



Review article

Effectiveness of ultrasound pretreatment on dried plant-based food quality: A meta-analysis

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Abstract

Importance of the work: Ultrasound has promising potential for pretreatment to enhance drying quality; however, there is a lack of quantitative synthesis across commodities and conditions.

Objectives: To assess the effectiveness of ultrasound pretreatment on dried plant-based products and to investigate the effects of commodity category, ultrasound pretreatment (UP) parameters and drying parameters based on subgroup analyses.

Materials and Methods: A meta-analysis of 55 Scopus-indexed studies was conducted using OpenMEE and applying Hedges' d and a random-effects model. The key quality parameters analyzed were color, rehydration ratio (RR), flavonoids (TFC), phenolics (TPC), vitamin C, antioxidant capacity based on 2,2-diphenyl-1-picrylhydrazyl (DPPH) antioxidant assay and water activity (Aw). Subgroup analyses examined commodity category, as well as ultrasound and drying parameters.

Results: Ultrasound pretreatment significantly ($p < 0.05$) improved most quality parameters, except DPPH and vitamin C. Large effect sizes were observed for RR (3.339), TFC (2.093), TPC (0.876) and Aw (−2.096). High heterogeneity (inconsistency index >75%) indicated substantial inter-study variability, necessitating subgroup analyses. These analyses confirmed that commodity categories, ultrasound pretreatment parameters (equipment, sample-to-water ratio, frequency, power, duration, temperature) and drying parameters (method and temperature) significantly influenced UP effectiveness.

Main finding: UP consistently improved multiple quality parameters, especially color stability, rehydration ratio, bioactive compound retention and water activity. Subgroup analysis revealed that treatment using 28 kHz, 300 W and 30°C for 30 min, followed by hot-air drying at 60°C, was particularly favorable for enhancing the drying quality of low-porosity root crops.

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Introduction

Drying is essential for preserving plant-based foods (Calín-Sánchez et al., 2020; Petikirige et al., 2022), but it can degrade their quality (Radojčin et al., 2021). Various pretreatment techniques have been developed to mitigate these losses, improving drying efficiency and product quality by modifying cellular structures and reducing physical and biochemical degradation (Deng et al., 2019; Radojčin et al., 2021).

Among these techniques, ultrasound pretreatment (UP) has gained increasing attention due to its ability to enhance mass and heat transfer during subsequent drying, because UP involves the application of high-frequency sound waves (>20 kHz) to materials before drying, leading to microstructural changes such as cell wall disruption and increased porosity (Deng et al., 2019; Radojčin et al., 2021; Kutlu et al., 2022), improving efficiency while minimizing texture degradation (Paniwnyk, 2016).

The impact of UP on the quality of dried products remains inconsistent across studies, mainly due to variations in the physical properties of raw materials, ultrasound parameters (power, frequency, duration and temperature) and the drying methods used (Radojčin et al., 2021). For example, using UP, the drying time has been reported to reduce by up to 40% in apples (Nowacka et al., 2012) while increasing in carrots (Nowacka and Wedzik, 2016). Similarly, while some studies have reported that UP enhanced ascorbic acid retention by removing dissolved oxygen (Aadil et al., 2013; Abid et al., 2013), others have indicated that it accelerated degradation due to increased air exposure (Ordóñez-Santos et al., 2017; Santhirasegaram et al., 2013). Additionally, UP duration does not consistently correlate with drying time, as a more prolonged pretreatment does not always result in faster drying (Fernandes, 2008; Nowacka et al., 2012; Sledz et al., 2016). These conflicting findings highlight the need for a systematic approach to evaluate UP's effectiveness and optimal application.

Meta-analysis provides a robust method to address such inconsistencies by synthesizing findings across studies, assessing effect sizes and identifying moderating factors (Abrahamse et al., 2015; Gurevitch et al., 2018; Hansen et al., 2022). In addition, it mitigates potential biases and enhances the reliability (Aguinis et al., 2011; Bergh et al., 2014). Applying meta-analysis to UP research can clarify its overall impact on drying efficiency and product quality,

resolving contradictions in published studies. Zhao et al. (2024) conducted the first meta-analysis on the application of UP in drying fruits and vegetables, providing an important foundation for subsequent research in this field. Building upon this study, the present research introduced two additional quality parameters that had not been previously analyzed: rehydration ratio (RR) and water activity (Aw). Furthermore, the present study expanded the scope of moderator analyses by examining the effects of commodity category, equipment type, weight ratio, pretreatment temperature, drying method and drying temperature on the effectiveness of UP. In addition, the Scopus database was used as the primary source for literature retrieval, as well as considering publication bias. Therefore, the objectives of the present study were to assess the effectiveness of ultrasound pretreatment on dried plant-based products and to investigate the effects of commodity categories, UP parameters and drying parameters based on subgroup analyses.

Materials and Methods

Data source

A systematic literature search was performed in February 2024 using the Scopus database. The search strategy involved combinations of the keywords: “drying,” “pretreatment,” “sonication,” “ultrasound” and “ultrasonic.” The search was limited to peer-reviewed journal articles. No publication year or study design restrictions were applied during the initial search stage. Inclusion criteria required studies to be fully accessible and written in English and to provide primary quantitative data for effect size calculation.

Study selection

A systematic selection of studies ensures an accurate and meaningful meta-analysis (Kormos, 2016). The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram (Fig. 1) illustrates the selection process, detailing records identified, screened, included and excluded at each stage (Liberati et al., 2009).

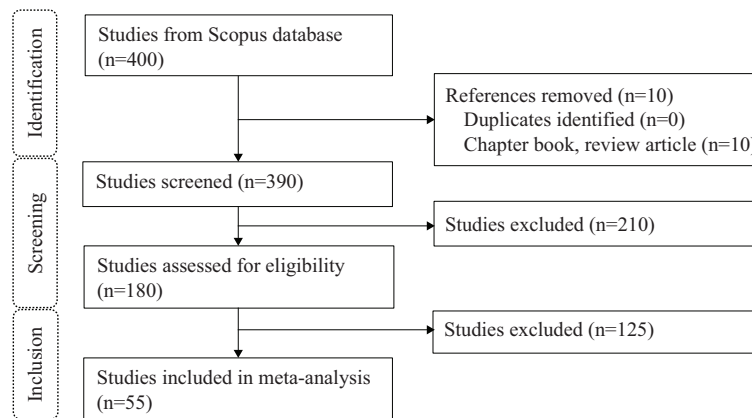


Fig. 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram: Study screening and selection process.

Eligibility was assessed using the PICO (Population, Intervention, Comparison, Outcome) framework: P (plant-based foods), I (UP using water as the medium), C (untreated versus UP sample) and O (quality parameters: total color differences (ΔE), RR, TPC, TFC, vitamin C, Aw and antioxidant capacity (2,2-diphenyl-1-picrylhydrazyl (DPPH) antioxidant assay). Only peer-reviewed journal articles published within the past 20 yr were considered, yielding 400 potential articles. After title and abstract screening, 10 articles (book chapters or reviews) were excluded. A further 210 were excluded for not meeting the eligibility criteria. Of the 180 full-text articles reviewed, 125 were removed due to irrelevant quality parameters (26), lack of pure UP application (40) or insufficient effect size data (59). Ultimately, 55 studies met the inclusion criteria and data were extracted accordingly.

Data extraction

Data were extracted from each included study to calculate effect sizes, gathering means, standard deviations and sample sizes for UP and control groups. Data from graphs or diagrams were digitized using WebPlotDigitizer (<https://automeris.io/>), ensuring accuracy and standardizing outcome measurement units for consistency in data analysis (Yulni et al., 2024). Additionally, coded values for moderation or subgroup analyses consisted of: ultrasound frequency, power, pretreatment temperature, duration, drying method, drying temperature and commodity categories. This extraction process ensured that relevant variables were identified accurately and integrated, enabling a comprehensive evaluation of UP effects across different methodological characteristics and moderating variables.

Data analysis

Extracted data were stored in CSV format using the Excel software (Microsoft Corp.; Redmond, WA, USA), while meta-analysis was conducted in OpenMEE (Wallace et al., 2017). The effect size metric used was Hedges'd, which accounts for sample size bias and effectively measures treatment effects (Sanchez-Meca and Marin-Martinez, 2010). A random-effects model was applied to estimate the generalized treatment effect while accounting for study variability (Borenstein et al., 2009). The confidence interval used was 95%, offering a measure of precision for the estimated effect obtained from the meta-analysis. The analysis applied a 95% confidence interval to ensure accuracy in effect size estimation, with interpretation following the classification of Cohen (1992): small ($d = 0.2$), medium ($d = 0.5$) and large ($d = 0.8$).

Study heterogeneity was assessed using the Q (moderator coefficient) and I^2 (inconsistency index) statistics (Higgins and Thompson, 2002). Significant Q values indicated heterogeneity, while I^2 values categorized heterogeneity as low (25%), moderate (50%) or high (75%) (Borenstein et al., 2009; Higgins et al., 2003). Due to significant heterogeneity, a subgroup analysis was performed to examine the impact of moderator variables on effect sizes (Borenstein et al., 2009), excluding subgroups with fewer than three comparisons (Ogbuewu and Mbajorgu, 2023).

Publication bias was assessed using the fail-safe N method, calculated using Rosenthal's method (Rosenthal, 1979), which estimates the number of missing studies required to nullify the significance (Viechtbauer, 2007). A fail-safe N greater than $5K + 10$ (where K is the number of included studies) indicated an absence of publication bias (Borenstein et al., 2009).

Results

Summary of studies included in meta-analysis

A meta-analysis was conducted on 55 studies published during 2014–2024 (Table 1) to investigate the impact of UP on the quality of dried plant-based products. The geographical distribution of studies spanned China, Iran, Brazil, Turkey, Poland, the USA, India, Canada, Australia and Ghana, reflecting global interest in UP applications. Most analyses included studies originating from countries with major advancements in food technology research.

Some studies were excluded due to insufficient data for effect size calculations, highlighting the need for standardized reporting in future research. Methodological consistency was maintained by predominantly using water as the medium in a bath or probe. However, variations in pretreatment and drying parameters contributed to heterogeneity, necessitating moderator analysis.

Among the studies meeting the inclusion criteria, 29 studies (152 comparisons) analyzed ΔE , 18 studies (59 comparisons) examined RR, 10 studies (56 comparisons) investigated TFC, 30 studies (138 comparisons) assessed TPC, 10 studies (59 comparisons) measured DPPH, 11 studies (69 comparisons) analyzed vitamin C and 13 studies (36 comparisons) focused on Aw. Variable moderators identified as potential sources of heterogeneity were coded for subgroup analysis, including pretreatment parameters (equipment, sample-to-water ratio, frequency, power, temperature and duration), drying parameters (method and temperature) and commodity categories. Commodities were classified into fruits, leaves, roots, mushrooms, flowers and seeds. Pretreatment conditions varied widely, with the equipment type being probe and bath, sample-to-water ratios 1:4–3:500, ultrasound frequencies 20–60 kHz, power levels 70–1,200 W, pretreatment duration 2–60 min and pretreatment temperatures 25–40°C. Drying methods consisted of hot-air, infrared, microwave, freeze and hybrid drying, with temperatures for hot-air drying in the range 40–80°C.

Table 1 Details of studies included in various meta-analyses

Commodity	Pretreatment parameter				Drying parameter		Outcome
	Frequency (kHz)	Power (W)	Time (min)	Temperature (°C)	Method	Temperature (°C)	
Fruits							
Apple (Bai et al., 2023)	20	240	10, 30, 60	40	HA	60	ΔE , TPC
Apple (Çetin and Sağlam, 2023)	40	150	20	25	HA, M-HA, M, F	60, 70	ΔE , TPC, DPPH, Vit. C
Apple (Matys et al., 2021)	21	180	60	21.7	HA	-	TPC, Aw
Apple (Amanor-Atiemoh et al., 2020)	20+60	-	30	25	-	70	TFC, TPC, DPPH
Apple (Fijalkowska et al., 2016)	21, 35	-	30	-	HA	-	Aw
Apple (Mothibe et al., 2014)	25	200	5	-	-	-	RR, Aw
Blackberry (Kaveh et al., 2020)	28	70	15, 30, 45	30	HA	50, 60, 70	ΔE
Blackberry (Taghinezhad et al., 2021)	28	-	15, 30, 45	-	I-HA	-	ΔE
Hawthorn (Kaveh et al., 2023)	28	70	15	-	M	-	ΔE , RR, TPC, DPPH
Hawthorn (Abbaspour-Gilandeh et al., 2021a)	37	70	20	30	HA, M-HA, I-HA	60	ΔE , RR, TPC
Red bell pepper (Rybak et al., 2022)	21	300	-	-	M-HA, HA	40, 50	RR, TPC, Vit C, Aw
Red bell pepper (Rybak et al., 2021)	21	300	30	-	F	-	RR, Aw
Longan (Deng et al., 2023)	40	240	30	-	HA	60	ΔE , TPC, Aw
Terebinth (Abbaspour-Gilandeh et al., 2021b)	28	70	30	30	HA, I	50, 60, 70	ΔE , RR, TPC
Olive (Aydar, 2021)	25	150000*	5	25	M	-	ΔE , TPC
Persimmon (Bozkir and Ergün, 2020)	35	480	10, 20, 30	30	HA	60	ΔE , TPC
Pumpkin (Chao et al., 2022)	20	360	10	25	FIR	-	ΔE
Grape (Quispe-fuentes et al., 2023)	40	-	30	-	Solar	-	TPC, Aw

Table 1 Continued

Commodity	Pretreatment parameter			Drying parameter		Outcome
	Frequency (kHz)	Power (W)	Time (min)	Temperature (°C)	Method	
Melon (Tepe and Kadakal, 2022)	35	320, 640	30	30	HA	RR
Papaya (de Arruda et al., 2023)	25	-	20	30	HA, I	TPC, Vit C, Aw
<i>P. emblica</i> (Huang et al., 2023)	-	200, 250, 300, 350	2, 4, 6, 8	-	HA	ΔE
Cranberry (Liu et al., 2020)	25	600	10	-	HA-MV	TPC
Goji berry (Ni et al., 2020a)	-	300	30	35	EH	RR
Bitter melon (Jin et al., 2019)	-	1200	-	25	HA, RFHA	ΔE, RR, Vit C, Aw
Pineapple (Rani and Tripathy, 2019)	40	-	20, 30	30	HA	ΔE
Kiwifruit (J. Wang et al., 2019)	20	400	10, 20, 30	-	HA	ΔE, Vit C
Tomato (Horuz et al., 2017)	25	300	20	26.4	M	ΔE, TPC, Vit C
Roots						
Ginger (Buvaneswaran et al., 2022)	20	-	15	-	HA	RR
Ginger (Osae et al., 2019b)	33	600	30	30	HA	TPC, DPPH
Ginger (Osae et al., 2019a)	33	600	30	30	HA	RR, TPC, DPPH
Turmeric (An et al., 2022)	-	-	-	-	PSMV	ΔE, TFC, TPC
Sweet potato (Rashid et al., 2022)	20, 40, 60	-	30	30	HA, I	TFC, TPC, Vit C
Sweet potato (Rashid et al., 2019a)	40, 60	-	30	30	HA	TFC, TPC
Sweet potato (Rashid et al., 2019b)	20, 40, 60	-	30	30	I	TFC, TPC
Potato (Karacabey et al., 2023)	20	2.56, 8.6	2, 4	18.5	HA	ΔE, RR, TPC, Vit C
Potato (Bai et al., 2022)	-	240	10, 30, 60	40	HA	ΔE, TPC, DPPH
Garlic (Guo et al., 2023)	40	200	10	25	HA	ΔE, RR
Garlic (Bozkir et al., 2019)	35	480	30	30	HA, M	RR, Aw
<i>C. pilosula</i> (Wang et al., 2023)	20, 40, 60	150, 180, 210	20, 30, 40	30	-	ΔE, TPC, DPPH
Carrot (Wang et al., 2018)	20	360, 720, 1080	30	25	I	ΔE
Carrot (Tepe, 2024)	35	-	15, 30	30	HA	RR
Beetroots (Kian-Pour et al., 2024)	25	-	10, 20, 30	25	HA	ΔE, RR, DPPH
Leaves						
Roselle leaves (Oladejo et al., 2023)	20	600	5, 10, 15	29	HA	ΔE, Vit C
Barley grass (Cao et al., 2018)	20	200, 600, 900, 1200	10	-	F	TFC, Aw
Mulberry leaves (Tao et al., 2016)	20	130	10	20	HA	TPC
Basil leaves (Sledz et al., 2017)	21, 35	-	20, 30	25	M-HA	TPC
Seeds:						
Ginkgo seed (Boateng et al., 2022)	28	100	30	30	I	ΔE, Vit C, Aw
Almond (Kaveh et al., 2018)	28	70	10, 20, 40	-	HA	ΔE
Pumpkin seeds (Barros et al., 2024)	-	120, 280	5	-	HA	TFC, Vit C, Aw
Flowers						
Rose (Barani et al., 2022)	20, 45	300	5, 10, 15	25	IF	TPC
Rose (Barani et al., 2021)	45, 80, 100	300	5	24	IF	TPC
Saffron (Pei et al., 2021)	42	360	0.5, 1	25	I	ΔE, TFC, DPPH
Mushrooms:						
<i>C. cibarius</i> (Sun et al., 2023)	-	100, 200, 300, 400, 500	20	15	HA	ΔE, RR, TFC, TPC, DPPH
Shiitake (Li et al., 2021)	40	180	30	-	HA	ΔE
White mushroom (Çakmak et al., 2016)	35	480	30	30	HA	RR, Aw

ΔE = total color difference; RR = rehydration ratio; TFC = total flavonoid content; Vit = vitamin; Aw = water activity; DPPH = 2,2-diphenyl-1-picrylhydrazyl; HA = hot air; I = infrared; M = microwave; S = sun; F = freeze; I-HA = infrared-hot air; IF = microwave-hot air; IF = infrared freeze; DA-HA = dehumidified air-hot air; * = unusually high value and excluded from analysis.

Publication bias

Publication bias is a critical concern in meta-analyses, as it can distort conclusions by overrepresenting studies with significant results, while studies with non-significant findings often remain unpublished (Abrahamse et al., 2015). As shown in Table 2, the fail-safe N values for ΔE , RR, TFC, TPC and Aw exceeded the $5K + 10$ threshold, suggesting that the findings for these parameters were relatively robust. In contrast, DPPH and vitamin C fell below this threshold, indicating potential vulnerability to publication bias. Specifically, an additional 330 studies with null results would be required to negate the significant finding for vitamin C. In contrast, DPPH had a fail-safe N value of zero, implying that no additional studies would be needed to overturn its non-significant result.

Given these findings, it is essential to consider the potential impact of publication bias on the analysis. The very low fail-safe N for DPPH raises concerns regarding the reliability of its effect estimate. Thus, DPPH was excluded from further discussion to prevent misleading interpretations of the effects of UP. Although the fail-safe N for vitamin C was relatively high (330 studies), it still did not meet the stricter $5K + 10$ threshold (355 studies in this case), suggesting that some caution is warranted when interpreting the results related to vitamin C.

Overall effect size

Hedges'd was used to measure the effect size, employing a random-effects model to account for inter-study variability and ensure robust effect estimates under heterogeneous conditions (Fig. 2). The analysis found a significant overall

effect size ($p < 0.05$) for all quality parameters except DPPH and vitamin C, suggesting that UP generally enhances product quality. The overall effect sizes (SMD) with 95% CIs or each parameter were as follows: ΔE (SMD = -1.208), RR (SMD = 3.339), TFC (SMD = 2.093), TPC (SMD = 0.876), DPPH (SMD = 0.148), vitamin C (SMD = 0.808) and Aw (SMD = -2.096), all with a 95% confidence interval (CI). Based on Cohen's guidelines for interpreting effect sizes, nearly all parameters exhibited a large effect (SMD >0.8), except for DPPH. Negative SMD values indicate that the pretreatment reduced the outcome variable compared to the control group.

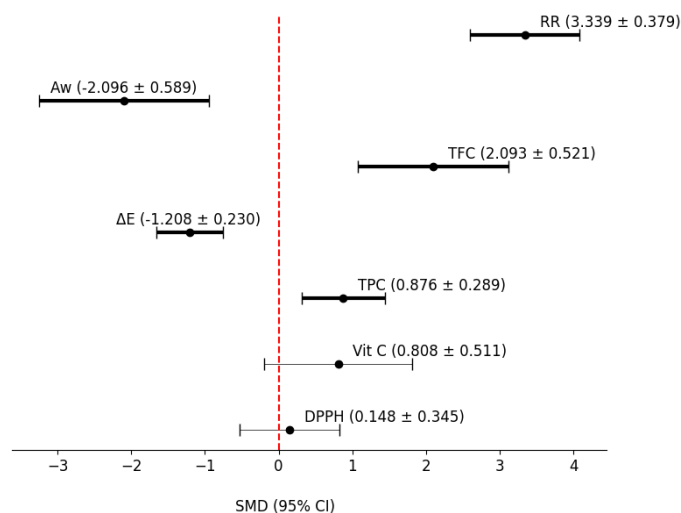


Fig. 2 Forest plot of standardized mean difference and 95% confidence interval (CI) of dried plant-based food quality (DPPH = 2,2-diphenyl-1-picrylhydrazyl; Vit C = vitamin C; TPC = total phenolic content; TFC = total flavonoid content; ΔE = total color difference; Aw = water activity; RR = rehydration ratio), where numeric values of standardized mean difference $\pm$ SE are shown beside each point estimate and bold line in plot signifies a robust model

Table 2 Heterogeneity and fail-safe N for output variables using Rosenthal approach for ultrasound-pretreated dried food quality

Output variable	ns	K	Heterogeneity (%)				Fail-safe N			
			Q	DF	p	I ²	N	p	α	5K+10
ΔE	29	152	793.028	151	<0.001	80.959	5338	<0.001	0.05	770
RR	18	59	255.895	58	<0.001	77.334	6638	<0.001	0.05	305
TFC (mg RE/g)	10	56	404.015	55	<0.001	86.387	975	<0.001	0.05	290
TPC (mg GAE/g)	30	138	814.322	137	<0.001	83.176	1735	<0.001	0.05	700
DPPH (% RSA)	10	59	298.190	58	<0.001	80.549	0	0.0785	0.05	305
Vitamin C (mg/100 g)	11	69	488.930	68	<0.001	86.092	330	<0.001	0.05	355
Aw	13	36	205.328	35	<0.001	82.954	821	<0.0001	0.05	190

ΔE = total color difference; RR = rehydration ratio; TFC = total flavonoid content; RE = rutin equivalent; TPC = total phenolic content; GAE = gallic acid equivalent; DPPH = 2,2-diphenyl-1-picrylhydrazyl; RSA = radical scavenging activity; ns = number of studies; K = number of comparisons; Q = coefficient of moderators; DF = degree of freedom; I² = inconsistency index = N = number of missing studies required to raise p (observed significance level) above α (target significance level).

Heterogeneity

The heterogeneity analysis (Table 2) revealed significant variation among reported effect sizes. The Q values were in the range 205.328–814.322, with degrees of freedom (DF) in the range 35–151 and all at $p < 0.001$, confirming a highly heterogeneous distribution. Additionally, the I^2 values consistently exceeded 75%, indicating substantial heterogeneity. These findings suggested that the observed differences among studies were not merely due to random error but reflected systematic variations in study characteristics, underscoring the importance of examining potential moderating variables influencing effect sizes.

Sub-group analysis: Commodity categories

Commodity categories significantly influenced quality variations (Table 3). UP had no significant effect on ΔE in mushrooms, on TPC in fruits, leaves and flowers and on Aw in fruits. The most notable effects ($p < 0.05$) were observed in ΔE for seeds (standardized mean difference, SMD = 7.058), RR for fruits (SMD = 3.768), TFC for roots (SMD = 3.741), TPC for roots (SMD = 1.850), vitamin C for seeds (SMD = 7.732) and Aw for seeds (SMD = -3.982). The UP had a more pronounced positive effect on roots, significantly improving ($p < 0.05$) in ΔE , RR, TFC, TPC and vitamin C.

Sub-group analysis: Pretreatment parameters

The effect of ultrasound equipment type was analyzed (Table 4). The ultrasonic bath had a significant influence ($p < 0.05$)

on the quality of dried products (except for vitamin C), producing positive effects on ΔE (SMD = -1.073), RR (SMD = 4.494), TFC (SMD = 2.195), TPC (SMD = 0.018) and Aw (SMD = -1.958). On the other hand, the ultrasound probe had significant positive effects ($p < 0.05$) on ΔE (SMD = -1.880), TFC (SMD = 1.798), vitamin C (SMD = 5.168) and Aw (SMD = -2.170), but had no significant effect ($p > 0.05$) on RR and TPC.

Beyond equipment type, the analysis of the sample-to-water ratio revealed that variations in pretreatment concentration produced different effects on the quality attributes of the dried products (Table 5). For ΔE , a significant reduction in color change was observed at a ratio of 3:500 (SMD = -3.067, $p < 0.005$), while other ratios showed no significant differences ($p > 0.05$). The RR increased significantly at ratios of 1:4 (SMD = 7.150, $p < 0.001$) and 1:6 (SMD = 1.575, $p < 0.001$). Similarly, TFC increased significantly at 1:4 (SMD = 6.242, $p < 0.001$) and 1:6 (SMD = 4.232, $p = 0.002$), but decreased at 1:20 (SMD = -2.942, $p = 0.018$). A significant improvement in TPC was also observed at 1:6 (SMD = 7.097, $p < 0.001$) and 1:10 (SMD = 17.895, $p = 0.013$). The vitamin C content increased significantly at ratios of 1:10 (SMD = 10.315, $p < 0.001$) and 3:500 (SMD = 8.054, $p < 0.001$), but decreased at 1:4 (SMD = -1.395, $p = 0.033$). Aw decreased significantly at ratios of 1:10 (SMD = -3.954, $p < 0.001$) and 1:20 (SMD = -5.517, $p < 0.001$). Overall, lower sample-to-water ratios (1:4 and 1:6) generally exhibited positive effects on RR and the bioactive compound contents (TFC and TPC), whereas higher ratios ($\geq 1:10$) tended to reduce Aw and, in some cases, led to greater color changes in the dried samples.

Table 3 Effects of commodity category subgroup on ultrasound-pretreated dried product quality

Output variable	Subgroup	SMD	95% CI		SE	<i>p</i>
			Lower	Upper		
Total color difference	Fruits	-1.599	-2.107	-1.090	0.259	<0.001
	Roots	-2.124	-3.412	-0.836	0.657	<0.001
	Mushrooms	-1.775	-4.054	0.503	1.162	0.127
	Seeds	7.058	4.175	9.940	1.471	<0.001
Rehydration ratio	Fruits	3.768	2.782	4.754	0.503	<0.001
	Roots	3.339	1.872	4.806	0.749	<0.001
	Mushrooms	1.798	0.448	3.147	0.689	0.009
Total flavonoid content (mg RE/g)	Roots	3.741	1.746	5.736	1.018	<0.001
	Leaves	-1.978	-3.521	-0.434	0.787	0.012
Total phenolic content (mg GAE/g)	Fruits	0.121	-0.567	0.810	0.351	0.730
	Roots	1.850	0.783	2.917	0.544	<0.001
	Leaves	0.037	-0.954	1.029	0.506	0.941
	Flowers	-2.344	-8.622	3.934	3.203	0.464
Vitamin C (mg/100 g)	Fruits	-1.395	-2.679	-0.110	0.655	0.033
	Roots	2.210	0.652	3.768	0.795	0.005
	Seeds	7.732	2.851	12.612	2.490	0.002
Water activity	Fruits	0.201	-1.281	1.683	0.756	0.790
	Seeds	-3.982	-5.193	-2.771	0.618	<0.001

SMD, standardized mean difference; CI, confidence interval; RE = rutin equivalent; GAE = gallic acid equivalent.

Table 4 Effects of ultrasonic equipment subgroup on ultrasound-pretreated dried product quality

Output variable	Subgroup	SMD	95% CI		SE	<i>p</i>
			Lower	Upper		
Total color difference	Bath	-1.073	-1.567	-0.578	0.252	<0.001
	Probe	-1.880	-2.972	-0.789	0.557	<0.001
Rehydration ratio	Bath	4.494	3.593	5.395	0.460	<0.001
	Probe	0.871	-0.200	1.941	0.546	0.111
Total flavonoid content	Bath	2.195	0.959	3.431	0.631	<0.001
	Probe	1.798	0.254	3.343	0.788	0.022
Total phenolic content	Bath	0.678	0.118	1.239	0.286	0.018
	Probe	2.834	-0.672	6.340	1.789	0.113
Vitamin C	Bath	-0.346	-1.434	0.742	0.555	0.533
	Probe	5.168	2.736	7.601	1.241	<0.001
Water activity	Bath	-1.958	-3.369	-0.547	0.720	0.007
	Probe	-2.170	-4.194	-0.145	1.033	0.036

SMD, standardized mean difference; CI, confidence interval.

Table 5 Effects of sample-to-water weight ratio subgroup on ultrasound-pretreated dried product quality

Output variable	Subgroup	SMD	95% CI		SE	<i>p</i>
			Lower	Upper		
Total color difference	1:4	-0.204	-0.720	0.313	0.263	0.440
	1:5	2.296	-1.278	5.870	0.657	0.208
	1:6	-1.176	-3.384	1.033	1.127	0.297
	1:100	0.287	-0.296	0.870	0.297	0.335
	3:500	-3.067	-5.213	-0.922	1.095	0.005
Rehydration ratio	1:4	7.150	4.663	9.638	1.269	<0.001
	1:6	1.575	0.747	2.402	0.422	<0.001
Total flavonoid content	1:4	6.242	3.259	9.225	1.522	<0.001
	1:6	4.232	1.511	6.954	1.389	0.002
	1:20	-2.942	-5.374	-0.510	1.241	0.018
	1:100	-0.278	-1.288	0.731	0.515	0.589
Total phenolic content	1:4	-1.123	-2.253	0.007	0.577	0.051
	1:5	0.821	-0.497	2.139	0.673	0.222
	1:6	7.097	5.124	9.070	1.007	<0.001
	1:10	17.895	3.707	32.083	7.239	0.013
	3:8	3.222	-2.139	8.583	2.735	0.239
	1/40	0.049	-1.015	1.114	0.543	0.928
	1:4	-1.395	-2.679	-0.110	0.655	0.033
Vitamin C	1:10	10.315	5.235	15.394	2.592	<0.001
	3:500	8.054	5.186	10.922	1.463	<0.001
Water activity	1:4	0.164	-1.490	1.817	0.844	0.846
	1:10	-3.954	-5.252	-2.656	0.662	<0.001
	1:20	-5.517	-7.552	-3.483	1.038	<0.001

SMD, standardized mean difference; CI, confidence interval.

Table 6 presents the results of the subgroup analysis investigating the effect of ultrasound frequency on the quality of dried products. Frequencies within the 20–60 kHz range significantly influenced quality parameters ($p < 0.05$), although certain exceptions were noted. The most prominent SMD values ($p < 0.05$) were recorded for ΔE at 28 kHz (SMD = -2.555), RR at 35 kHz (SMD = 10.995), TFC

at 40 kHz (SMD = 4.930), TPC at 28 kHz (SMD = 1.367), vitamin C at 20 kHz (SMD = 4.185) and Aw at 25 kHz (SMD = 3.507). Overall, these findings indicated that frequencies around 28 kHz were particularly effective in preserving and enhancing the quality of dried products. In contrast, frequencies above 40 kHz may harm specific quality attributes.

Table 6 Effects of ultrasound frequency subgroup on quality of ultrasound-pretreated dried products

Output variable	Subgroup (kHz)	SMD	95% CI		SE	<i>p</i>
			Lower	Upper		
Total color difference	20	-1.967	-2.974	-0.960	0.514	<0.001
	25	0.892	-0.894	2.677	0.911	0.328
	28	-2.555	-3.943	-1.167	0.708	<0.001
	40	-0.985	-1.708	-0.261	0.369	0.008
Rehydration ratio	20	0.039	-0.839	0.916	0.448	0.931
	28	3.405	2.265	4.544	0.581	<0.001
	35	8.953	5.824	12.082	1.597	<0.001
Total flavonoid content (mg RE/g)	20	1.126	-0.732	2.985	0.948	0.235
	40	4.930	1.156	8.703	1.925	0.010
	60	1.497	-2.458	5.451	2.018	0.458
Total phenolic content (mg GAE/g)	20	0.625	-1.299	2.549	0.982	0.524
	21	0.160	-0.613	0.934	0.395	0.684
	25	0.508	-0.559	1.576	0.545	0.351
	28	1.367	0.550	2.183	0.417	0.001
	35	-0.826	-1.834	0.181	0.514	0.108
	40	-0.030	-1.370	1.311	0.684	0.965
	45	11.454	-10.460	33.368	11.181	0.306
	60	-0.654	-2.590	1.281	0.988	0.508
Vitamin C (mg/100 g)	20	4.185	2.179	6.192	1.024	<0.001
	25	-0.527	-4.186	3.132	1.867	0.778
	40	-1.236	-2.880	0.408	0.839	0.141
Water activity	21	-4.078	-8.263	0.107	2.135	0.056
	25	3.507	0.494	6.520	1.537	0.023
	35	1.569	-4.642	7.781	3.169	0.620

SMD, standardized mean difference; CI, confidence interval; RE = rutin equivalent; GAE = gallic acid equivalent.

In addition to frequency, ultrasound power levels are critical in determining product quality. As shown in Table 7, ultrasound power levels in the range 70–1,200 W significantly influenced product quality ($p < 0.05$). The most substantial improvements ($p < 0.05$) were observed at specific power levels: ΔE at 180 W (SMD = -10.706), RR at 480 W (SMD = 20.060), TFC at 300 W (SMD = 3.878), TPC at 600 W (SMD = 11.427), vitamin C at 400 W (SMD = 9.114) and Aw at 300 W (SMD = -12.577). Among these, a power level of 300 W was considered effective, as it significantly reduced ΔE and Aw while enhancing RR, TFC, TPC and vitamin C ($p < .05$). Nonetheless, using low power, particularly 150 W, should be used cautiously, as it may adversely affect ΔE and TPC.

Another critical factor influencing UP effectiveness is pretreatment duration. As shown in Table 8, pretreatment durations in the range 2–60 min had varying impacts on quality parameters. The most pronounced SMDs were recorded for

ΔE at 45 min (SMD = -7.894), RR at 10 min (SMD = 8.794), TFC at 30 min (SMD = 4.024), TPC at 30 min (SMD = 2.339), vitamin C at 5 min (SMD = 32.314) and Aw at 10 min (SMD = -4.512). Overall, a 30 min UP duration was the most favorable, significantly reducing ΔE and enhancing RR, TFC, TPC and vitamin C ($p < 0.05$).

Furthermore, pretreatment temperature also substantially affects product quality. As shown in Table 9, the most frequently applied water temperatures for UP were 25°C, 30°C and 40°C, with 30°C demonstrating the highest effectiveness in preserving product quality. At this temperature, UP significantly ($p < 0.05$) reduced ΔE (SMD = -7.580) and Aw (SMD = -0.487), while significantly enhancing RR (SMD = 6.284), TFC (SMD = 3.589) and TPC (SMD = 1.825). In contrast, UP at 25°C yielded no beneficial effects and was associated with quality deterioration. It showed no significant ($p > 0.05$) impact on ΔE (SMD = 0.030), TFC (SMD = 0.876) or TPC (SMD = -0.630) and significantly reduced ($p < 0.05$) vitamin C (SMD = -2.780).

Table 7 Effects of ultrasound power sub-group on quality of ultrasound-pretreated dried products

Output variable	Subgroup (W)	SMD	95% CI		SE	<i>p</i>
			Lower	Upper		
Total color difference	70	-2.190	-3.827	-0.552	0.835	0.009
	150	0.001	-0.478	0.479	0.244	0.998
	180	-10.706	-13.293	-8.118	1.320	<0.001
	200	-1.825	-4.259	0.608	1.241	0.141
	240	-0.542	-1.355	0.271	0.415	0.192
	300	-0.953	-1.699	-0.206	0.381	0.012
	360	-0.098	-0.863	0.667	0.390	0.802
	400	-5.321	-7.899	-2.743	1.315	<0.001
Rehydration ratio	70	3.264	2.281	4.247	0.501	<0.001
	200	12.052	5.387	18.718	3.401	<0.001
	300	1.458	0.298	2.617	0.592	0.014
	480	20.060	6.815	33.304	6.758	0.003
Total flavonoid content (mg RE/g)	200	3.642	-1.194	8.478	2.467	0.140
	300	3.878	1.135	6.622	1.400	0.006
Total phenolic content (mg GAE/g)	70	1.488	0.718	2.257	0.393	<0.001
	150	-3.383	-5.374	-1.391	1.016	<0.001
	180	0.145	-0.614	0.904	0.387	0.707
	200	4.061	0.353	7.768	1.892	0.032
	240	-2.377	-6.376	1.622	2.040	0.244
	300	2.127	0.548	3.706	0.806	0.008
	600	11.427	3.697	19.157	3.944	0.004
Vitamin C (mg/100 g)	300	2.255	0.735	3.776	0.776	0.004
	400	9.114	5.095	13.134	2.051	<0.001
Water activity	200	4.139	-2.023	10.301	3.144	0.188
	300	-12.577	-21.002	-4.153	4.298	0.003
	480	-4.546	-22.477	13.385	9.149	0.619
	1200	-2.876	-5.309	-0.443	1.241	0.021

SMD, standardized mean difference; CI, confidence interval; RE = rutin equivalent; GAE = gallic acid equivalent.

Table 8 Effects of pretreatment duration subgroup on quality of ultrasound-pretreated dried products

Output variable	Subgroup (min)	SMD	95% CI		SE	<i>p</i>
			Lower	Upper		
Total color difference	2	-0.461	-1.626	0.704	0.594	0.438
	4	0.030	-1.034	1.095	0.543	0.956
	5	-0.236	-3.140	2.668	1.482	0.874
	10	0.030	-1.603	1.663	0.833	0.972
	15	-1.918	-3.530	-1.278	0.575	<0.001
	20	-0.353	-1.107	0.401	0.385	0.358
	30	-4.872	-6.356	-3.388	0.757	<0.001
	40	4.527	0.290	8.764	2.162	0.036
	45	-7.894	-9.888	-5.900	1.017	<0.001
	60	-0.352	-3.690	2.987	1.704	0.836
Rehydration ratio	10	8.794	4.860	12.728	2.007	<0.001
	15	1.685	0.815	2.556	0.444	<0.001
	20	1.988	1.194	2.782	0.405	<0.001
	30	6.176	4.502	7.849	0.854	<0.001
Total flavonoid content (mg RE/g)	10	-2.162	-4.106	-0.218	0.992	0.029
	30	4.024	2.138	5.910	0.962	<0.001
Total phenolic content (mg GAE/g)	5	0.493	-2.890	3.875	1.726	0.775
	10	0.154	-1.975	2.284	1.087	0.887
	15	0.231	-0.336	0.798	0.289	0.424
	20	-0.639	-2.045	0.767	0.717	0.373
	30	2.339	1.373	3.305	0.493	<0.001
	40	-0.029	-0.986	0.928	0.488	0.952
	60	-0.655	-3.259	1.948	1.328	0.622

Table 8 Continued

Output variable	Subgroup (min)	SMD	95% CI		SE	<i>p</i>
			Lower	Upper		
Vitamin C (mg/100 g)	5	32.314	13.307	51.321	9.698	<0.001
	10	1.301	-1.032	3.633	1.190	0.275
	15	8.499	3.095	13.902	2.757	0.002
	20	-2.906	-4.602	-1.209	0.866	<0.001
	30	2.619	0.820	4.418	0.918	0.004
Water activity	5	-1.826	-4.979	1.326	1.609	0.256
	10	-4.512	-7.539	-1.485	1.544	0.003
	15	-2.013	-4.036	0.011	0.051	0.256
	30	-1.988	-4.535	0.558	1.299	0.126

SMD, standardized mean difference; CI, confidence interval; RE = rutin equivalent; GAE = gallic acid equivalent.

Table 9 Effects of pretreatment temperature subgroup on quality of ultrasound-pretreated dried products

Output variable	Subgroup (°C)	SMD	95% CI		SE	<i>p</i>
			Lower	Upper		
Total color difference	25	0.030	-0.495	0.556	0.268	0.911
	30	-7.580	-9.485	-5.675	0.972	<0.001
Rehydration ratio	25	6.323	4.394	8.252	0.984	<0.001
	30	6.284	4.758	7.811	0.779	<0.001
Total flavonoid content (mg RE/g)	25	0.876	-0.514	2.265	0.709	0.217
	30	3.589	1.568	5.610	1.031	<0.001
Total phenolic content (mg GAE/g)	25	-0.630	-1.808	0.548	0.601	0.294
	30	1.825	0.849	2.801	0.498	<0.001
	40	-4.679	-9.608	0.250	2.515	0.063
Vitamin C (mg/100 g)	25	-2.780	-4.152	-1.408	0.700	<0.001
	30	2.027	-0.017	4.071	1.043	0.052
Water activity	30	-0.487	-3.441	2.468	1.507	0.747

SMD, standardized mean difference; CI, confidence interval; RE = rutin equivalent; GAE = gallic acid equivalent.

Sub-group analysis: Drying parameters

Following UP, the choice of drying method significantly influenced product quality, contributing to variations observed in the meta-analysis results. As presented in [Table 10](#), different drying methods had distinct effects. Specific methods had no significant ($p > 0.05$) impact such as hot-air drying on TFC

and TPC, infrared drying on vitamin C and microwave or microwave and hot-air drying on ΔE , TPC and vitamin C. Among the evaluated techniques, hot-air drying produced the most favorable results, significantly ($p < 0.05$) reducing ΔE and Aw while enhancing RR and vitamin C content. In contrast, microwave-based drying methods were less effective post-UP, failing to significantly ($p > 0.05$) improve ΔE , TPC or vitamin C.

Table 10 Effects of drying method subgroup on quality of ultrasound-pretreated dried products

Output variable	Subgroup	SMD	95% CI		SE	<i>p</i>
			Lower	Upper		
Total color difference	HA	-0.910	-1.635	-0.186	0.370	0.014
	I	-4.091	-6.444	-1.738	1.201	<0.001
	M	-0.828	-1.659	0.004	0.424	0.051
	I-HA	-3.743	-5.014	-2.472	0.649	<0.001
	M-HA	-1.068	-2.850	0.714	0.909	0.240
Rehydration ratio	HA	3.391	2.384	4.397	0.513	<0.001
	M	1.944	1.173	2.716	0.394	<0.001
Total flavonoid content (mg RE/g)	HA	0.299	-1.343	1.942	0.838	0.721
	I	6.951	4.476	9.426	1.263	<0.001

Table 10 Continued

Output variable	Subgroup	SMD	95% CI		SE	<i>p</i>
			Lower	Upper		
Total phenolic content (mg GAE/g)	HA	0.861	-0.379	2.102	0.633	0.173
	I	3.832	2.062	5.601	0.903	<0.001
	M	0.205	-0.407	0.816	0.312	0.512
	M-HA	0.110	-1.692	1.913	0.920	0.904
	IF	-2.344	-8.622	3.934	3.203	0.464
Vitamin C (mg/100 g)	HA	3.068	1.373	4.764	0.865	<0.001
	I	0.073	-2.674	2.819	1.401	0.958
	M	-0.125	-2.836	2.585	1.383	0.928
	M-HA	-0.792	-2.808	1.224	1.029	0.441
Water activity	HA	-2.891	-4.048	-1.733	0.590	<0.001
	F	-6.835	-10.236	-3.435	1.735	<0.001

SMD = standardized mean difference; CI = confidence interval; HA = hot air drying; I = infrared drying; M = microwave drying; I-HA = infrared hot air drying; M-HA = microwave hot air drying; IF = infrared-freeze drying; F = freeze-drying; RE = rutin equivalent; GAE = gallic acid equivalent.

Given these favorable outcomes, a further subgroup analysis was conducted to investigate the effect of drying temperature under hot-air drying conditions. Drying temperatures for this method were in the range 40–80°C (Table 11). Significant ($p < 0.05$) effects were observed for ΔE at 45°C and 65°C,

RR and vitamin C in the range 50–70°C, TFC at 80°C, TPC at 60°C and Aw at 50°C and 60°C. Among these, 60°C was the most favorable drying temperature, significantly ($p < 0.05$) reducing Aw, while enhancing RR, TPC and vitamin C.

Table 11 Effects of drying temperature subgroup on quality of ultrasound-pretreated dried products

Output variable	Subgroup (°C)	SMD	95% CI		SE	<i>p</i>
			Lower	Upper		
Total color difference	80	-0.945	-3.198	1.308	1.150	0.411
	70	-0.826	-1.577	-0.076	0.383	0.031
	65	-3.480	-5.316	-1.644	0.937	<0.001
	60	-1.321	-2.086	-0.556	0.390	<0.001
	50	-2.061	-4.304	0.182	1.144	0.072
	40	2.797	-0.522	6.116	1.693	0.099
Rehydration ratio	70	3.891	2.072	5.710	0.928	<0.001
	60	3.248	1.765	4.730	0.756	<0.001
	50	3.733	1.168	6.298	1.309	0.004
	40	1.128	0.346	1.910	0.399	0.005
Total flavonoid content (mg RE/g)	80	2.030	-0.614	4.675	1.349	0.132
	70	2.610	0.709	4.512	0.970	0.007
	60	3.570	1.468	5.671	1.072	<0.001
Total phenolic content (mg GAE/g)	80	2.688	-1.505	6.881	2.139	0.209
	70	0.661	-0.579	1.901	0.633	0.296
	60	2.156	0.871	3.440	0.655	0.001
	55	0.291	-0.551	1.134	0.430	0.498
	50	1.252	-0.373	2.878	0.829	0.131
	40	0.214	-0.625	1.052	0.428	0.618
Vitamin C (mg/100 g)	80	5.614	-1.122	12.350	3.437	0.102
	70	0.462	-1.558	2.483	1.031	0.654
	60	1.244	-0.209	2.697	0.741	0.093
	50	2.924	-2.874	8.723	2.958	0.323
Water activity	70	0.240	-1.885	2.364	1.084	0.825
	60	-2.308	-3.986	-0.631	0.856	0.007
	50	-4.293	-6.462	-2.125	1.106	<0.001

SMD, standardized mean difference; CI, confidence interval; RE = rutin equivalent; GAE = gallic acid equivalent.

Discussion

Ultrasound pretreatment has been studied widely as a non-thermal blanching method, offering advantages over conventional thermal blanching by effectively inactivating enzymes and preserving bioactive compounds (Rathnakumar et al., 2023). Its application at low temperatures minimizes thermal degradation (Ergün, 2022), enhancing the qualitative attributes of the materials.

Beyond its physicochemical benefits, UP also exerts a substantial influence on the sensory attributes and consumer perception of the final product (Carneiro and Pimentel, 2025). Ultrasonically treated samples have consistently higher sensory scores compared to untreated controls, with improved color and reduced volume shrinkage (Abdoli et al., 2018; Jin et al., 2019; Rani and Tripathy, 2019), superior textural characteristics, such as lower hardness and greater chewiness (Komes et al., 2013; Nowacka et al., 2024), and enhanced retention of aromatic compounds (Song et al., 2021; Kaveh et al., 2025). Collectively, these findings highlight UP as a promising approach for improving both the visual and sensory quality of dried plant-based foods. The underlying mechanisms responsible for these effects are attributed primarily to acoustic cavitation, which generates localized high temperature and pressure, disrupting cellular structures and enhancing mass transfer (Li et al., 2015; Olughu et al., 2021). Such effects accelerate moisture removal while preserving essential nutrients (Wang et al., 2019; J. Zhang et al., 2021; Abbaspour-Gilandeh et al., 2021a). Additionally, the “sponge effect,” induced by successive compression and rarefaction cycles of acoustic waves, facilitates moisture diffusion by overcoming surface tension forces (Xu et al., 2022).

While these mechanisms contribute collectively to the improved drying performance and nutritional retention of UP-treated materials, the effectiveness of UP in maintaining product quality remains dependent on several operational factors (Deng et al., 2019). Accordingly, optimizing the pretreatment and drying parameters is crucial to maximizing the benefits of UP. The subgroup analysis in the present study addressed part of this complexity by examining the heterogeneity among studies; however, inconsistencies in reported moderator variables still limited direct comparisons of their specific impacts on product quality.

Effects of UP on dried product quality

The present meta-analysis evaluated the impact of UP on the quality of dried plant-based food products, focusing on studies using water to minimize variability. UP significantly improved quality parameters such as ΔE , RR, TFC, TPC and Aw ($SMD > 0.8$, $p < 0.05$), demonstrating a substantial effect compared to the control. Conversely, there was no significant ($p > 0.05$) impact for DPPH and vitamin C, implying that this treatment may not significantly influence these two parameters.

However, it is essential to consider the potential publication bias affecting the analysis of these parameters. Specifically, the very low Rosenthal's Fail-safe N value for DPPH (0 studies) raises concerns about the accuracy of the analysis. Therefore, DPPH was excluded from further consideration to avoid misinterpretation of UP effects. Furthermore, although Rosenthal's Fail-safe N for vitamin C was relatively high (330 studies), the risk of publication bias remains, especially since the 5K+10 threshold was even higher (355 studies). Therefore, caution should be exercised when interpreting the results related to vitamin C.

A significant ($p < 0.05$) reduction in ΔE following UP application indicates that the color of dried products closely resembles that of fresh products. This phenomenon is likely associated with UP's ability to inactivate the enzymes involved in browning reactions (Piyasena et al., 2003; Jang and Moon, 2011), thereby minimizing color changes between fresh and dried products. In addition, UP can reduce oxygen levels within the material, inhibiting oxidation-induced discoloration (Chu et al., 2021; Chao et al., 2022). In addition, the acoustic cavitation generated during UP disrupts the cellular structure, promoting product homogenization and preventing browning from both enzymatic and non-enzymatic reactions (Kutlu et al., 2022). Furthermore, the reduction in drying time helps to preserve color by minimizing exposure to high temperatures and oxygen, which can otherwise degrade pigments (Kroehnke et al., 2021; Wu et al., 2022). The increase in the RR in dried products is strongly correlated with an improved water absorption capacity, indicating minimized structural damage to the product (Yi et al., 2016; Huang et al., 2023). In addition, the RR reflects the extent of physical and structural changes during drying (Kahraman et al., 2021). The significant ($p < 0.05$) result with a large effect size ($SMD > 0.8$) for the RR suggested that UP effectively enhanced the rehydration capacity of dried products compared to the control group. This improvement could be attributed to the structural modifications induced by

UP, which facilitate the formation of pores, microchannels, larger tunnels and additional spaces within the material, all of which contribute to increased internal tension (Tao et al., 2019; Wang et al., 2019; Wu et al., 2020a). Furthermore, ultrasound cavitation and mechanical effects increase the porosity, expand cell structures, widen capillaries and cause a looser internal matrix, ultimately improving water absorption during rehydration (Abbaspour-Gilaneh et al., 2021b).

The findings of the present study further emphasized the substantial impact of UP in enhancing the retention of bioactive compounds, particularly flavonoids and phenolics, in dried plant-based products. Ultrasound waves induce alterations in inbound phenolics and facilitate the inactivation of enzymes that affect polyphenols, thereby supporting the retention of these bioactive compounds (Li et al., 2020). Since phenolics are heat-sensitive, their retention was substantially enhanced in the UP samples, due to the reduced drying duration. Furthermore, the pore formation induced by UP enhances the accessibility and extraction efficiency of TPC, leading to higher retention levels (Abbaspour-Gilaneh et al., 2020; Kaveh et al., 2021; Wiktor et al., 2016). Concurrently, the retention of TFC was substantially improved. The reduced drying time associated with UP minimizes the oxidative degradation of flavonoids during the drying process (Shang et al., 2023).

While Zhao et al. (2024) reported a non-significant effect of UP on the TPC and TFC, the analysis in the present study indicated a substantial increase in both parameters following UP. This substantial difference was further strengthened by the inclusion of publication bias analysis, which enhanced the robustness of the present findings. Specifically, the fail-safe N analysis for the TPC and TFC yielded values of 1,735 and 975 studies, respectively, far exceeding the critical threshold values of $5K + 10$ (700 and 290 studies, respectively), as presented in Table 2. Thus, there was no indication of significant publication bias, reinforcing the credibility of the observed increases in the TPC and TFC. Notably, these findings were supported by Jiang et al. (2022), suggesting that the cavitation effect generated by ultrasound induces intense shear forces that rupture cell walls, facilitating the release of intracellular flavonoids and enhancing the retention of these bioactive compounds.

Water activity determines a dried product's stability and shelf life (Barros et al., 2024). Although evaluating food stability is inherently complex, generally, a low A_w value is associated with extended shelf life due to reduced microbial growth and biochemical degradation (Barros et al., 2019).

UP influences the A_w of dried products by altering plant tissue structure, which facilitates moisture removal during drying. The mechanical effects of ultrasound, such as the formation of microchannels and the sponge effect, result in reduced cellular adhesion, increased intercellular spaces and mild cell wall damage. These structural modifications enhance mass transfer, making moisture escape from the product easier and improving overall water diffusivity (Rodrigues et al., 2009). Consequently, UP samples tend to have lower A_w values than an untreated control, signifying improved drying efficiency and greater stability for long-term storage.

Vitamin C retention is regarded widely as an essential indicator of the nutritional quality of dried fruits and vegetables (Goula and Adamopoulos, 2006). However, the present study identified no significant ($p > 0.05$) impact of UP on vitamin C levels. The absence of a substantial difference in the vitamin C content between the UP and control groups could be attributed to variations in UP duration (0.5–30 min). Prolonged exposure to ultrasound may lead to vitamin C degradation (Oladejo et al., 2017), primarily due to its high solubility in water and sensitivity to heat and oxidative stress (Davey et al., 2000). Often, this degradation process is linked to oxidation and pyrolysis triggered by hydroxyl radicals generated through cavitation during ultrasound processing (Pingret et al., 2013). In addition, the impact of UP on vitamin C retention is influenced by other factors such as the initial vitamin C concentration in the raw material, drying conditions and any interactions between multiple processing parameters, including product type, drying method and environmental conditions (Amanor-Atiemoh et al., 2020; Ashtiani et al., 2017; Horuz et al., 2017).

Effect of commodity categories on dried product quality following ultrasound pretreatment

The present study examined various commodity subgroups (fruits, leaves, roots, mushrooms, flowers and seeds). The effectiveness of UP in enhancing dried product quality varied depending on the food matrix, particularly porosity, which influenced the impact of UP (Radojčin et al., 2021; Xu et al., 2022). Porosity played a key role in the sponge effect, which altered the material texture during UP (Rodríguez et al., 2018).

The subgroup analysis revealed that UP had the greatest, significant ($p < 0.05$), positive effect on root crops, improving ΔE , RR, the TFC and TPC. Generally (excluding rhizomes), root crops have low porosity, with reported values of 0.029 for carrots (Krokida and Maroulis, 1997), 0.043 for sweet potatoes

(Monteiro et al., 2022) and 0.134 for garlic (Lozano et al., 1983). UP induces microchannel formation and increases porosity in low-porosity materials such as sweet potatoes, enhancing water diffusivity, accelerating drying and reducing nutrient degradation (Wu et al., 2020b). However, in highly porous materials, the cavitation effect mainly affects intercellular spaces, preventing major structural changes (Umaña et al., 2022). Consequently, UP is more effective for commodities with low porosity, by having a major impact on the final dried product's quality.

Effect of pretreatment parameters on dried product quality

Pretreatment parameters influence the effectiveness of UP, with one of the important ones being the type of ultrasonic equipment. The ultrasonic bath, an indirect irradiation system, is economical and straightforward; however, attenuation, reflection and acoustic impedance within the medium can reduce the ultrasound intensity and cause non-uniform cavitation (Sancheti and Gogate, 2017; Rodríguez et al., 2018). In contrast, the ultrasonic probe provides direct irradiation with higher cavitation intensity, as the titanium tip is immersed close to the sample, resulting in more focused sonication (Gamboa-Santos et al., 2013). However, excessive cavitation may induce localized overheating and degradation of heat-sensitive compounds (Xu et al., 2022).

Subgroup analysis showed that both systems enhanced the quality of dried plant-based foods. The adverse effects of the probe system on the TPC and RR may be related to overheating caused by excessive cavitation. Overall, both systems can be effective when combined with optimized process parameters such as pretreatment time (Kek et al., 2013), medium temperature control (Cao et al., 2020) and pulsed mode application (Ren et al., 2018).

The sample-to-water ratios applied in the studies investigated varied considerably depending on the material density. Materials with higher density, such as fruit or root, generally have lower sample-to-water ratios, whereas materials with lower density tend to have higher ratios. However, no study specifically examined the influence of sample weight or medium volume on UP effectiveness. The subgroup analysis indicated that lower sample-to-water ratios (1:4 and 1:6) were more effective generally than higher ratios (>1:10), which could be attributed to the intensity of energy received by the material; when the medium volume is too large, most ultrasonic energy dissipates into the surrounding water instead of being absorbed by the sample, thereby reducing the effective power

intensity delivered to the material. Ultimately, this difference in energy intensity affects the efficiency of UP (Zhao et al., 2017).

The ultrasound frequency substantially affects the cavitation rate, which is crucial for drying efficiency (Yao, 2016). Low-frequency ultrasound (20–100 kHz), often classified as high-power ultrasound, is widely used in food processing because it enhances the quality of dried products (Rahman and Lamsal, 2021). Different ultrasound frequencies have varying effects on product quality, with the subgroup analysis revealing that frequencies in the range 20–40 kHz were most effective in preserving and enhancing quality, particularly at 28 kHz, which improved color, RR and the TPC. Lower frequencies are preferred as they reduce energy absorption by the medium, allowing for deeper penetration (Jambrak et al., 2007). This frequency range optimizes cavitation by extending rarefaction and compression cycles, considerably altering product structure, accelerating drying and minimizing potential damage (Yadollahinia et al., 2009; Rahman and Lamsal, 2021).

However, frequencies above 40 kHz can degrade product quality. High-frequency waves generate intense mechanical vibrations and cavitation, potentially damaging cells and increasing oxygen transfer within the matrix (Lee et al., 2018). These effects promote micropore formation (L. Zhang et al., 2021), accelerate browning and increase substance migration, leading to greater nutritional loss (Ying et al., 2024). Additionally, higher frequencies raise the medium temperature, further exacerbating nutrient degradation, particularly in heat-sensitive compounds (Rahman and Lamsal, 2021).

Ultrasound power is crucial in determining acoustic energy effects during drying (Rodríguez et al., 2018). Higher power disrupts intermolecular forces in water, accelerating moisture migration and reducing drying time (Jiang et al., 2021; Pandiselvam et al., 2023). This acceleration is attributed to cavitation and sponge effects, creating microchannels and enhancing water diffusion. However, excessive power can cause structural damage and chemical changes (Tao et al., 2021). In addition, increased power levels lead to pronounced cell deformation and microchannel formation (Wang et al., 2018), compromising product quality (Abbaspour-Gilandeh et al., 2021a).

Notably, while the watt is the standard unit of electrical power, energy transmission to a product decreases due to inefficiencies in converting electrical signals into ultrasound waves and acoustic attenuation (Xu et al., 2022). Hence, although precise units such as watts per cubic meter, watts per square meter and watts per gram exist (Xu et al., 2022), their adoption remains limited, reducing data accuracy.

Precise energy delivery data enhances reproducibility and enables subgroup analyses incorporating relevant moderators (Musielak et al., 2016). Based on the subgroup analysis, 300 W was the most effective, as it improved multiple quality parameters. In the present study, 300 W corresponds to an energy per emission area of 3 W/cm² (Rybak et al., 2022) or an energy density of 1.25 W/mL (Sun et al., 2023). Conversely, 150 W is not recommended due to adverse effects on color and the TPC. Balancing power levels is essential to maximize benefits while minimizing degradation.

The duration of UP has a marked impact on dried product quality as increased UP time enhances mass and heat transfer (Taghinezhad et al., 2021) and creates larger spaces within the tissue, improving rehydration (Wang et al., 2019). However, prolonged exposure can cause solid loss due to nutrient depletion (Wang et al., 2019) and pigment degradation from heat and pressure generated by cavitation (Xi et al., 2020). A 30 min UP duration is most favorable, positively influencing color, RR, the TFC and TPC. For example, Bai et al. (2023) demonstrated that this duration shortened drying time, due to sufficient micropore openings for moisture diffusion. Additionally, increased cell wall permeability facilitated bioactive compound release (Chemat et al., 2011; Rawson et al., 2011).

Pretreatment temperature remains an underexplored factor, with none of the 55 studies in the present meta-analysis examining its variations. However, when temperature variations were analyzed collectively, 30°C enhanced all quality parameters compared to 25°C and 40°C. UP is advantageous as it can be conducted at room temperature, preventing material overheating (Jahanbakhshi et al., 2020). Notably, 30°C improved final product quality, while 25°C and 40°C negatively affected the TPC.

Ni et al. (2020b) suggested that temperature does not significantly affect cavitation. However, other studies reported that 30°C optimized the dried product quality, while Schössler et al. (2014) emphasized that optimal temperature was crucial for effective cavitation. At 30°C, cavitation bubble formation increases without diminishing collapse intensity. Higher temperatures raise vapor pressure, reducing viscosity and promoting bubble formation. However, low-viscosity liquids produce bubbles with more steam, reducing collapse intensity (Schössler et al., 2014; Urango et al., 2022).

Effect of drying parameters on dried product quality using UP

Selecting a drying method is crucial in determining the quality of the final product, especially when combined with UP. Different drying techniques affect quality differently and the appropriate method can enhance product characteristics (Rybak et al., 2022). Based on the subgroup analysis, UP helped to address limitations in hot-air drying, particularly those associated with high temperatures, by improving the retention of RR and the TPC. The enhanced heat and mass transfer in ultrasound-assisted drying accelerates the process, reducing the negative impact of heat exposure (Xu et al., 2022). In contrast, conventional and hybrid microwave drying were less compatible with UP, showing minimal quality improvement; while it effectively reduced drying time and energy consumption, its high energy input and rapid heating led to greater quality degradation (Yuniarti et al., 2024).

Drying temperature plays a key role in drying characteristics and product quality. Higher temperatures shorten the drying time by increasing the driving force for heat and mass transfer (Huang et al., 2020). UP, which enhances heat and mass transfer, helps to mitigate the adverse effects of hot-air drying. However, excessively high temperatures degrade heat-sensitive bioactive compounds due to the combined effects of acoustic and thermal energy (Rodríguez et al., 2018). The subgroup analysis identified 60°C as the most favorable drying temperature when combined with UP, as it positively influenced the RR, TPC, Vitamin C and Aw. These findings aligned with Huang et al. (2020), who stated that 60°C balanced the drying kinetics and product quality preservation.

This meta-analysis identified strong evidence that UP enhanced the drying performance and quality of plant-based products. Contrary to earlier meta-analyses, the present study identified significant improvements in the TPC and TFC, supported by a fail-safe N far exceeding the critical threshold ($5K + 1$) that confirmed the robustness of these findings. Quality improvements were observed consistently across multiple parameters, consisting of color stability, rehydration ratio, bioactive compound retention and water activity. These effects were strongly influenced by ultrasonic operating parameters, drying conditions and commodity-specific properties.

In conclusion, the synthesis indicated that UP at 28 kHz, 300 W and 30°C for 30 min, followed by hot-air drying at 60°C, represented the most favorable combination for low-porosity root crops.

This study had several limitations. Not all the studies considered reported on complete ultrasonic parameters, such as acoustic intensity, power density or energy input, which limited providing a more detailed interpretation of ultrasound effects. In addition, there was a potential publication bias observed in the outcomes related to vitamin C and antioxidant activity (DPPH). Future research should provide more detailed reporting of UP parameters, particularly power density and acoustic intensity, and continue investigating key quality indicators, such as vitamin C retention and antioxidant activity, to build more consistent evidence and to minimize publication bias. Furthermore, the effects of UP pretreatment on other quality outcomes, including protein, fat and fiber, should be explored.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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