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Does a Freeze-thaw Pretreatment Enhance the Quality of Dried Foods? A Meta-Analysis

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Abstract

Based on the results of several studies, it's questionable if freeze-thaw pretreatment can improve dried product qualities. To answer this question, a meta-analysis was conducted to explain the effect of freeze-thaw pretreatment on the quality of dried products. This research aimed to determine the impact of freeze-thaw pretreatment on the quality of dried plant-based foods. The data was sourced from the Scopus database, and the selection criteria were based on the PRISMA protocol. All meta-analysis calculations were performed using OpenMEE Software. The results revealed that freeze-thaw pretreatment significantly affected ΔE, TFC, and TPC. However, freeze-thaw pretreatment does not significantly affect shrinkage and hardness. Based on the analysis subgroup found, the best freezing temperatures are -20 °C and -196 °C because both temperatures favourably impact TFC and hardness. Moreover, freeze-thaw pretreatment is suitable for infrared hot air, near-infrared, and hot air–microwave vacuum drying. The freeze-thaw pretreatment has also been effective in enhancing the quality of lotus roots, cranberries, and red dragons.

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1. Introduction

Drying is a technique used to reduce water content and activity to inhibit degradation (Onwude et al., 2017). This method extends food shelf life and boosts nutritional and economic value (Vallespir et al., 2019). However, the heat process during drying also reduces the quality of the final product.

To improve the quality of the final product, various pretreatments are carried out before drying. One such pretreatment is the freeze-thaw method, which shows promising prospects for research and application due to its simplicity and low cost (Zhang et al., 2022). This method brings about structural changes in food constituents, reduces drying time, and enhances their physicochemical and bioactive properties (Guo et al., 2020; Zhang et al., 2022). The freeze-thaw pretreatment has been found to reduce the hardness, adhesiveness, and gumminess of dried cape gooseberries, resulting in improved texture (Junqueira et al., 2017). In addition, freeze-thaw-dried grapes have been found to contain higher antioxidant and TPC levels (Noshad & Ghasemi, 2020). However, some studies have reported contradictory findings, indicating that freeze-thaw pretreatment reduces the quality of dried products. For instance, ascorbic acid and TPC in beetroots, apples, and eggplants were found to decrease after the freeze-thaw treatment (Vallespir et al., 2019), while dried berries became harder, chewier, and gummier (Zielinska et al., 2015).

The question of whether freeze-thaw pretreatment is beneficial for drying raises a contradiction. To address this question, a statistical technique called meta-analysis can be used to determine the impact of freeze-thaw pretreatment on the quality of dried products. Meta-analysis involves summarizing the results of independent studies to conclude the significance of the treatment effect on the control (Červenka et al., 2018). By synthesizing the outcomes of multiple studies and determining their effect sizes, the primary conclusion may be drawn regarding the significance of the treatment effect on the control (Borenstein et al., 2009). In this case, a meta-analysis was conducted on drying, as reported by Červenka et al. (2018) and Kurniasari et al. (2022). Červenka et al. (2018) investigated the effect of drying temperature on the concentrations of ascorbic acid, flavonoids, and phenolics, while Kurniasari et al. (2022) studied how the drying method influences the bioactivity of ginger. The results showed that the drying temperature had a significant impact on the value of ascorbic acid but not on the levels of phenolics and flavonoids (Červenka et al., 2018), while the drying method had different effects on phenolics, flavonoids, 6-gingerol, and antioxidant content (Kurniasari et al., 2022).

In this study, the impact of freeze-thaw pretreatment on the quality of dried products will be examined by employing meta-analysis. This research aimed to determine the effects of freeze-thaw pretreatment on the quality of dried plant-based foods.

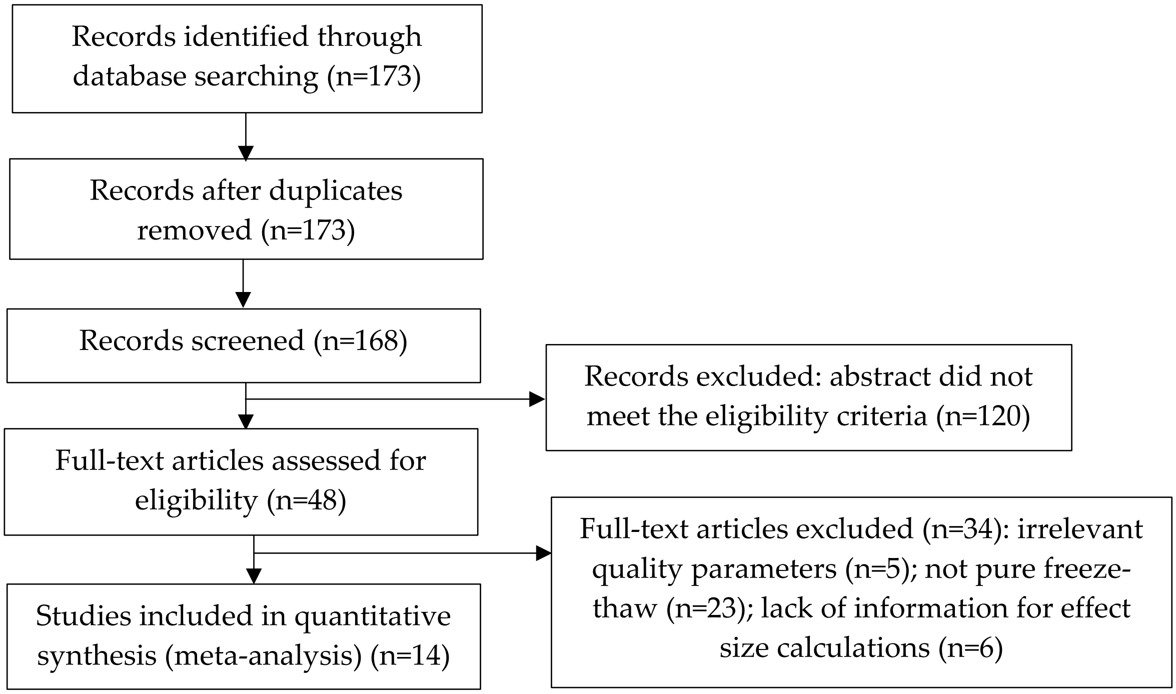

Figure 1. Flow chart of literature selection procedure based on PRISMA protocol

2. Research Method

2.1 Data Source and Selection Criteria

During June 2023, a thorough search was carried out on the Scopus database (https://www.scopus.com) to find research studies related to the impact of freeze-thaw pretreatment on the quality of dehydrated plant-based foods. The search criteria were narrowed down to English-written peer-reviewed journal articles and specifically targeted the keywords drying, pretreatment, and freezing. The selection of the relevant literature was based on the PICO protocol (Ogbuewu & Mbajiorgu, 2023), an acronym for Population (referring to plant-based food), Intervention (referring to freeze-thaw pretreatment), Comparison (referring to freeze-thaw pretreatment and without pretreatment), and Outcomes (referring to ΔE, *TFC*, *TPC*, shrinkage, and hardness). Preferred reporting items for systematic review and meta-analysis (PRISMA) protocol were also used to reduce bias and ensure meta-analysis quality (Liberati et al., 2009). **Figure 1** represents the literature selection procedure based on PRISMA that summarizes the details of the article search.

Through a comprehensive search of the Scopus database, a total of 173 articles were identified. After screening, five articles were deemed unsuitable as they were not published in a peer-reviewed journal. The remaining 48 articles were then thoroughly evaluated in full text, resulting in the exclusion of 34. Ultimately, a total of 14 articles were selected for the final meta-analysis.

2.2 Data Synthesis

The data used to calculate the effect size was obtained from studies that met the criteria for meta-analysis. This data was derived from the control and pretreatment of dried product quality and included relevant figures such as mean, standard deviation, and sample size. To ensure consistency, WebPlot-Digitizer (https://apps.automeris.io/wpd/) was employed to transform data from charts and histograms into standardized units. Additionally, data was collected to investigate how the quality observed was affected by various moderator variables, such as freezing temperature, drying method, and commodity.

2.3 Statistical Analysis

The Open MEE Software was used for all meta-analysis calculations (Wallace et al., 2017). The effect size was determined by calculating the mean difference between samples with and without freeze-thaw pretreatment (control) in the form of standardized mean differences (SMD), with a 95% confidence interval (CI).

Subgroup analysis on variable moderators was performed to determine the effect of variables on the impact of freeze-thaw pretreatment on outcome measurement, with subgroups with three comparisons omitted from the meta-analysis (Ogbuewu & Mbajiorgu, 2023). The sources of heterogeneity were assessed by employing the QM (coefficient of moderators) and I^2 (inconsistency index). (Higgins & Thompson, 2002). It was considered significant if the lower and upper ranges of SMD's 95% CI did not include 0.

3. Result and Discussion

3.1 The effect of freeze-thaw pretreatment on the quality of dried plant-based foods

A meta-analysis was conducted on 14 studies that met the criteria (as shown in **Table 1**) to examine the impact of freeze-thaw pretreatment on the quality of dried plant-based foods. The analysis considered various quality parameters such as total color difference (ΔE), total flavonoid content (*TFC*), total phenolic content (*TPC*), shrinkage, and hardness. The findings of the meta-analysis are summarized in **Table 2**.

Table 1. Summary of data synthesis of qualities of dried plant-based foods with freeze-thaw pretreatment

Commodity	Freezing temperature (°C)	Drying method	Parameter	References
Grapes	-18	Solar	2, 3, 5	(Quispe-fuentes et al., 2023)
Grapes	-20, -196	HA	1, 3, 4	(Noshad & Ghasemi, 2020)
Red dragon fruits	-20, -80, -196	MIR, NIR	1, 2, 3, 4, 5	(Bassey et al., 2023)
Red dragon fruits	-20	Infrared	1, 2, 3, 4, 5	(Bassey et al., 2022)
Cranberries	-18, -196	HA, HA-MV	2, 3	(Zhou et al., 2021)
Cranberries	-18, -196	HA-MV	2, 3, 5	(Z. L. Liu et al., 2020)
Cranberries	-18, -196	HA, MV	5	(Zielinska et al., 2019)
Cranberries	-20, -196	HA	4	(Zielinska et al., 2018)
Cape gooseberries	-18, -196	HA	1, 5	(Junqueira et al., 2017)
Blueberries	-20	HA, MV, HA-MV	4, 5	(Zielinska et al., 2015)
Apples	-80	EP	5	(Bi et al., 2015)
Lotus roots	-20, -40, -60, -80	I-C	1, 2, 3, 4, 5	(Zhang et al., 2022)
VBT leaves	-18	HA	3	(Miao et al., 2020)
P. grandiflorum	-20	HA, PSMV	1	(Y. yuan Liu et al., 2021)

VBT – *Vaccinium bracteatum* Thunb; HA – hot air; MV – microwave vacuum; I-C – infrared-convective; EP – explosion puffing; MIR – mid infrared; NIR – near infrared; PSMV – pulse-spouted microwave vacuum; 1 – total color difference; 2 – total flavonoid content; 3 – total phenolic content; 4 – shrinkage; 5 – hardness.

This study shows that using freeze-thaw pretreatment has a significant impact ($P < 0.05$) on ΔE, *TFC*, and *TPC* of dried plant-based foods compared to the control. However, it does not significantly affect ($P > 0.05$) shrinkage and hardness. Freeze-thaw pretreatment hurts discoloration by increasing ΔE of dried foods compared to the control. This is consistent with the findings of Vallespir et al. (2018), who reported that frozen beetroots, apples, and eggplants had a higher ΔE than the control. The destruction of cellular structural integrity results in the enzymatic browning reaction of enzymes and polyphenolic compounds, which causes a color change (Vallespir et al., 2019).

The total flavonoid content of dried plant-based foods improved by freeze-thaw pretreatment compared to the control. Cell damage due to freeze-thaw pretreatment promotes the extraction of total flavonoids, leading to a higher *TFC* (Xu et al., 2021). In contrast, freeze-thaw pretreatment has an unfavourable effect on the *TPC* of dried plant-based foods compared to the control. The reduction in phenolic chemicals may be due to their interactions with other substances, such as proteins, or changes in their chemical structure brought on by drying (Piroozi et al., 2023). Ice crystal formation may also cause cellular wall rupture, leading to bioactive chemicals' loss and/or oxidation (Vallespir et al., 2019). Due to drip loss and oxidation reactions, the *TPC* of the frozen potato was substantially lower than the control (Zhu et al., 2020).

Table 2. Pooled results freeze-thaw pretreatment and control on quality plant-based foods

Output variables	n^s	n^c	SMD	95% CI		SE	P-value	Heterogeneity			
				lower	upper			Q_M	DF	P-value	I^2
ΔE	6	20	1.916	1.056	2.776	0.439	< 0.001	63.396	19	< 0.001	70.03
TFC (mg QE/g dry matter)	6	18	0.891	0.232	1.549	0.336	0.008	38.533	17	0.002	55.883
TPC (mg GAE/g dry matter)	8	25	-1.594	-2.359	-0.829	0.39	< 0.001	81.446	24	< 0.001	70.533
Shrinkage (%)	6	32	-0.367	-1.351	0.617	0.502	0.465	266.578	31	< 0.001	88.371
Hardness (N)	9	44	-0.484	-1.116	0.148	0.323	0.133	712.073	43	< 0.001	93.961

ΔE = total color difference; *TFC* = total flavonoid content; *TPC* = total phenolic content; n^s = number of studies; n^c = number of comparisons; SMD = standardized mean difference; CI = confidence interval; SE = standard error; Q_M = coefficient of moderators; DF = degree of freedom; I^2 = Inconsistency index.

The freeze-thaw process does not influence (P > 0.05) shrinkage and hardness of dried plant-based foods compared to the control, but their values tended to decrease. The drying temperature and drying time play the largest roles in the shrinkage (Noshad & Ghasemi, 2020). Differences in food structure and drying techniques could be responsible for some of the variation in reported shrinkage results (Bassey et al., 2023). Freeze-thaw enhanced the product's porosity, resulting in low hardness (Zhang et al., 2022). Conversely, the surface removes water faster than it migrates from the inside, forming a hard coating of previously dissolved solutes (Quispe-fuentes et al., 2023). Some caramelization and Maillard reactions have been attributed to increased hardness (Khiari et al., 2021). This contradicting could be the origin of variations in hardness levels, resulting in meta-analysis calculations that are not significantly different.

3.2 Subgroup analysis: The effect of moderator variable on the quality of dried plant-based foods

3.2.1 Freezing temperature

Table 3 displays a breakdown of the freezing temperature sub-group analysis. The results indicate that a temperature of -18 °C does not have a significant impact (P > 0.05) on *TFC*, *TPC*, and hardness of dried foods compared to the control. However, at -20 °C, there is a significant effect on ΔE, *TFC*, and hardness (P < 0.05), while *TPC* and shrinkage remain unaffected significantly (P > 0.05) compared to the control. Freezing at -80 °C does not considerably influence (P > 0.05) ΔE, *TFC*, and shrinkage, but it significantly reduces (P < 0.05) *TPC*, and hardness compared to the control. On the other hand, a temperature of -196 °C has a significant effect (P < 0.05), which increases *TFC* and shrinkage while lowering hardness. However, it does not significantly impact (P > 0.05) ΔE and *TPC*. It is important to note that higher freezing temperatures result in longer freezing times, increased ice crystal formation, and more tissue cell damage (Chung et al., 2013; Ergün et al., 2021).

Based on the results of the data analysis, it seems that temperatures of -20 and -196 °C are both feasible for freezing. Zhang et al. (2022) also came to the same conclusion: -20 °C is the optimum freezing temperature out of -40, -60, and -80 °C. On the other hand, freezing in liquid nitrogen (-196

°C) may have minimized structural damage and preserved quality due to the rapid freezing rate and small crystals formed during the process (Vallespir et al., 2019).

Table 3. Sub-group analysis of the effect of freezing temperature on the quality of dried plant-based foods

Output variables	Subgroup (freezing temperature, °C)	SMD	95% CI		SE	P-value
			Lower	Upper		
ΔE	-20	2.082	1.162	3.002	0.469	< 0.001
	-80	0.835	-1.303	2.973	1.091	0.444
	-196	0.994	-0.949	2.936	0.991	0.316
TFC (mg QE/g dry matter)	-18	0.695	-0.267	1.657	0.491	0.157
	-20	1.662	0.075	3.249	0.810	0.040
	-80	0.466	-0.474	1.407	0.480	0.331
	-196	1.849	0.226	3.472	0.828	0.026
TPC (mg GAE/g dry matter)	-18	-2.973	-6.079	0.132	1.584	0.061
	-20	-1.026	-2.141	0.089	0.569	0.071
	-80	-1.373	-2.427	-0.319	0.538	0.011
	-196	-1.672	-3.386	0.041	0.874	0.056
Shrinkage (%)	-20	0.841	-0.219	1.901	0.541	0.120
	-80	-1.346	-5.095	2.403	1.913	0.482
	-196	3.340	1.248	5.433	1.068	0.002
Hardness (N)	-18	0.618	-0.467	1.703	0.553	0.264
	-20	1.216	0.485	1.948	0.373	0.001
	-80	-3.160	-4.127	-2.194	0.493	< 0.001
	-196	-2.048	-3.347	-0.749	0.663	0.002

ΔE = total color difference; *TFC* = total flavonoid content; *TPC* = total phenolic content; SMD = standardized mean difference; CI = confidence interval; SE = standard error.

3.2.2 Drying method

The findings of the sub-group analysis of the effect of the drying method are presented in **Table 4**. This study revealed that drying with hot air (HA) has a significant impact ($P < 0.05$) on both the ΔE and *TPC* of dried foods while having no significant influence ($P > 0.05$) on shrinkage and hardness when compared to the control. In contrast, infrared-convective (I-C) drying significantly impacts ($P < 0.05$) shrinkage, ΔE, *TPC*, and hardness, though *TFC* remains unaffected significantly ($P > 0.05$). Mid-infrared (MIR) drying has no significant effect ($P > 0.05$) on the observed qualities. Mid-infrared (MIR) drying has no significant effect ($P > 0.05$) on all qualities observed. Near-infrared drying significantly affects ($P < 0.05$) shrinkage and *TFC*, but not ΔE, *TPC*, or hardness. Hot air–microwave vacuum (HA-MV) drying only significantly affects ($P < 0.05$) *TFC*, but not *TPC*, shrinkage, or hardness.

Table 4. Sub-group analysis of the effect of the drying method on the quality of dried plant-based foods

Output variables	Subgroup	SMD	95% CI		SE	P-value
			Lower	Upper		
ΔE	HA	2.365	1.687	3.043	0.346	< 0.001
	I-C	4.552	1.862	7.243	1.373	< 0.001
	MIR	-0.683	-4.392	3.027	1.893	0.718
	NIR	0.902	-1.032	2.836	0.987	0.361
TFC (mg QE/g dry matter)	HA-MV	1.050	0.078	2.023	0.496	0.034
	I-C	-0.545	-1.386	0.296	0.429	0.204
	MIR	0.478	-0.472	1.428	0.485	0.324
	NIR	2.535	0.267	4.804	1.157	0.028
TPC (mg GAE/g dry matter)	HA	-3.370	-5.640	-1.100	1.158	0.004
	HA-MV	-1.180	-3.123	0.764	0.992	0.234
	I-C	-2.030	-3.038	-1.023	0.514	< 0.001
	MIR	-0.656	-1.605	0.294	0.485	0.176
	NIR	-1.436	-3.600	0.728	1.104	0.194
Shrinkage (%)	HA	2.182	0.797	3.567	0.707	0.002
	HA-MV	1.496	-1.122	4.113	1.335	0.263
	I-C	-11.516	-15.719	-7.312	2.145	< 0.001
	MIR	0.198	-1.245	1.640	0.736	0.788
	NIR	1.743	0.650	2.835	0.557	0.002
Hardness (N)	HA	-1.027	-2.340	0.285	0.670	0.125
	HA-MV	0.725	-0.757	2.207	0.756	0.338
	I-C	-3.141	-4.365	-1.917	0.625	< 0.001
	MIR	-0.620	-6.738	5.498	3.122	0.842
	NIR	0.781	-3.065	4.627	1.962	0.691

ΔE = total color difference; *TFC* = total flavonoid content; *TPC* = total phenolic content; SMD = standardized mean difference; CI = confidence interval; SE = standard error; HA – hot air; MV – microwave vacuum; I-C – infrared-convective; EP – explosion puffing; MIR – mid infrared; NIR – near infrared.

In general, it can be concluded that numerous drying methods have a favorable effect on dried product quality, notably I-C (shrinkage and hardness), NIR (*TFC*), and HA-MV (*TFC*). Convective air at high temperatures will accelerate drying (Červenka et al., 2018). Transfers energy on infrared drying quickly from heat emitter to foodstuffs without heating the environment, preserving product quality (Adak et al., 2017). Vacuum drying increases heat transmission between frozen cells and rapid water evaporation from ice crystals (Shyu & Hwang, 2001). In the final drying stage, replacing hot air with microwaves substantially increased *TFC* (Zhou et al., 2021).

3.2.3 Commodity

Freeze-thaw pretreatment has been employed for drying various types of commodities. A sub-group analysis was conducted to investigate the impact of freeze-thaw pretreatment on the quality of dried food in various commodities (**Table 5**).

Table 5. Sub-group analysis of the effect of the commodity on the quality of dried plant-based foods

Output variables	Subgroup	SMD	95% CI		SE	P-value
			Lower	Upper		
ΔE	Lotus roots	4.552	1.862	7.243	1.373	< 0.001
	Red dragons	0.401	-1.200	2.002	0.817	0.623
	Grapes	2.118	1.278	2.958	0.428	< 0.001
TFC (mg QE/g dry matter)	Cranberries	1.276	0.153	2.399	0.573	0.026
	Lotus roots	-0.545	-1.386	0.296	0.429	0.204
	Red dragons	1.558	0.427	2.689	0.577	0.007
TPC (mg GAE/g dry matter)	Cranberries	-0.355	-1.770	1.059	0.722	0.623
	Lotus roots	-2.030	-3.038	-1.023	0.514	< 0.001
	Red dragons	-0.794	-1.572	-0.015	0.397	0.046
	Grapes	-3.646	-5.956	-1.336	1.179	0.002
Shrinkage (%)	Cranberries	1.479	-0.651	3.608	1.086	0.174
	Blueberries	1.549	-0.178	3.276	0.881	0.079
	Lotus roots	-11.516	-15.719	-7.312	2.145	< 0.001
	Red dragons	0.628	-0.406	1.662	0.528	0.234
	Grapes	2.894	1.380	4.408	0.772	< 0.001
Hardness (N)	Cranberries	-0.550	-1.478	0.377	0.473	0.245
	Blueberries	1.197	0.407	1.987	0.403	0.003
	Lotus roots	-3.141	-4.365	-1.917	0.625	< 0.001
	Red dragons	0.061	-2.359	2.481	1.235	0.961
	Blueberries	-0.118	-0.924	0.687	0.411	0.774

ΔE = total color difference; *TFC* = total flavonoid content; *TPC* = total phenolic content; SMD = standardized mean difference; CI = confidence interval; SE = standard error.

A statistically significant increase ($P < 0.05$) in the ΔE is observed in dried lotus roots and grapes compared to the control. In contrast, applying freeze-thaw pretreatment to red dragons does not have a statistically significant impact on ΔE. The cranberries and red dragons significantly rise ($P < 0.05$) in *TFC* compared to the control. For lotus roots, the freeze-thaw pretreatment has no significant impact ($P > 0.05$). Compared to controls, total phenolic content is reduced in the presence of freeze-thaw pretreatment on cranberries, lotus roots, red dragons, and grapes. However, only on cranberries is the effect insignificant ($P > 0.05$). Compared to the control, lotus roots experienced significantly lower shrinkage ($P < 0.05$), whereas grapes experienced substantially more significant shrinkage ($P < 0.05$). In contrast, the freeze-thaw pretreatment has an insignificant impact ($P > 0.05$) on the shrinkage of cranberries, blueberries, and red dragons. The hardness of blueberries exhibited a statistically significant increase ($P < 0.05$), but lotus roots demonstrated a substantial drop ($P < 0.05$) compared to the control. The freeze-thaw pretreatment does not substantially impact ($P > 0.05$) the hardness of cranberries, blueberries, and red dragons. The influence of freezing on a product's quality depends upon the product's type and the rate at which freezing occurs (Chassagne-Berces et al., 2009).

After analyzing the results, it appears that implementing a freeze-thaw pretreatment for lotus roots may be a promising solution, as it has been shown to significantly decrease shrinkage and hardness. Additionally, this pretreatment is advantageous for maintaining the bioactive components, such as *TFC*, in fruits like cranberries and red dragons.

4. Conclusion

Meta-analysis was performed in this study to determine the effect of freeze-thaw pretreatment on dried food quality compared to the controls. Freeze-thaw pretreatment has different effects on the qualities of dried plant-based foods. It has improved *TFC* but degraded *TPC* and color change. Freeze-thaw pretreatment is recommended at freezing temperatures of -20 and -196 °C and is suitable for infrared hot air, near-infrared, and hot air – microwave vacuum drying. The freeze-thaw pretreatment has also enhanced the quality of lotus roots, cranberries, and red dragons.

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