainless steel slicer.

2.3 Infrared Drying. Infrared drying was performed using a laboratory-scale infrared dryer (IR-3000, LabTech, USA) equipped with medium-wave infrared lamps (wavelength: 2.5-4.0 µm). Strawberry slices (4 mm thickness) were placed in a single layer on the drying tray. The drying conditions were as follows:

Table 1.

Parameter	Value
Drying temperature	60°C
Infrared power	500 W
Distance between lamp and sample	15 cm
Air velocity	1.0 m/s
Total drying time	8 hours

Samples were weighed every 30 minutes during the first 2 hours, then every hour until constant weight was achieved.

2.4 Freeze-Drying (Lyophilization). Freeze-drying was performed using a laboratory-scale lyophilizer (Labconco FreeZone, Kansas City, MO, USA). Strawberry slices (4 mm thickness) were pre-frozen at -40°C for 12 hours, then subjected to freeze-drying under the following conditions:

Table 2.

Parameter	Value
Chamber pressure	0.081 mbar
Condenser temperature	-70°C
Primary drying time	52 hours
Secondary drying temperature	+25°C

2.5 Determination of Initial Dry Matter. To determine initial moisture content, approximately 100 g of fresh strawberry slices from each cultivar were dried in a conventional oven at 105°C for 24 hours until constant weight (AOAC International, 2019).

2.6 ANALYTICAL METHODS

2.6.1 Moisture Content

Moisture content was determined using the oven drying method (105°C, 24 hours). Moisture percentage was calculated as:

$$\textbf{Moisture (\%)} = [(W_1 - W_2) / W_1] \times 100$$

where W_1 = initial weight, W_2 = weight after drying.

2.6.2 Vitamin C Content

Vitamin C (ascorbic acid) content was determined using the 2,6-dichlorophenolindophenol (DCPIP) titration method. Five grams of strawberry powder was mixed with 50 mL of 3% metaphosphoric acid, homogenized, and filtered. The filtrate was titrated with DCPIP solution until a pink color persisted. Results were expressed as mg ascorbic acid per 100 g fresh weight.

2.6.3 Total Carbohydrates

Total carbohydrate content was determined using the phenol-sulfuric acid method. Absorbance was measured at 490 nm using a UV-Vis spectrophotometer. Glucose was used as the standard (AOAC International, 2019).

2.7 Statistical Analysis. All experiments were performed in triplicate. Results were expressed as mean ± standard deviation (SD). Two-way ANOVA was used to determine significant differences between drying methods and cultivars. Tukey's post-hoc test was applied for multiple comparisons ($p < 0.05$). Statistical analyses were performed using SPSS software (version 26.0, IBM Corporation).

3. RESULTS

3.1 Drying Kinetics. The total drying time for infrared drying was 8 hours for all cultivars, while freeze-drying required 52 hours.

During infrared drying, moisture content decreased rapidly during the first 3 hours (from approximately 90% to 45%), followed by a slower reduction phase. Malwina showed the fastest drying rate among the three cultivars, reaching final moisture below 5% after 7.5 hours. Portola required the longest drying time (8 hours) due to its higher initial moisture content (91.5%).

For freeze-drying, all cultivars reached final moisture below 4% after 52 hours with no significant differences among cultivars.

Table 3. Drying parameters for both methods

Parameter	Infrared drying	Freeze-drying
Total drying time	8 hours	52 hours
Temperature	60°C	-70°C to +25°C
Final moisture (Malwina)	4.2 ± 0.3%	3.2 ± 0.2%
Final moisture (Portola)	4.8 ± 0.4%	3.8 ± 0.3%
Final moisture (San Andreas)	4.5 ± 0.3%	3.5 ± 0.2%

3.2 Initial Composition of Fresh Cultivars

The initial composition of fresh strawberry cultivars is presented in Table 4 Significant differences were observed among cultivars for all parameters.

Table 4. Initial composition of fresh strawberry cultivars (mean ± SD, n=3)

Parameter	Malwina	Portola	San Andreas
Moisture (%)	89.2 ± 0.3	91.5 ± 0.4	90.1 ± 0.3
Vitamin C (mg/100g)	58.6 ± 1.5	52.3 ± 1.2	62.4 ± 1.8
Total carbohydrates (%)	8.2 ± 0.2	6.8 ± 0.1	7.5 ± 0.2
Organic acids (mg%)	52.4 ± 1.5	58.6 ± 1.8	67.8 ± 2.0
Proteins (%)	0.78 ± 0.04	0.62 ± 0.03	0.71 ± 0.03
L* (lightness)	38.5 ± 0.5	36.2 ± 0.4	37.8 ± 0.5
a* (redness)	32.4 ± 0.6	35.1 ± 0.5	34.2 ± 0.6
b* (yellowness)	18.6 ± 0.4	19.2 ± 0.3	18.9 ± 0.4
Antioxidant activity (%)	85.6 ± 1.2	78.9 ± 1.5	82.3 ± 1.3

3.3 Quality Comparison: Infrared vs. Freeze-Drying

The quality parameters of strawberries dried by both methods are compared in Table 5.

Table 5. Quality parameters of dried strawberries by method and cultivar (mean ± SD, n=3)

Parameter	**Cultivar**	**Infrared drying (60°C, 8h)**	**Freeze-drying (-70°C, 52h)**
Moisture (%)	Malwina	4.2 ± 0.3	3.2 ± 0.2
	Portola	4.8 ± 0.4	3.8 ± 0.3
	San Andreas	4.5 ± 0.3	3.5 ± 0.2
Vitamin C (mg/100g)	Malwina	42.5 ± 1.2	55.2 ± 1.0
	Portola	35.8 ± 1.0	49.5 ± 0.9
	San Andreas	45.2 ± 1.3	58.8 ± 1.1
Carbohydrates (%)	Malwina	52.8 ± 1.5	52.4 ± 1.5
	Portola	48.2 ± 1.2	48.6 ± 1.2
	San Andreas	49.5 ± 1.3	50.3 ± 1.3
Organic acids (mg%)	Malwina	38.5 ± 1.0	48.2 ± 1.2
	Portola	42.5 ± 1.2	51.4 ± 1.5
	San Andreas	48.5 ± 1.4	60.5 ± 1.8
Proteins (%)	Malwina	4.2 ± 0.2	5.1 ± 0.3
	Portola	3.5 ± 0.2	4.2 ± 0.2
	San Andreas	3.8 ± 0.2	4.8 ± 0.2
L*	Malwina	42.5 ± 0.6	52.4 ± 0.5
	Portola	40.2 ± 0.5	50.8 ± 0.4
	San Andreas	41.5 ± 0.5	51.6 ± 0.5
a*	Malwina	18.5 ± 0.4	24.2 ± 0.4
	Portola	20.2 ± 0.4	26.5 ± 0.4
	San Andreas	19.5 ± 0.4	25.8 ± 0.4
Antioxidant activity (%)	Malwina	62.5 ± 1.5	79.8 ± 1.2
	Portola	55.8 ± 1.3	71.5 ± 1.4
	San Andreas	59.2 ± 1.4	76.2 ± 1.3
Parameter	Cultivar	Infrared drying (60°C, 8h)	Freeze-drying (-70°C, 52h)

3.4 Nutrient Retention Comparison. Table 6 presents the nutrient retention percentages for both drying methods.

Table 6. Nutrient retention (%) by method and cultivar

Nutrient	**Cultivar**	**Infrared drying**	**Freeze-drying**
Vitamin C	Malwina	72.5 ± 1.5	94.2 ± 1.0
	Portola	68.3 ± 1.2	94.5 ± 1.1
	San Andreas	72.3 ± 1.4	94.0 ± 1.0
Carbohydrates	Malwina	89.2 ± 1.2	89.5 ± 1.2
	Portola	86.1 ± 1.3	86.2 ± 1.5
	San Andreas	88.0 ± 1.4	88.5 ± 1.3
Organic acids	Malwina	73.5 ± 1.2	92.0 ± 1.0
	Portola	72.5 ± 1.3	87.7 ± 1.3
	San Andreas	71.5 ± 1.4	89.2 ± 1.2
Proteins	Malwina	88.5 ± 1.5	91.5 ± 1.1
	Portola	85.2 ± 1.4	88.7 ± 1.2
	San Andreas	86.5 ± 1.3	90.2 ± 1.0
Antioxidant activity	Malwina	73.0 ± 1.6	93.1 ± 1.2

Nutrient	Cultivar	Infrared drying	Freeze-drying
	Portola	70.8 ± 1.4	90.5 ± 1.3
	San Andreas	72.0 ± 1.5	92.5 ± 1.2
Nutrient	Cultivar	Infrared drying	Freeze-drying
Vitamin C	**Malwina**	**72.5 ± 1.5**	**94.2 ± 1.0**

3.5 Summary of Results

- ✓ **Freeze-drying** preserved significantly higher levels of vitamin C (94.0-94.5%), organic acids (87.7-92.0%), and antioxidant activity (90.5-93.1%) compared to infrared drying.
- ✓ **Infrared drying** required substantially less time (8 hours vs. 52 hours) and showed good preservation of carbohydrates (86.1-89.2%) and proteins (85.2-88.5%).
- ✓ **Malwina** cultivar consistently showed the best nutrient retention under both drying methods.
- ✓ **Color parameters** (L, *a*) were better preserved by freeze-drying (higher lightness and redness values).

4. DISCUSSION

4.1 Drying Kinetics. The total drying time for infrared drying (8 hours) was significantly shorter than for freeze-drying (52 hours). This difference is explained by the fundamental mechanisms of each method. Infrared radiation directly penetrates the food material and generates heat within the product, accelerating water evaporation from both surface and internal layers. In contrast, freeze-drying relies on sublimation of ice under vacuum, which is inherently slower (Sun et al., 2024; Zhao et al., 2017).

4.2 Vitamin C Retention. Vitamin C is highly sensitive to heat and oxidative degradation. Freeze-drying preserved 94.0-94.5% of vitamin C across all cultivars, while infrared drying preserved only 68.3-72.5%. This significant difference (approximately 22-26% higher retention in freeze-drying) is attributed to the low-temperature conditions of lyophilization. During infrared drying at 60°C, vitamin C degradation occurs through both thermal and oxidative pathways (Abouelenein et al., 2021).

Among cultivars, San Andreas showed the highest vitamin C retention under infrared drying (72.3%), likely due to its higher initial vitamin C content (62.4 mg/100g) and firmer tissue structure that may provide better protection against thermal degradation.

4.3 Organic Acid Retention. Organic acids (citric, malic, succinic) are also heat-sensitive. Freeze-drying showed superior retention (87.7-92.0%) compared to infrared drying (71.5-73.5%). The 15-20% difference in organic acid retention between methods is consistent with previous studies (Giampieri et al., 2015).

Interestingly, Malwina showed the highest organic acid retention under freeze-drying (92.0%) despite having the lowest initial organic acid content (52.4 mg%). This suggests that factors beyond initial concentration, such as the specific composition of organic acids or their binding within cell structures, influence retention.

4.4 Carbohydrate and Protein Retention. For carbohydrates and proteins, the differences between drying methods were smaller (approximately 2-3% higher retention in freeze-drying). Both methods showed excellent retention for these nutrients (carbohydrates: 86.1-89.5%; proteins: 85.2-91.5%). This indicates that carbohydrates and proteins are more stable under thermal processing compared to vitamins and organic acids (Kumar & Sharma, 2022).

4.5 Color Preservation. Freeze-dried strawberries had significantly higher L* (lightness) and a* (redness) values compared to infrared-dried samples. The higher redness (a*) in freeze-dried samples (24.2-26.5 vs. 18.5-20.2) indicates better preservation of anthocyanins, the pigments responsible for strawberry's red color. Anthocyanins degrade rapidly at temperatures above 50°C, explaining their better preservation during freeze-drying (Saridas & Paydas Kargi, 2023).

4.6 Antioxidant Activity. Antioxidant activity followed a similar pattern to vitamin C retention. Freeze-drying preserved 90.5-93.1% of antioxidant activity, while infrared drying preserved 70.8-73.0%. The strong correlation between vitamin C content and antioxidant activity ($r = +0.89$, $p < 0.05$) suggests that vitamin C is a major contributor to the antioxidant capacity of strawberries.

4.7 Cultivar Performance. Malwina consistently showed the best nutrient retention under both drying methods. This cultivar had the lowest initial moisture content (89.2%), highest initial carbohydrate (8.2%) and protein (0.78%) levels, and firm fruit texture. These characteristics likely contributed to better structural integrity during drying and reduced nutrient loss (Cornell University, 2014; Saridas & Paydas Kargi, 2023).

Portola showed the lowest nutrient retention under both methods, consistent with its high initial moisture (91.5%) and low initial nutrient levels.

4.8 Practical Implications. For applications where **maximum nutrient preservation** is critical (e.g., functional foods, nutraceuticals, infant foods), **freeze-drying is recommended** despite its higher cost and longer processing time.

For applications where **processing speed and energy efficiency** are priorities (e.g., large-scale industrial production, snack foods), **infrared drying at 60°C is recommended** as it provides acceptable nutrient retention (68-89% depending on nutrient) with substantial time savings.

For both methods, **Malwina cultivar** is recommended as it consistently outperformed Portola and San Andreas.

5. CONCLUSION

This study compared the effects of infrared drying (60°C, 8 hours) and freeze-drying (-70°C, 52 hours) on the quality parameters of three strawberry cultivars: Malwina, Portola, and San Andreas.

The main conclusions are:

1. Freeze-drying is superior for nutrient preservation – It retained significantly higher levels of vitamin C (94.0-94.5%), organic acids (87.7-92.0%), and antioxidant activity (90.5-93.1%) compared to infrared drying (vitamin C: 68.3-72.5%; organic acids: 71.5-73.5%; antioxidants: 70.8-73.0%).

2. Infrared drying is faster and more energy-efficient – It required only 8 hours compared to 52 hours for freeze-drying, with good retention of carbohydrates (86.1-89.2%) and proteins (85.2-88.5%).

3. Malwina is the best-performing cultivar – This cultivar showed the highest nutrient retention under both drying methods, likely due to its low initial moisture content, high initial nutrient levels, and firm fruit texture.

4. Cultivar selection matters – Portola, with the highest initial moisture and lowest nutrient levels, consistently showed the lowest retention under both methods.

5. Method selection depends on application – Freeze-drying is recommended for maximum quality (functional foods, premium products), while infrared drying is recommended for rapid, cost-effective processing (snack foods, large-scale production).

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