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Quantitative Assessment of Drying Methods for Preserving Bioactive Compounds, Antioxidant Properties, and Color Quality of Citrus Matrices: A Meta-analysis

Ana-kpan Dome Vincent BEKUONÉ SOMÉ[1], Mamounata DIAO[1,*], Rocksane Octavia Kiswendsida NIKIEMA[1], David BAZIÉ[1], Désiré OUARO[1], Zakaria DINDANÉ[1], Roger DAKUYO[1], Fréderic Anderson KONKOBO[1], Hemayoro SAMA[1,2], Samson GUENNÉ[1,2], Crépin Ibingou DIBALA[1], Mamoudou Hama DICKO[1]

[1]Laboratory of Biochemistry, Biotechnology, Food Technology and Nutrition (LABIOTAN), Department ofBiochemistry/Microbiology (DBM), University Joseph KI-ZERBO, Burkina Faso. Tél: (226) 25337373; 03BP 7131 Ouagadougou 03 - Burkina Faso
[2]Laboratory of Biochemistry and Applied Chemistry (LABIOCA), Department of Biochemistry/Microbiology (DBM), University Joseph KI-ZERBO, Burkina Faso. Tél. : (226) 25337373; 03BP 7021 Ouagadougou 03 - Burkina Faso
*Corresponding author: mamounata.diao@ujkz.bf

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Abstract Drying is a key technology for the preservation and processing of citrus fruits; however, its effects on bioactive compounds, antioxidant properties, and quality attributes vary considerably by method. This study aims to quantitatively evaluate the effects of different drying methods on the bioactive compounds, antioxidant activities, and colorimetric parameters of citrus matrices using a multilevel meta-analysis conducted in accordance with PRISMA guidelines. A total of 23 studies comprising 413 effect estimates were included. Effect sizes were calculated using multilevel random-effects models estimated by restricted maximum likelihood (REML) and combined with a robust variance estimate. The results show significant decreases in vitamin C content (34%), total phenolic compounds (29.4%), and total flavonoids (37.8%) after drying compared with fresh or control samples. Freeze-drying generally exhibits the best retention of bioactive compounds, while solar and hot air drying result in the greatest losses. Conversely, some variables, notably ABTS activity and narirutin content, show apparent increases after drying (>100% retention), which can be attributed to improved extractability or concentration effects rather than a true increase in compounds. Colorimetric parameters are relatively less affected by drying processes. High heterogeneity (I^2 > 98%) is observed for most variables studied, reflecting the diversity of citrus matrices, drying conditions, and analytical methods used, thereby justifying subgroup analyses. This meta-analysis therefore provides quantitative data to guide the selection of appropriate drying technologies to preserve the functional quality of citrus-derived products.

Keywords: *Citrus fruits, Drying methods, Bioactive compounds, Antioxidant activity, Meta-analysis*

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1. Introduction

Citrus fruits represent a significant share of global fruit production and are widely processed into juices and derivative products. Approximately one-third of total production is destined for industrial processing, generating substantial quantities of co-products [1]. Peels and pulps, which comprise 50 to 65% of the fruit's weight, are a rich source of bioactive compounds, including polyphenols, flavonoids, and vitamin C, and are recognized for their nutraceutical properties [1]. Long considered waste, these co-products are now attracting increasing interest as valuable functional ingredients in the food industry [2]. Recent studies have also highlighted the potential of citrus fruits and their co-products in developing functional foods and nutraceutical ingredients for sustainable food applications [3,4]. Dehydration is a key step in the management and valorization of these matrices. Drying reduces water activity, extends shelf life, and limits microbial growth, while also facilitating the extraction of

phenolic compounds [1,5]. However, drying conditions strongly influence the stability and recovery of bioactive compounds. High temperatures generally promote the degradation of heat-sensitive compounds and decrease antioxidant activity, while moderate conditions can improve polyphenol extractability by disrupting cell walls [1]. Thus, the effect of drying results from a complex balance between degradation and the release of bioactive compounds. Conventional techniques, such as hot-air or solar drying, are widely used for their simplicity and low cost, but they often lead to significant losses of vitamins, polyphenols, and organoleptic qualities [1]. Conversely, freeze-drying better preserves nutrients, color, and aroma thanks to low temperatures and reduced pressure, though it incurs a high energy cost [2]. In parallel, several emerging technologies, including microwave, infrared, and vacuum drying, have been developed to simultaneously improve product quality and process efficiency. These technologies modify heat and mass transfer as well as the structure of plant matrices, directly influencing the accessibility of bioactive compounds [1]. Recent studies have also shown that innovative drying technologies can improve flavonoid retention and antioxidant capacity, depending on thermal parameters and plant matrix characteristics [4]. Despite these advances, comparing the effects of different technologies remains difficult due to the wide variability in operating conditions, pretreatments, and matrices studied. Furthermore, literature remains fragmented, with studies often focusing on a single technology or a limited number of compounds. This methodological heterogeneity limits the identification of optimal drying strategies for preserving the bioactive compounds of citrus fruits [1]. To date, quantitative data that simultaneously integrate the effects of different drying technologies on the bioactive compounds, antioxidant properties, and colorimetric attributes of citrus matrices remain limited. In this context, the present study aims to conduct a multilevel quantitative meta-analysis to evaluate the effect of the main drying methods on the retention of bioactive compounds, antioxidant activities, and colorimetric parameters of citrus matrices. This approach also aims to identify the main sources of heterogeneity associated with drying technologies, operating conditions, and matrix characteristics, thereby providing scientific data to guide the selection of drying strategies for the preservation and valorization of citrus-derived products.

2. Methodology

2.1. Data Sources and Search Strategy

A literature search was conducted in accordance with PRISMA recommendations, using the Web of Science, Scopus, and PubMed as bibliographic databases, with complementary searches conducted through ScienceDirect, SpringerLink, and Wiley Online Library. The search was initially conducted between September 2024 and February 2025 and updated in July 2026. Grey literature was explored via Google Scholar, and the references of selected articles were manually reviewed. References were managed using Zotero, and study selection was performed independently by two reviewers.

2.2. Inclusion and Exclusion Criteria

Experimental studies published between 2010 and 2026 on citrus matrices subjected to various drying processes were included. The variables studied included bioactive compounds, antioxidant activities, and colorimetric parameters. Studies without usable quantitative data, as well as reviews and conference proceedings, were excluded.

2.3. Study Selection

After removing duplicates, titles, abstracts, and full texts were independently reviewed by two reviewers. Discrepancies were resolved by consensus. The selection process is presented in the PRISMA diagram.

2.4. Data Extraction and Management

The extracted information concerned study characteristics, drying conditions, response variables, and statistical parameters (mean, standard deviation, and sample size). Additional information related to the evaluated citrus matrices and drying methods was also recorded when available. The extracted data were used for qualitative description of the selected studies and quantitative synthesis. Multiple comparisons from the same study were retained to maximize the available information while accounting for dependence among observations in the statistical analyses.

2.5. Quality Assessment and Risk of Bias

The risk of bias was assessed using a framework adapted for experimental studies in food science, inspired by the Joanna Briggs Institute and Cochrane approaches. The results were summarized in heat maps and domain-level distributions.

2.6. Data Analysis

All statistical analyses were performed using RStudio. Effect sizes were calculated as log response ratios (logRR) or standardized mean differences (SMDs), depending on the outcome variable and measurement scale. Because multiple effect sizes could be extracted from the same study, multilevel random-effects models were fitted using restricted maximum likelihood (REML), with effect sizes nested within studies. Cluster-robust variance estimation with CR2 correction was applied to account for within-study dependence. Heterogeneity was assessed using Cochran's Q test, I^2 statistics, and variance components from the multilevel models. Subgroup analyses and meta-regression models were conducted to explore potential sources of heterogeneity related to drying methods and study characteristics. Sensitivity analyses were performed using a leave-one-study-out approach, sequentially removing each study's effect sizes to assess the robustness of the pooled estimates. Potential small-study effects were assessed using funnel plots and Egger's regression test when at least 10 independent studies were available.

Funnel plot asymmetry was interpreted cautiously as an indication of potential publication bias. The certainty of evidence was qualitatively evaluated using an approach adapted from GRADE principles.

3. Results

3.1. Selection of Studies

The study selection followed PRISMA guidelines and is summarized in Figure 1. A total of 949 articles were identified. After removing duplicates and screening titles and abstracts, 624 articles were excluded. Thus, 325 articles were retained for further analysis. Of these, an additional 176 documents were excluded, including books, literature reviews, and meta-analyses. The remaining 149 articles underwent full-text review. Following this step, 126 studies were excluded for failing to meet the predefined eligibility criteria. These exclusions mainly concerned studies involving citrus-based formulations, composite or mixed matrices containing citrus ingredients rather than direct citrus matrices subjected to controlled drying treatments, as well as studies lacking sufficient methodological details or quantitative data required for meta-analysis. Finally, 23 studies were included in the qualitative and quantitative synthesis.

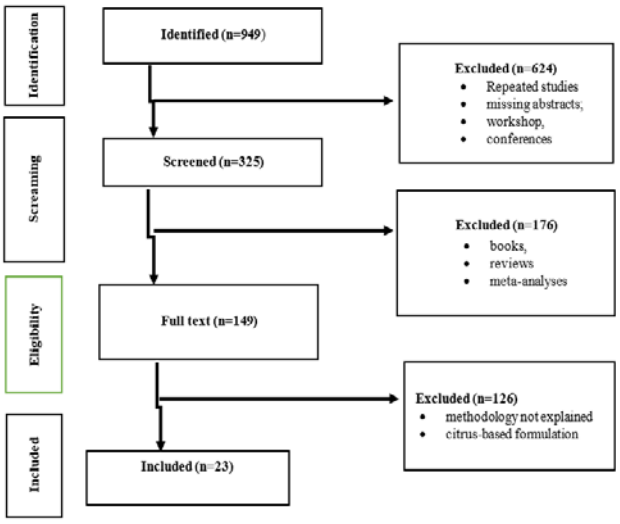


Figure 1. PRISMA flowchart of selection

PRISMA flowchart describing the study selection process for the systematic review. A total of 949 records were initially identified. After screening and eligibility assessment, 23 studies were included in the final analysis. Reasons for exclusion at each stage are indicated in the diagram.

3.2. Characteristics of the Included Studies

3.2.1. Data Volume and Variables Studied

Table 1 presents the distribution of the variables studied, the number of corresponding studies, and the number of associated independent comparisons, distinguishing between solid and liquid matrices. A total of 413 independent comparisons were extracted from the 23 included studies presented in Table 2. Total phenolic compounds (TPC) constitute the most documented variable, with 108 comparisons from 8 studies. Colorimetric parameters (L*, a*, b*, ΔE) are reported in 6 studies, totaling 61 comparisons. Antioxidant activity measured by DPPH is described in 6 studies (48 comparisons), while FRAP and ABTS tests are reported in 5 studies (39 comparisons) and 1 study (6 comparisons), respectively. Vitamin C is analyzed across 6 studies, yielding 47 comparisons. Regarding specific flavonoids, hesperidin was reported in two studies (22 comparisons), naringin in three studies (24 comparisons), narirutin in one study (16 comparisons), and neohesperidin in two studies (8 comparisons). Total flavonoids (TFC) were described in 4 studies, totaling 34 comparisons. Most comparisons involved solid matrices, including whole fruits, citrus peels, and pomace. Liquid matrices were underrepresented and were used only for DPPH antioxidant activity analysis.

3.2.2. Typology of Drying Processes

The drying methods identified in the included studies were grouped into different technological categories, namely freeze-drying (FD), hot air drying (HAD), infrared drying (IR), microwave drying (MW), vacuum drying (VD), solar or shade drying (SUN), spray drying (SD), and hybrid processes (HYBRID) (Supplementary Table S1). For each category, several names and technological variants were identified in the literature. This terminological diversity necessitated harmonizing the methods into standardized analytical categories to allow comparison within the meta-analysis.

3.2.3. Distribution of Operating Parameters of Drying Processes

Table 3 presents a descriptive summary of the operating parameters for the identified drying methods, including the number of observations, temperatures, and treatment times. Median temperatures range from 52.5°C for freeze-drying to 150°C for spray drying, while the other processes fall between 22.5°C and 80°C. Drying times also exhibit significant variability, ranging from 35 minutes for microwave drying to 4320 minutes for solar drying.

3.2.4. Assessment of the Risk of Bias

The risk-of-bias assessment revealed a predominance of low-to-moderate levels across most studies. However, some limitations were identified, particularly regarding reproducibility and the description of experimental conditions. Variability between methodological domains was also observed, suggesting heterogeneous quality among the included studies. The detailed results of this assessment are presented in Figure 2, which shows the distribution of bias levels across studies and domains.

3.3. Results of the Meta-analysis

3.3.1. Overall Effects of Drying Processes

The overall results of the multilevel meta-analysis are presented in Table 4. Overall, the drying processes resulted in significant changes in several bioactive compounds and functional properties. Vitamin C showed a significant decrease (logRR = -0.416; 95% CI [-0.608; -0.223]), corresponding to a mean retention of 66%.

Similarly, total polyphenols (TPC) and total flavonoids (TFC) showed decreases (logRR = -0.334 and -0.475), with mean retentions of 71.6% and 62.2%, respectively. Regarding antioxidant activities, ABTS activity showed a significant increase (logRR = 0.968), corresponding to a mean retention of 263%. In contrast, DPPH and FRAP activities did not show significant changes. Specific flavonoids showed variable results depending on the compounds studied. Hesperidin (logRR = -0.947), naringin (logRR = -0.077), and neohesperidin (logRR = -0.785) showed no significant changes, while narirutin showed a significant increase (logRR = 0.769), corresponding to a mean retention of 215.7%. The colorimetric parameters L*, a*, and b* showed no significant changes. The overall color change (ΔE), expressed as SMD, also showed no significant effect. High heterogeneity was observed across most of the variables studied, with I^2 values exceeding 98%.

3.3.2. Heterogeneity of Results

High heterogeneity was observed for almost all variables studied, with I^2 values exceeding 98%. The variable ΔE had an I^2 value of 59.4%. Cochran's tests (Q) were significant for all analyses ($p < 0.001$). Detailed Q and I^2 values are presented in Table 4.

3.3.3. Effect of Drying Methods (subgroup analyses)

•Regarding bioactive compounds and antioxidant activities

The effects of the different drying methods are illustrated in Figure 3. For vitamin C, the observed retention rates were 81.4% for freeze-drying (FD), 70.1% for vacuum drying (VD), 61.0% for hot air drying (HAD), and 55.0% for solar drying (SUN). For total polyphenols (TPC), the observed retention rates were 99.6% for FD, 75.4% for VD, 73.7% for MW, 65.6% for HAD, and 58.6% for SUN. For total flavonoids (TFC), the retention rates were 98.7% for FD, 93.2% for VD, 81.5% for HAD, 62.3% for SUN, and 28.7% for MW. Specific flavonoids also showed variations depending on the drying method. For hesperidin, the observed retention rates were 59.6% for FD, 43.3% for HAD, 67.8% for MW, and 17.0% for OD. For naringin, the observed values were 100.6% for FD, 85.2% for HAD, and 98.2% for MW. For narirutin, the observed retention rates were 256.7% for FD, 182.0% for HAD, and 215.2% for MW. Neohesperidin showed retention rates of 78.1% for FD, 31.7% for HAD, and 32.1% for OD. Antioxidant activities also varied depending on the drying method. For ABTS, the observed retention rates were 448.2% for FD and 201.0% for HAD. For DPPH, the observed values were 119.9% for FD, 102.5% for VD, and 99.7% for HAD. Regarding FRAP, the observed retention rates were 133.7% for FD, 113.7% for VD, and 89.6% for HAD. Detailed results for all variables, including specific flavonoids and colorimetric parameters, are provided inTable S2.

Table 1. General description of the corpus

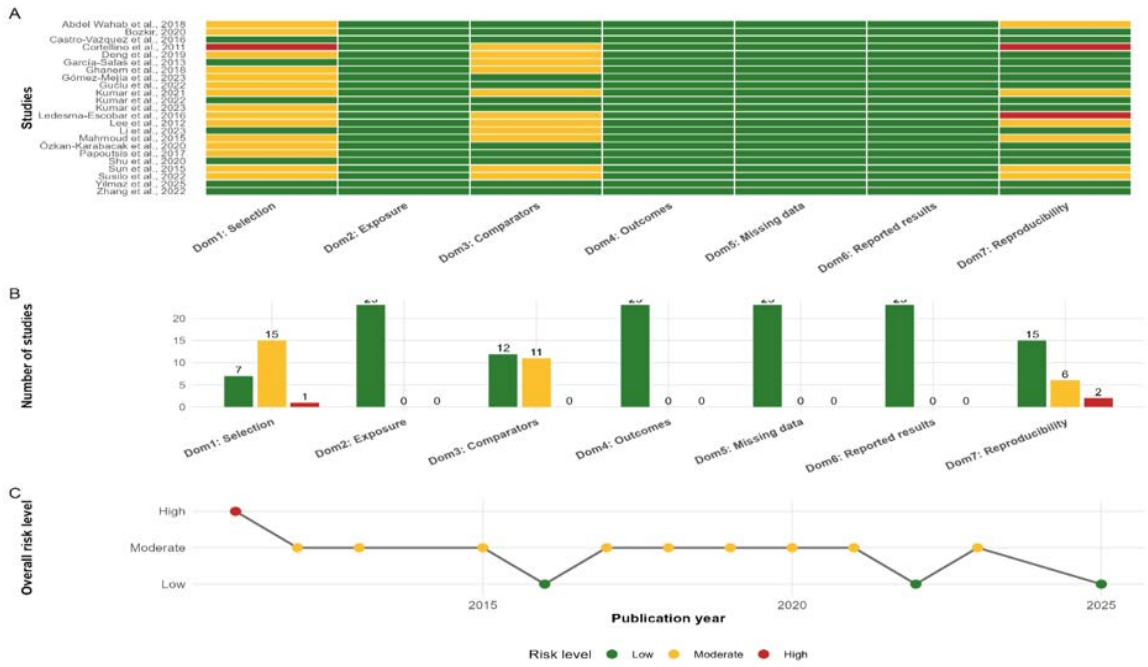
Variable	N studies	Comparisons	Solid matrices	Liquid matrices
Color (L, a, b*, ΔE)	6	61	61	0
ABTS	1	6	6	0
DPPH	6	48	40	8
FRAP	5	39	39	0
Hesperidin	2	22	22	0
Naringin	3	24	24	0
Narirutin	1	16	16	0
Neo-hesperidin	2	8	8	0
TFC	4	34	34	0
TPC	8	108	108	0
Vitamin C	6	47	47	0

TPC: Total Phenolic Content (total polyphenols); TFC: Total Flavonoid Content (total flavonoids); ABTS: 2,2'-azinobis-(3-ethylbenzothiazoline-6-sulfonic acid); DPPH: 2,2-diphenyl-1-picrylhydrazyl; FRAP: Ferric Reducing Antioxidant Power; ΔE: overall color difference.

Table 2. List of included studies

No.	Title	Country	Reference
1	Drying Characteristics of Lemon By-product (Citrus limon v. lunari): Effects of Drying Modes on Quality Attributes Kinetics'	Tunisia	[6]
2	Vacuum drying as a natural preservation method of post-harvest lemon might accelerate drying duration and produce high-quality of dried lemon slices	Indonesia	[7]
3	Effects of hot air, vacuum infrared, and vacuum microwave dryers on the drying kinetics and quality characteristics of orange slices	Türkiye	[8]
4	Microwave pre-treatment for vacuum drying of orange slices: Drying characteristics, rehydration capacity and quality properties	Türkiye	[9]
5	Hot air impingement drying kinetics and quality attributes of orange peel	China	[10]
6	Bioactive Flavonoids, Antioxidant Behavior, and Cytoprotective Effects of Dried Grapefruit Peels (Citrus paradisi Macf.)	Spain	[11]
7	Effect of vacuum-drying, hot air-drying and freeze-drying on polyphenols and antioxidant capacity of lemon (Citruslimon) pomace aqueous extracts	Australia	[12]
8	Comparative Study of the Effect of Sample Pretreatment and Extraction on the Determination of Flavonoids from Lemon (Citruslimon)	Spain	[13]

No.	Title	Country	Reference
9	Quantification of Flavonoids, Phenols and Antioxidant Potential from Dropped Citrus reticulata Blanco Fruits Influenced by Drying Techniques	India	[14]
10	Impact of drying methods on natural antioxidants, phenols and flavanones of immature dropped Citrus sinensis L. Osbeck fruits	India	[15]
11	Effects of drying methods on phytochemical compounds and antioxidant activity of physiologically dropped un-matured citrus fruits	China	[16]
12	Elucidation of the impact of four different drying methods on the phenolics, volatiles, and color properties of the peels of four types of Citrus fruits	Türkiye	[17]
13	Comparative Analysis of the Impact of Three Drying Methods on the Properties of Citrus reticulata Blanco cv. Dahongpao Powder and Solid Drinks	China	[18]
14	Bioactive Compounds in Some Citrus Peels as Affected by Drying Processes and Quality Evaluation of Cakes Supplemented with Citrus Peels Powder	Egypt	[19]
15	Effect of Some Different Drying Methods on the Chemical Analysis of Citrus By-Products.	Egypt	[20]
16	Effect of Storage and Drying Treatments on Antioxidant Activity and Phenolic Composition of Lemon and Clementine Peel Extracts	Spain	[21]
17	The effect of microwave vacuum drying process on citrus: drying kinetics, physicochemical composition and antioxidant activity of dried citrus (Citrus reticulata Blanco) peel	China	[22]
18	Influence of technological processes on phenolic compounds, organic acids, furanic derivatives, and antioxidant activity of whole-lemon powder	Spain	[23]
19	New prospective for high quality ingredients obtained from citrus fruit peel	Italy	[24]
20	Variations of Bioactive Phytochemicals and Antioxidant Capacity of Navel Orange Peel in Response to Different Drying Methods	China	[25]
21	Elucidation of flavanones, phenols and antioxidant capacity influenced by drying methods from physiologically dropped underutilized Citrus grandis fruits	India	[4]
22	Impact of Ultrasound Pretreatment and Temperature on Drying Kinetics and Quality Characteristics of Blood Orange Slices: Comparison with Different Drying Methods	Turkey	[26]
23	Effects of Hot Air- and Freeze-Drying Methods on Physicochemical Properties of Citrus 'Hallabong' Powders	Korea	[27]



(A) Heatmap showing the risk of bias evaluation for each study across the seven assessed domains.
(B) Distribution of studies according to the level of risk (low, moderate, or high) for each domain.
(C) Temporal evolution of the overall risk of bias according to publication year. Green indicates low risk, yellow indicates moderate risk, and red indicates high risk of bias.

Figure 2. Analysis of the risk of bias in studies

Values are expressed as relative percentages compared with the reference condition. Blue indicates higher relative values, whereas red indicates lower relative values. FD: freeze-drying; HAD: hot air drying; IR: infrared drying; MW: microwave drying; OD: oven drying; SUN: sun drying; VD: vacuum drying. TPC: total phenolic content; TFC: total flavonoid content; DPPH, ABTS, and FRAP: antioxidant activity assays

Figure 3. Effects of drying methods on bioactive compounds and antioxidant activities

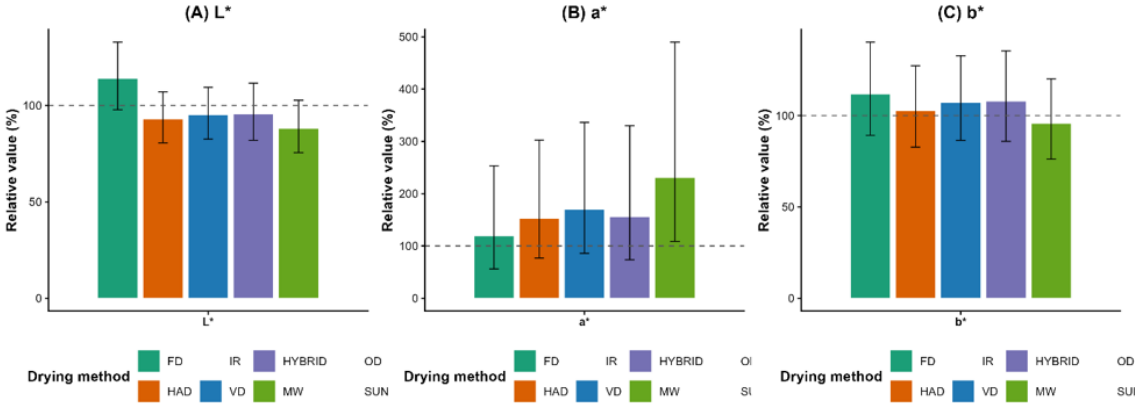


Figure 4. Effects of drying methods on the colorimetric parameters L*, a*, and b*. (A) Lightness (L*), (B) redness/greenness coordinate (a*), and (C) yellowness/blueness coordinate (b*). The dashed horizontal line represents the reference value (100%). Error bars indicate standard deviation. FD: freeze-drying; HAD: hot-air drying; IR: infrared drying; VD: vacuum drying; MW: microwave drying

Table 3. Descriptive summary of drying parameters by method

Code	Observations	Average temperature	Median temperature	Minimum temperature	Maximum temperature	Average duration (min)	Median duration (min)	Minimum duration (min)	Maximum duration (minimum)
FD	50	-59.14	-52.5	-80.0	-50.0	2430.0	2160.0	720.0	4320.0
HAD	80	56.06	50.0	40.0	110.0	1758.63	1590.0	75.0	5760.0
HYBRID	21	80.00	80.0	50.0	95.0	275.24	240.0	60.0	1440.0
IR	3	50.00	50.0	40.0	60.0	413.33	413.0	200.0	626.0
MW	13	40.00	40.0	20.0	60.0	34.85	35.0	6.0	162.0
SD	1	150.00	150.0	150.0	150.0	-	-	-	-
SUN	11	27.81	22.5	20.0	35.0	8875.64	4320.0	2880.0	20160.0
VD	38	62.86	60.0	25.0	110.0	551.74	390.0	25.0	2880.0

FD: freeze-drying; HAD: hot-air drying; HYBRID: hybrid drying; IR: infrared drying; MW: microwave drying; SUN: sun drying; VD: vacuum drying; SD: Spray drying. Note: Spray drying (SD) was identified as a drying method for citrus matrices; however, only one study reported this method. Therefore, SD parameters are presented descriptively.

Table 4. Overall results of the meta-analysis and heterogeneity

Variable	Type of effect	k	N studies	Estimate	IC 95%	Retention(%)	Q	p(Q)	I^2 (%)	Heterogeneity
Vitamin C	logRR	47	6	-0.416	[-0.608 ; -0.223]	66 [54.4;80.0]	100,521.40	<0.001	99.9	Considerable
TPC	logRR	108	8	-0.334	[-0.579 ; -0.089]	71.6 [56.0; 91.5]	13,378,775.11	<0.001	99.5	Considerable

Variable	Type of effect	k	N studies	Estimate	IC 95%	Retention(%)	Q	p(Q)	I² (%)	Heterogeneity
TFC	logRR	34	4	-0.475	[-0.997 ; 0.047]	62.2 [36.9; 104.9]	48,787.85	<0.001	99.9	Considerable
ABTS	logRR	6	1	0.968	[0.604; 1.332]	263.2 [182.9; 378.7]	432.84	<0.001	98.2	Considerable
DPPH	logRR	48	6	0.031	[-0.360 ; 0.421]	103.1 [69.7; 152.4]	8,466.58	<0.001	98.6	Considerable
FRAP	logRR	39	5	0.028	[-0.380 ; 0.437]	102.9 [68.4; 154.9]	3,233.20	<0.001	99.1	Considerable
Hesperidin	logRR	22	2	-0.947	[-3.060 ; 1.166]	38.8 [4.7; 321.0]	25,270.46	<0.001	99.9	Considerable
Naringine	logRR	24	3	-0.077	[-1.025 ; 0.872]	92.6 [35.9; 239.1]	9,727.39	<0.001	99.7	Considerable
Narirutin	logRR	16	1	0.769	[0.545 ; 0.992]	215.7 [172.5; 269.6]	18,050.67	<0.001	99.5	Considerable
Neohesperidin	logRR	8	2	-0.785	[-2.535 ; 0.965]	45.6 [7.9; 262.5]	4,973.09	<0.001	99.9	Considerable
L*	logRR	61	6	-0.054	[-0.187 ; 0.079]	94.8 [83.0; 108.3]	46,686.78	<0.001	99.7	Considerable
a*	logRR	61	6	0.501	[-0.176 ; 1.177]	165.0 [83.9; 324.4]	219,052.75	<0.001	98.5	Considerable
b*	logRR	61	6	0.049	[-0.167 ; 0.265]	105.0 [84.6; 130.3]	38,749.29	<0.001	99.4	Considerable
ΔE	SMD	54	5	84,590	[-43,428; 212,607]	–	206.13	<0.001	59.4	Substantial

TPC: Total Phenolic Content; TFC: Total Flavonoid Content; ABTS: 2,2'-azinobis-(3-ethylbenzothiazoline-6-sulfonic acid); DPPH: 2,2-diphenyl-1-picrylhydrazyl; FRAP: Ferric Reducing Antioxidant Power; ΔE: overall color difference; 95% CI: 95% confidence interval; k: number of comparisons; Q: Cochran's heterogeneity statistic; p(Q): probability value associated with the Q and I² heterogeneity tests (%)

•Regarding colorimetric parameters

The colorimetric parameters L*, a*, b*, and ΔE did not show significant variation across the drying methods (Figure 4). For ΔE specifically, the estimates, expressed as standardized mean differences (SMDs), ranged from 80.98 to 113.02 depending on the method (Table S2), with confidence intervals that systematically included zero, confirming the absence of a significant effect.

3.3.4. Overall Tests of the Effects of the Methods

The results of the overall tests of the effects of the drying methods revealed significant effects of the drying methods for several variables, including vitamin C (QM = 63.53; $p < 0.001$), total polyphenols (TPC) (QM = 15.87; $p = 0.026$), ABTS activity (QM = 141.27; $p < 0.001$), FRAP activity (QM = 12.17; $p = 0.007$), narirutin (QM = 43.85; $p < 0.001$), neohesperidin (QM = 8.27; $p = 0.041$), as well as the colorimetric parameters L* (QM = 58.52; $p < 0.001$), a* (QM = 14.80; $p = 0.011$) and b* (QM = 14.80; $p = 0.011$). 13.83; $p = 0.017$). No significant effect was observed for DPPH, hesperidin, naringin, and ΔE. Detailed results are presented in Table S3.

3.3.5. Meta-regression

Meta-regressions revealed significant associations between temperature and the colorimetric parameters L* (estimate = -0.0015; 95% CI [-0.003; -0.000]; $p = 0.021$) and a* (estimate = 0.0198; 95% CI [0.011; 0.029]; $p < 0.001$). Drying time was also significantly associated with a* (estimate = 0.0030; 95% CI [0.002; 0.004]; $p < 0.001$). In contrast, no significant association was observed between total polyphenols (TPC) and temperature (estimate = -0.0014; 95% CI [-0.005, 0.002]; $p = 0.443$) or duration (estimate = 0.0000; 95% CI [-0.000, 0.000]; $p = 0.253$), nor between b* and temperature (estimate = -0.0001; 95% CI [-0.003, 0.002]; $p = 0.965$). The results are provided in Supplementary Table S4.

3.3.6. Sensitivity Analysis

Leave-one-study-out sensitivity analysis was performed to assess the stability of the overall estimates. Excluding each study in turn did not significantly change the effect sizes for the variables studied. The overall estimates remained generally stable across all analyses. Summary and detailed results of the sensitivity analyses are presented in Supplementary Table S5. The corresponding influence plots are shown in Figures S1, S2, and S3 for bioactive compounds and flavonoids, antioxidant activities, and colorimetric parameters, respectively.

3.3.7. Publication Bias

Publication bias was assessed using funnel plots and Egger's test when sufficient studies were available. Funnel plots show variable distributions depending on the parameters studied. Visual asymmetries are observed for some variables. Funnel plots corresponding to bioactive compounds, specific flavonoids, and antioxidant activities are shown in Figure S4, while those for colorimetric parameters are shown in Figure S5. Detailed results of Egger's tests are presented in Supplementary Table S6.

4. Discussion

4.1. Overall Effects of Drying Processes on Bioactive Compounds

The results of this meta-analysis show that drying processes generally reduce the levels of the main bioactive compounds in citrus matrices. Vitamin C appears to be one of the most sensitive compounds, with an average retention of 66% and a significant decrease (logRR = -0.416). Total polyphenols (TPC) and total flavonoids (TFC) also show significant decreases, with average

retentions of 71.6% and 62.2%, respectively. These results confirm the high sensitivity of vitamin C to thermal and oxidative treatments, as reported by Santos and Silva [28]. The decrease in phenolic and flavonoid compounds is also consistent with the observations of Kumar et al. [15]. However, the differences observed among the variables suggest varying levels of stability that depend on the chemical structure, cellular localization, and thermal sensitivity of the bioactive compounds.

4.2. Effects of Drying Methods

Subgroup analyses reveal significant differences between drying technologies. Freeze-drying (FD) exhibits the highest retention rates for vitamin C (81.4%), TPCs (99.6%), and TFCs (98.7%), confirming its effectiveness in preserving heat-sensitive compounds through low temperatures and limited oxidative processes [15]. Conversely, solar drying (SUN) and hot air drying (HAD) result in the greatest losses, likely due to prolonged exposure to heat and oxygen [29]. Microwave drying (MW) shows more contrasting effects, with good retention of TPCs (73.7%) but a significant decrease in TFCs (28.7%), suggesting variable effects depending on the nature of the compounds [30]. Despite the good performance of freeze-drying, its energy cost limits its industrial application. In this context, hybrid processes appear as promising alternatives, offering an interesting compromise between preservation of bioactive compounds, energy efficiency, and industrial applicability for the sustainable valorization of citrus matrices and co-products.

4.3. Behavior of Specific Flavonoids

Specific flavonoids exhibit contrasting responses depending on the compound and drying method. Hesperidin shows relatively low retention under HAD (43.3%) and OD (17.0%), while higher values are observed under FD (59.6%) and MW (67.8%). Naringin exhibits retention close to 100%, while narirutin reaches very high values under FD (256.7%) and MW (215.2%). These retentions exceeding 100% likely reflect apparent relative increases in the measured concentrations after drying. Several mechanisms can explain these observations, including the disruption of cellular structures, which improves the extractability of phenolic compounds [31], as well as certain chemical transformations induced by heat treatment [16]. These results are consistent with previous studies reporting an apparent improvement in some flavonoids after drying [15]. Conversely, neohesperidin exhibits lower retention, suggesting greater instability under prolonged heat treatment.

4.4. Antioxidant Activities

Antioxidant activities vary depending on the analytical test. ABTS activity shows the most significant increases, with retentions reaching 448.2% under FD and 201.0% under HAD, while DPPH and FRAP show more moderate variations. These differences may be related to the specific chemical mechanisms assessed by each method. The observed increases have already been reported in the literature and may be associated with improved extractability of phenolic compounds or the formation of new antioxidant compounds resulting from Maillard reactions [16,29]. Chen et al. specifically point out that certain drying conditions can increase apparent antioxidant activity by releasing bound compounds or transforming complex molecules [29]. The coexistence of decreases in bioactive compounds and increases in certain antioxidant activities illustrates the complexity of the transformations induced by drying processes.

4.5. Colorimetric Parameters

The colorimetric parameters L*, a*, and b* did not show significant variation across the overall analyses, although some differences were observed depending on the drying method. Meta-regression analyses, in particular, showed significant associations between temperature and the parameters L* and a*. Regarding ΔE, the observed estimates ranged from 80.98 to 113.02 across drying methods, with no overall significant effect. These results are generally consistent with several studies reporting that some biochemical changes induced by drying do not necessarily translate into significant visual changes [32]. The variability observed between studies may be related to differences in matrices, operating conditions, and instrumental methods used for color evaluation.

4.6. Heterogeneity of Results

One of the main findings of this study is the very high heterogeneity observed across most variables, with I^2 values exceeding 98%. This heterogeneity is confirmed by significant Q tests across all analyses. This variability can be explained by several factors, including the diversity of the matrices studied, differences in operating conditions, applied pretreatments, and the heterogeneity of analytical methods used between studies [29]. Meta-regression analyses show that certain parameters, particularly temperature, significantly influence some colorimetric variables. However, these factors only explain a limited portion of the observed heterogeneity.

4.7. Strengths and Limitations of the Study

This study has several important strengths. To our knowledge, it is one of the first multilevel meta-analyses dedicated to the effects of drying processes on the bioactive compounds and functional properties of citrus matrices. The use of multilevel models with REML estimation and robust CR2 variance accounted for dependence among comparisons within the same study. The simultaneous integration of bioactive compounds, specific flavonoids, antioxidant activities, and colorimetric parameters is also a significant advantage. However, several limitations must be highlighted. The number of studies remains limited for certain variables, particularly specific flavonoids and some antioxidant activities. Furthermore, the high heterogeneity observed limits the generalizability of the overall estimates. Finally, methodological differences across studies complicate direct comparisons of results. However, the use of cluster-

robust (CR2) inference yielded reliable estimates of uncertainty while accounting for dependence among effect sizes from the same studies (Supplementary Table S7). The assessment of the certainty of evidence revealed variable levels of confidence across the evaluated parameters, mainly due to high heterogeneity and the limited number of available studies for certain outcomes. The detailed results of this evaluation are presented in Supplementary Table S8.

4.8. Implications and Perspectives

The results obtained highlight the importance of selecting drying technologies to preserve bioactive compounds in citrus fruits. Freeze-drying appears to be the most effective method overall, although some alternative technologies may offer specific advantages depending on the compounds studied. These results open up avenues for optimizing citrus processing methods and valorizing co-products rich in bioactive compounds. Future studies using standardized protocols and more in-depth mechanistic approaches will be necessary to better understand the transformations induced by drying processes.

5. Conclusion

Drying processes are important strategies for the preservation, stabilization, and valorization of citrus matrices. However, their effects on nutritional and functional attributes remain highly variable depending on the drying technology used, the operating conditions applied, and the characteristics of the matrices studied. This multilevel meta-analysis provides quantitative data on the impact of drying processes on the biochemical composition, antioxidant properties, and colorimetric quality of citrus matrices. Overall, drying significantly reduces the levels of the main bioactive compounds, including vitamin C, total phenolic compounds, and total flavonoids, confirming their sensitivity to thermal and oxidative stresses. Among the technologies evaluated, freeze-drying showed the best capacity for retaining bioactive compounds, while solar drying and hot air drying were associated with the greatest losses. However, responses for specific flavonoids and antioxidant activity varied with the compounds and the analytical methods used, suggesting that drying-induced changes result from both degradation and changes in compound extractability. Retention rates exceeding 100%, observed for certain parameters such as narirutin content and some antioxidant activities, should therefore be interpreted as apparent increases related to concentration effects or improved extractability rather than actual compound synthesis. Colorimetric parameters generally appear more stable, although some variations may occur depending on processing conditions. The significant heterogeneity observed between studies highlights the important influence of citrus matrices, drying technology parameters, and analytical methodologies, emphasizing the need for more standardized experimental protocols. Overall, these results provide scientific evidence to guide the selection of appropriate drying strategies to preserve functional quality and enhance the valorization potential of citrus products and by-products.

Conflict of Interest Statement

The authors received no specific funding for this work and declared no conflicts of interest.

Author Contributions

Ana-kpan Dome Vincent Bekuoné Somé: Conceptualization, Methodology, Investigation, Data curation, Formal analysis,Writing original draft; **Mamounata Diao**: Conceptualization, Methodology, Validation, Supervision, Writing review & editing; **Rocksane Octavia Kiswendsida Nikiema**: Investigation, Data curation, Literature screening, Writing review & editing;

David Bazié: Methodology, Validation, Writing review & editing;

Désiré Ouaro: Investigation, Data curation, Risk of bias assessment, Writing review & editing;

Zakaria Dindané: Investigation, Data curation, Risk of bias assessment, Writing review & editing;

Roger Dakuyo: Data curation, Validation, Writing review & editing;

Fréderic Anderson Konkobo: Investigation, Data curation, Writing review & editing

Hemayoro Sama: Validation, Writing review & editing; **Samson Guenné**: Validation, Writing review & editing; **Mamoudou Hama Dicko**: Supervision and Validation

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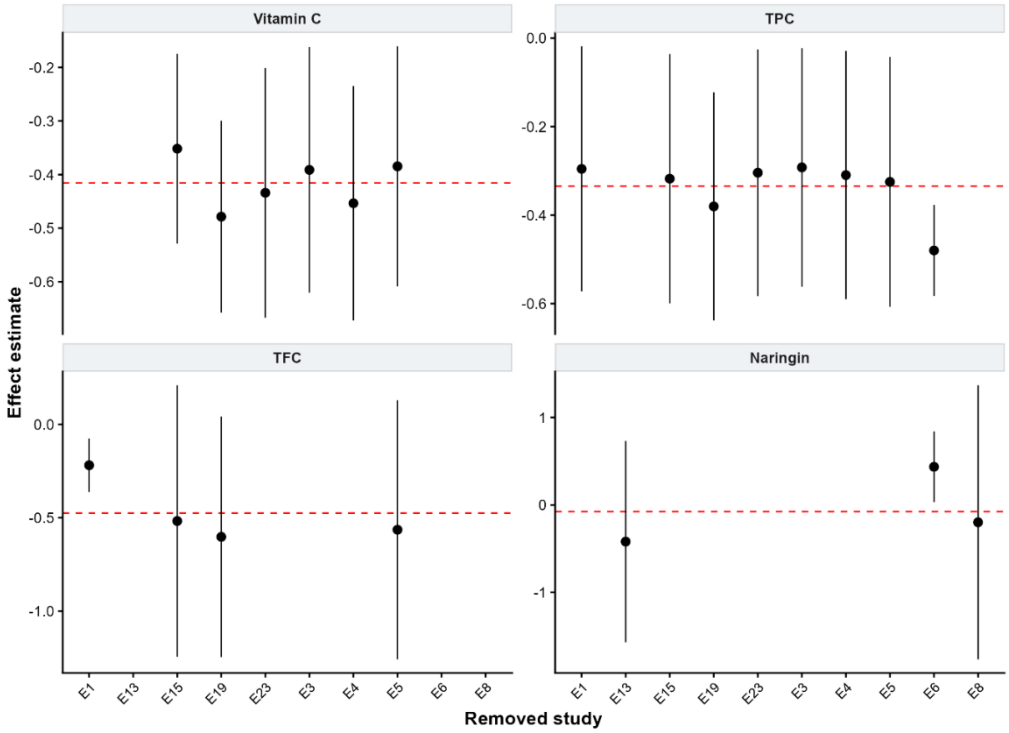
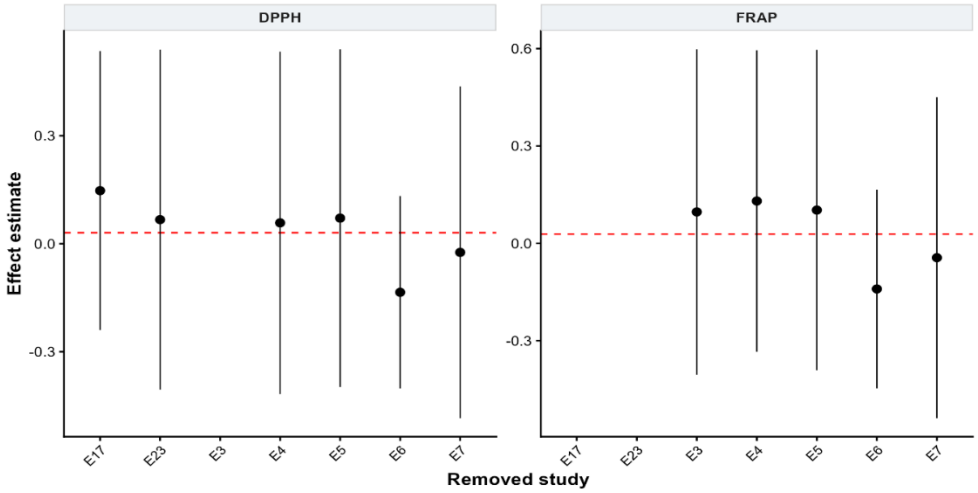
Supplementary

Figure S1. Leave-one-study-out sensitivity analyses for bioactive compounds and flavonoids



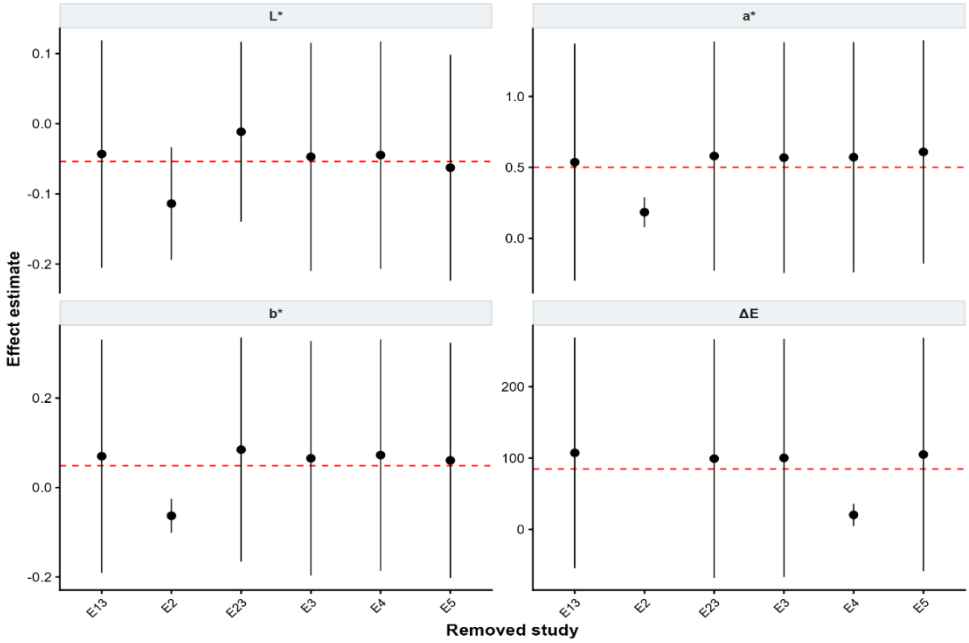
Each point represents the pooled effect estimate obtained after sequentially excluding one study. Horizontal dashed red lines indicate the original pooled estimates obtained from the full dataset. The stability of the pooled estimates indicates that individual studies have limited influence on the overall results.

Figure S2. Leave-one-study-out sensitivity analyses for antioxidant activities



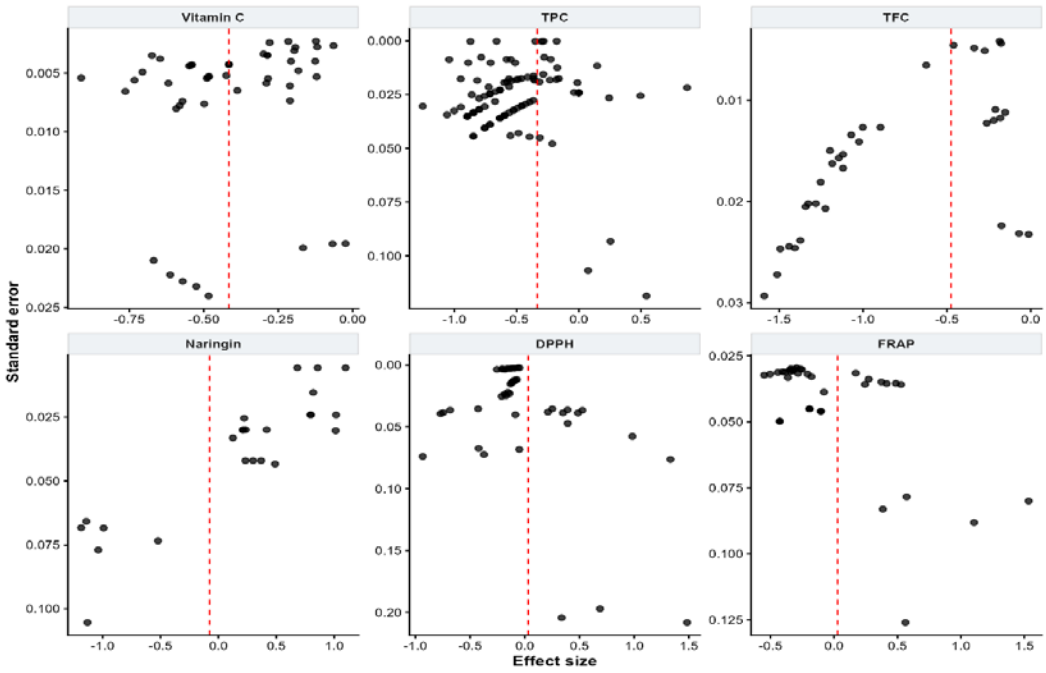
Sequential omission of individual studies did not substantially alter the pooled estimates of antioxidant activity, indicating robustness of the meta-analytic results.

Figure S3. Leave-one-study-out sensitivity analyses for colorimetric parameters



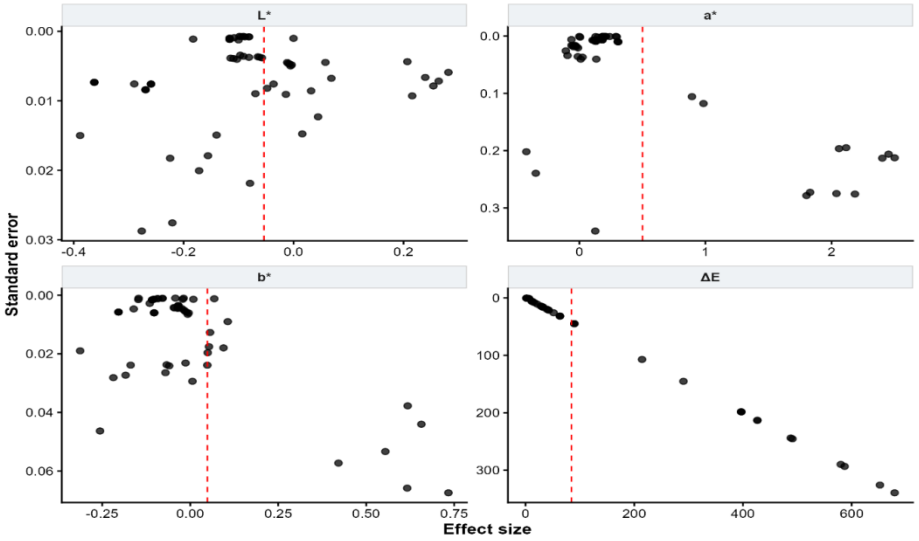
The pooled estimates for colorimetric parameters remained stable across sequential exclusions of individual studies, although slight variations were observed for some parameters due to the limited number of available comparisons.

Figure S4. Funnel plots for bioactive compounds, flavonoids and antioxidant activities



Funnel plots were used to assess potential publication bias visually. Dashed vertical lines represent pooled effect estimates. Visual asymmetry observed in some variables should be interpreted cautiously, given the limited number of studies and their high heterogeneity.

Figure S5. Funnel plots for colorimetric parameters



Funnel plots for colorimetric parameters showed variable dispersion patterns across studies. Interpretation of potential asymmetry remains limited due to the relatively small number of comparisons available for some parameters.

Table S1. Classification of selected drying methods

Drying method	Included designations/methods	Code
Freeze-drying	Freeze drying; Freeze Drying; Vacuum Freeze Drying; Freeze-dried; Lyophilized.	FD
Hot air drying	Hot air drying; Air oven drying; Oven drying; Drying in a drying oven; Tray dryer; Hot air impingement drying; Air-dried; Hot air oven; Hot air drying	HAD
Infrared drying	Infrared drying; IR drying; Infrared drying; Infrared dryer	IR
Microwave drying	Microwave drying; MW drying; Microwave drying; Microwave-assisted drying.	MW
Vacuum drying	Vacuum drying; Vacuum drying; Vacuum oven drying	VD
Hybrid drying	Microwave-Vacuum drying; Vacuum Infrared drying; Ultrasound-Assisted Vacuum Drying.	HYBRID
Sun drying / in the shade	Sun drying; Sun drying; Solar drying; Shade drying; Natural drying	SUN
Spray drying	Spray drying; Spray drying; Spraying; Spray-dried powders	SD

Table S2. Detailed subgroup analyses by drying method for bioactive compounds, antioxidant activities, and colorimetric parameters.

Variable	Method	Type_effect	Estimate	IC	p	Retention_txt
Vitamin C	FD	logRR	-0.206208147	[-0.394 ; -0.018]	0.032	81.4 [67.4; 98.2]
Vitamin C	HAD	logRR	-0.493758651	[-0.637 ; -0.351]	<0.001	61.0 [52.9 ; 70.4]
Vitamin C	HYBRID	logRR	-0.253275888	[-0.431 ; -0.076]	0.005	77.6 [65.0 ; 92.7]
Vitamin C	SUN	logRR	-0.598392760	[-0.788 ; -0.409]	<0.001	55.0 [45.5 ; 66.4]
Vitamin C	VD	logRR	-0.354601848	[-0.500 ; -0.209]	<0.001	70.1 [60.6; 81.1]
TPC	FD	logRR	-0.003867867	[-0.390 ; 0.382]	0.984	99.6 [67.7; 146.5]
TPC	HAD	logRR	-0.420837460	[-0.678 ; -0.164]	0.001	65.6 [50.8; 84.9]
TPC	HYBRID	logRR	-0.235092136	[-0.678 ; 0.208]	0.298	79.0 [50.8 ; 123.1]
TPC	IR	logRR	-0.393848060	[-0.707 ; -0.081]	0.014	67.4 [49.3; 92.2]
TPC	MW	logRR	-0.304849623	[-0.611 ; 0.001]	0.051	73.7 [54.3; 100.1]
TPC	SUN	logRR	-0.533895932	[-1.016 ; -0.052]	0.030	58.6 [36.2 ; 95.0]
TPC	VD	logRR	-0.282427806	[-0.577 ; 0.013]	0.061	75.4 [56.1; 101.3]
TFC	FD	logRR	-0.012739026	[-0.320 ; 0.295]	0.935	98.7 [72.6; 134.3]
TFC	HAD	logRR	-0.204602840	[-0.306 ; -0.103]	<0.001	81.5 [73.6; 90.2]
TFC	MW	logRR	-1.249077755	[-1.318 ; -1.181]	<0.001	28.7 [26.8; 30.7]
TFC	SUN	logRR	-0.473919737	[-0.650 ; -0.298]	<0.001	62.3 [52.2; 74.2]
TFC	VD	logRR	-0.069897440	[-0.377 ; 0.238]	0.656	93.2 [68.6; 126.8]
ABTS	FD	logRR	1.500151864	[1.204; 1.796]	<0.001	448.2 [333.4 ; 602.6]
ABTS	HAD	logRR	0.698142663	[0.488; 0.908]	<0.001	201.0 [163.0 ; 247.9]
DPPH	FD	logRR	0.181336973	[-0.249 ; 0.611]	0.408	119.9 [78.0 ; 184.3]
DPPH	HAD	logRR	-0.002562270	[-0.390 ; 0.385]	0.990	99.7 [67.7; 146.9]
DPPH	HYBRID	logRR	0.110415879	[-0.335 ; 0.556]	0.627	111.7 [71.5; 174.4]
DPPH	VD	logRR	0.024812360	[-0.367 ; 0.417]	0.901	102.5 [69.3; 151.7]
FRAP	FD	logRR	0.290643445	[-0.195 ; 0.776]	0.240	133.7 [82.3 ; 217.3]
FRAP	HAD	logRR	-0.110108283	[-0.539 ; 0.318]	0.615	89.6 [58.4; 137.5]

Variable	Method	Type_effect	Estimate	IC	p	Retention_txt
FRAP	VD	logRR	0.128375498	[-0.305 ; 0.562]	0.562	113.7 [73.7; 175.4]
Hesperidin	FD	logRR	-0.517785226	[-2.000 ; 0.964]	0.494	59.6 [13.5; 262.3]
Hesperidin	HAD	logRR	-0.835885746	[-2.459 ; 0.787]	0.313	43.3 [8.6; 219.7]
Hesperidin	MW	logRR	-0.388730838	[-1.934 ; 1.157]	0.622	67.8 [14.5; 317.9]
Hesperidin	OD	logRR	-1.769168642	[-3.394 ; -0.145]	0.033	17.0 [3.4 ; 86.5]
Naringine	FD	logRR	0.005938455	[-0.931 ; 0.942]	0.990	100.6 [39.4 ; 256.6]
Naringine	HAD	logRR	-0.160522260	[-1.091 ; 0.770]	0.735	85.2 [33.6 ; 216.0]
Naringine	MW	logRR	-0.018412112	[-0.970 ; 0.933]	0.970	98.2 [37.9; 254.3]
Narirutin	FD	logRR	0.942862068	[0.483 ; 1.403]	<0.001	256.7 [162.1 ; 406.7]
Narirutin	HAD	logRR	0.598772894	[0.139; 1.059]	0.011	182.0 [114.9 ; 288.3]
Narirutin	MW	logRR	0.766272167	[0.440 ; 1.093]	<0.001	215.2 [155.3; 298.2]
Neohesperidin	FD	logRR	-0.247035418	[-1.951 ; 1.457]	0.776	78.1 [14.2; 429.2]
Neohesperidin	HAD	logRR	-1.149299840	[-3.054 ; 0.756]	0.237	31.7 [4.7; 212.9]
Neohesperidin	OD	logRR	-1.137776976	[-2.889 ; 0.614]	0.203	32.1 [5.6; 184.8]
L*	FD	logRR	0.131501358	[-0.022 ; 0.285]	0.093	114.1 [97.8; 132.9]
L*	HAD	logRR	-0.073630447	[-0.216 ; 0.068]	0.309	92.9 [80.6; 107.1]
L*	HYBRID	logRR	-0.044300722	[-0.199 ; 0.110]	0.574	95.7 [82.0 ; 111.6]
L*	MW	logRR	-0.126798544	[-0.280 ; 0.027]	0.106	88.1 [75.5; 102.7]
L*	VD	logRR	-0.050218745	[-0.191 ; 0.091]	0.485	95.1 [82.6; 109.5]
a*	FD	logRR	0.174322771	[-0.580 ; 0.928]	0.650	119.0 [56.0 ; 253.0]
a*	HAD	logRR	0.420954309	[-0.265 ; 1.107]	0.229	152.3 [76.7; 302.6]
a*	HYBRID	logRR	0.443177267	[-0.307 ; 1.194]	0.247	155.8 [73.5; 329.9]
a*	MW	logRR	0.835624744	[0.082; 1.589]	0.030	230.6 [108.6 ; 490.0]
a*	VD	logRR	0.530979374	[-0.150 ; 1.212]	0.127	170.1 [86.0 ; 336.1]
b*	FD	logRR	0.111611106	[-0.115 ; 0.338]	0.335	111.8 [89.1; 140.3]
b*	HAD	logRR	0.025465190	[-0.190 ; 0.241]	0.817	102.6 [82.7; 127.2]
b*	HYBRID	logRR	0.075531755	[-0.152 ; 0.303]	0.515	107.8 [85.9; 135.4]
b*	MW	logRR	-0.044075206	[-0.271 ; 0.183]	0.704	95.7 [76.2; 120.1]
b*	VD	logRR	0.068626056	[-0.146 ; 0.283]	0.531	107.1 [86.4; 132.7]
ΔE	FD	SMD	85.995136660	[-44,448; 216,438]	0.196	N A
ΔE	HAD	SMD	86.436549705	[-44.003 ; 216.876]	0.194	N A
ΔE	HYBRID	SMD	113.017524899	[-21,494; 247,529]	0.100	N A
ΔE	MW	SMD	86.870738657	[-43.573 ; 217.314]	0.192	N A
ΔE	VD	SMD	80.978420737	[-49,603; 211,560]	0.224	N A

FD: freeze-drying; HAD: hot-air drying; HYBRID: hybrid drying; IR: infrared drying; MW: microwave drying; SUN: sun drying; VD: vacuum drying; OD: osmotic drying. logRR: logarithmic response ratio; SMD: standardized mean difference; CI: confidence interval. Retention values were calculated as exp(logRR) × 100. Retention percentages do not applyto ΔE because the analyses were performed using SMD. NA: not applicable or insufficiently available data for the corresponding analysis.

Table S3. Results of subgroup analyses by bioactive compounds, antioxidant activities, and colorimetric parameters

Variable	QM	df	p
Vitamin C	63.53	5	<0.001
TPC	15.87	7	0.026
TFC	1319.05	5	<0.001
ABTS	141.27	2	<0.001
DPPH	2.89	4	0.577
FRAP	12.17	3	0.007
Hesperidin	7.12	4	0.130
Naringine	1.32	3	0.725
Narirutin	43.85	3	<0.001
Neohesperidin	8.27	3	0.041
L*	58.52	5	<0.001
a*	14.80	5	0.011
b*	13.83	5	0.017
ΔE	5.84	5	0.322

TPC: Total Phenolic Content (total polyphenols); TFC: Total Flavonoid Content (total flavonoids); ABTS: 2,2'-azinobis-(3-ethylbenzothiazoline-6-sulfonic acid); DPPH: 2,2-diphenyl-1-picrylhydrazyl; FRAP: Ferric Reducing Antioxidant Power; ΔE: overall color difference; QM: omnibus test statistic of moderators (Wald/Q-model test) used in meta-regression or in subgroup analyses to assess the overall effect of the moderator on the effect size; df (degrees of freedom): degrees of freedom associated with the statistical test ; ***p****: probability value associated with the statistical test, indicating the level of significance of the observed effect.*

Table S4. Detailed exploratory meta-regression analyses for selected variables.

Variable	Moderator	Estimate	IC	p	k
TPC	temperature	-0.0013719543227	[-0.005 ; 0.002]	0.443	62
TPC	duration	0.0000006766122	[-0.000 ; 0.000]	0.253	62
L*	temperature	-0.0014539942878	[-0.003 ; -0.000]	0.021	23
L*	duration	-0.0000860521062	[-0.000 ; 0.000]	0.466	23
a*	temperature	0.0197858975818	[0.011 ; 0.029]	<0.001	23
a*	duration	0.0030448453322	[0.002; 0.004]	<0.001	23
b*	temperature	-0.0000555349181	[-0.003 ; 0.002]	0.965	23
b*	duration	0.0001201404439	[-0.000 ; 0.001]	0.621	23

Meta-regressions were performed only for variables with sufficient numbers of comparisons and available moderator information. Temperature was expressed in °C and duration in minutes. CI: confidence interval.

Table S5. Detailed leave-one-study-out sensitivity analysis results

Variable	Removed_study	k_remaining	Estimate	IC	Retention_IC	Relative change percentage
Vitamin C	E3	38	-0.39117410	[-0.620 ; -0.162]	67.6 [53.8 ; 85.0]	5.9
Vitamin C	E4	33	-0.45350587	[-0.672 ; -0.235]	63.5 [51.1; 79.1]	9.1
Vitamin C	E5	42	-0.38463326	[-0.608 ; -0.161]	68.1 [54.4; 85.1]	7.5
Vitamin C	E15	41	-0.35166736	[-0.529 ; -0.175]	70.4 [58.9 ; 84.0]	15.4
Vitamin C	E19	44	-0.47852391	[-0.658 ; -0.300]	62.0 [51.8 ; 74.1]	15.1
Vitamin C	E23	37	-0.43401145	[-0.667 ; -0.201]	64.8 [51.3; 81.8]	4.4
TPC	E1	51	-0.29550141	[-0.572 ; -0.019]	74.4 [56.4; 98.1]	11.6
TPC	E3	99	-0.29213048	[-0.561 ; -0.023]	74.7 [57.0 ; 97.7]	12.6
TPC	E4	96	-0.30951741	[-0.590 ; -0.029]	73.4 [55.4; 97.1]	7.4
TPC	E5	103	-0.32491042	[-0.607 ; -0.043]	72.3 [54.5; 95.8]	2.8
TPC	E6	102	-0.47976972	[-0.583 ; -0.377]	61.9 [55.8; 68.6]	43.5
TPC	E15	102	-0.31765758	[-0.599 ; -0.036]	72.8 [54.9; 96.5]	5.0
TPC	E19	105	-0.38023627	[-0.638 ; -0.123]	68.4 [52.8; 88.5]	13.7
TPC	E23	98	-0.30423001	[-0.583 ; -0.026]	73.8 [55.8; 97.5]	9.0
TFC	E1	14	-0.21854043	[-0.362 ; -0.075]	80.4 [69.6; 92.8]	54.0
TFC	E5	29	-0.56393525	[-1.258 ; 0.130]	56.9 [28.4; 113.9]	18.7
TFC	E15	28	-0.51726709	[-1.244 ; 0.210]	59.6 [28.8; 123.3]	8.9
TFC	E19	31	-0.60204000	[-1.246 ; 0.042]	54.8 [28.8; 104.3]	26.8
ABTS	E6	0	N A	[NA; NA]	NA [NA ; NA]	N / A
DPPH	E4	36	0.05797311	[-0.418 ; 0.534]	106.0 [65.9 ; 170.5]	89.8
DPPH	E5	43	0.07119008	[-0.398 ; 0.540]	107.4 [67.2; 171.6]	133.1
DPPH	E6	42	-0.13482527	[-0.402 ; 0.133]	87.4 [66.9; 114.2]	541.4
DPPH	E7	41	-0.02400274	[-0.485 ; 0.437]	97.6 [61.6; 154.8]	178.6
DPPH	E17	40	0.14741155	[-0.240 ; 0.535]	115.9 [78.7 ; 170.7]	382.6
DPPH	E23	38	0.06686450	[-0.405 ; 0.539]	106.9 [66.7; 171.4]	118.9
FRAP	E3	30	0.09685102	[-0.404 ; 0.598]	110.2 [66.7; 181.8]	239.9
FRAP	E4	27	0.13040275	[-0.334 ; 0.595]	113.9 [71.6; 181.3]	357.6
FRAP	E5	34	0.10260200	[-0.391 ; 0.596]	110.8 [67.7; 181.5]	260.0
FRAP	E6	33	-0.14041114	[-0.446 ; 0.166]	86.9 [64.0 ; 118.0]	592.7
FRAP	E7	32	-0.04414916	[-0.539 ; 0.450]	95.7 [58.4; 156.9]	254.9
Hesperidin	E6	16		[NA; NA]	NA [NA ; NA]	
Hesperidin	E13	6		[NA; NA]	NA [NA ; NA]	
Naringine	E6	18	0.43584776	[0.032; 0.840]	154.6 [103.3; 231.6]	669.4
Naringine	E8	22	-0.19844562	[-1.765 ; 1.369]	82.0 [17.1 ; 393.0]	159.3
Naringine	E13	8	-0.41961783	[-1.571 ; 0.731]	65.7 [20.8; 207.8]	448.2
Narirutin	E13	0	N / A	[NA; NA]	NA [NA ; NA]	N / A
Neohesperidin	E6	2	N / A	[NA; NA]	NA [NA ; NA]	N / A
Neohesperidin	E8	6	N / A	[NA; NA]	NA [NA ; NA]	N / A
L*	E2	55	-0.11381683	[-0.194 ; -0.034]	89.2 [82.4; 96.7]	111.6
L*	E3	52	-0.04714620	[-0.210 ; 0.115]	95.4 [81.1; 112.2]	12.3
L*	E4	47	-0.04464585	[-0.207 ; 0.117]	95.6 [81.3; 112.4]	17.0
L*	E5	56	-0.06269160	[-0.224 ; 0.098]	93.9 [80.0 ; 110.3]	16.6
L*	E13	45	-0.04320114	[-0.205 ; 0.119]	95.8 [81.4; 112.6]	19.7
L*	E23	50	-0.01147361	[-0.140 ; 0.117]	98.9 [87.0 ; 112.4]	78.7
a*	E2	55	0.18405454	[0.079; 0.289]	120.2 [108.2; 133.5]	63.2

Variable	Removed_study	k_remaining	Estimate	IC	Retention_IC	Relative change percentage
a*	E3	52	0.56862841	[-0.245 ; 1.382]	176.6 [78.3 ; 398.3]	13.6
a*	E4	47	0.57196497	[-0.240 ; 1.384]	177.2 [78.7 ; 398.9]	14.3
a*	E5	56	0.60898185	[-0.178 ; 1.396]	183.9 [83.7 ; 403.7]	21.6
a*	E13	45	0.53669471	[-0.298 ; 1.372]	171.0 [74.2 ; 394.2]	7.2
a*	E23	50	0.57998408	[-0.228 ; 1.388]	178.6 [79.6 ; 400.5]	15.9
b*	E2	55	-0.06305312	[-0.101 ; -0.025]	93.9 [90.4; 97.5]	229.2
b*	E3	52	0.06546014	[-0.197 ; 0.328]	106.8 [82.2; 138.8]	34.2
b*	E4	47	0.07262645	[-0.186 ; 0.332]	107.5 [83.0 ; 139.3]	48.9
b*	E5	56	0.06078175	[-0.202 ; 0.324]	106.3 [81.7; 138.3]	24.6
b*	E13	45	0.07007806	[-0.191 ; 0.331]	107.3 [82.6; 139.2]	43.6
b*	E23	50	0.08478253	[-0.166 ; 0.335]	108.8 [84.7; 139.9]	73.8
ΔE	E3	45	100.15383972	[-66.539 ; 266.847]	NA	18.4
ΔE	E4	41	20.42548008	[4.846 ; 36.005]	NA	75.9
ΔE	E5	49	105.00415722	[-58.373 ; 268.381]	NA	24.1
ΔE	E13	38	107.23958534	[-54.145 ; 268.624]	NA	26.8
ΔE	E23	43	99.20895222	[-67,982; 266,400]	NA	17.3

Relative_change_percent indicates the percentage change in the pooled effect estimate after exclusion of an individual study. Retention values were calculated as exp(logRR) × 100. NA indicates unavailable estimates resulting from insufficient information after excluding individual studies.

Table S6. Publication bias assessment using funnel plots and Egger-type regression

Variable	k	N_studies	Egger_intercept	Egger_slope	Egger_p	Interpretation
Vitamin C	47	6	-0.294	-11,804	0.280	No significant funnel plot asymmetry
TPC	108	8	-0.143	-7.324	0.003	Potential small-study effect/asymmetry
TFC	34	4	0.058	-36.105	<0.001	Potential small-study effect/asymmetry
ABTS	6	1	N A	N A	N A	Not assessed: fewer than 10 comparisons
DPPH	48	6	-0.012	1.091	0.364	No significant funnel plot asymmetry
FRAP	39	5	-0.248	6.157	0.051	No significant funnel plot asymmetry
Hesperidin	22	2	-0.200	-16,694	0.028	Potential small-study effect/asymmetry
Naringine	24	3	0.549	-14,156	<0.001	Potential small-study effect/asymmetry
Narirutin	16	1	0.860	-3.659	0.510	No significant funnel plot asymmetry
Neohesperidin	8	2	N A	N A	N A	Not assessed: fewer than 10 comparisons
L*	61	6	0.023	-11,793	<0.001	Potential small-study effect/asymmetry
a*	61	6	0.243	4.440	<0.001	Potential small-study effect/asymmetry
b*	61	6	0.133	-5.514	0.004	Potential small-study effect/asymmetry
ΔE	54	5	2.038	1.996	<0.001	Potential small-study effect/asymmetry

Egger-type regression analyses were performed only for variables with sufficient numbers of comparisons. Funnel plot asymmetry should be interpreted cautiously for variables with a limited number of studies or comparisons. NA indicates that Egger-type regression could not be performed because of insufficient numbers of studies or comparisons.

Table S7. CR2 robust inference analyzes by variable and drying method.

Variable	Method	Estimate_CR2	SE_CR2	p_CR2	p_CR2_txt
Vitamin C	FD	-0.206208147	0.07708082771776394	0.09839837968162572	0.098
Vitamin C	HAD	-0.493758651	0.07149872462555720	0.00104307489014512	0.001
Vitamin C	HYBRID	-0.253275888	0.06641670687803740	0.01321019214634128	0.013
Vitamin C	SUN	-0.598392760	0.07612671941961666	0.00095300543453704	<0.001
Vitamin C	VD	-0.354601848	0.08716337735834544	0.01111986623497053	0.011
TPC	FD	-0.003867867	0.19427915879186183	0.98542359998272944	0.985
TPC	HAD	-0.420837460	0.12710259859639375	0.01401967571519102	0.014
TPC	HYBRID	-0.235092136	0.11764107374498417	0.10085546048811721	0.101
TPC	IR	-0.393848060	0.12393949782814372	0.01902874861888489	0.019
TPC	MW	-0.304849623	0.12424239704491137	0.04939334798812930	0.049
TPC	SUN	-0.533895932	0.10100359327068956	0.01182970331593656	0.012
TPC	VD	-0.282427806	0.09901013256795674	0.04449319388556806	0.044
TFC	FD	-0.012739026	0.00000000002356525	0.00000000007752378	<0.001
TFC	HAD	-0.204602840	0.00482368998448175	0.00323465780081519	0.003
TFC	MW	-1.249077755	0.00139995297465984	0.00071351632616241	<0.001
TFC	SUN	-0.473919737	0.00004021727166295	0.00005402414852043	<0.001
TFC	VD	-0.069897440	0.00000000002356212	0.00000000001118100	<0.001
DPPH	FD	0.181336973	0.42932804854740564	0.69204025356459664	0.692
DPPH	HAD	-0.002562270	0.15382283722833798	0.98735597823353616	0.987

Variable	Method	Estimate_CR2	SE_CR2	p_CR2	p_CR2_txt
DPPH	HYBRID	0.110415879	0.20002811509985152	0.60488167429636919	0.605
DPPH	VD	0.024812360	0.22525981937243308	0.91663002371924607	0.917
FRAP	FD	0.290643445	0.67074395598798986	0.69274926523356584	0.693
FRAP	HAD	-0.110108283	0.19695893284309726	0.60615354997950177	0.606
FRAP	VD	0.128375498	0.21022315348092824	0.57550638216716710	0.576
Hesperidin	FD	-0.517785226	0.71783462702257184	0.60218311157575022	0.602
Hesperidin	HAD	-0.835885746	0.72060670680889094	0.45293528378428854	0.453
Hesperidin	MW	-0.388730838	0.72032032330989404	0.68495387770477112	0.685
Hesperidin	OD	-1.769168642	0.71196313102234587	0.24356704943548341	0.244
Naringine	FD	0.005938455	0.42210969679089361	0.99005350865962760	0.990
Naringine	HAD	-0.160522260	0.50964834191998354	0.78264170283135215	0.783
Naringine	MW	-0.018412112	0.46570140388902154	0.97206261643485092	0.972
Neohesperidin	FD	-0.247035418	0.84770326307906119	0.81947733048506832	0.819
Neohesperidin	HAD	-1.149299840	0.84561730062550433	0.40382678103513092	0.404
Neohesperidin	OD	-1.137776976	0.84849342363072155	0.40792875874008694	0.408
L*	FD	0.131501358	0.11244626070546035	0.30414501490623114	0.304
L*	HAD	-0.073630447	0.07816682016478914	0.39012286063127982	0.390
L*	HYBRID	-0.044300722	0.07085155753495606	0.55937371415865211	0.559
L*	MW	-0.126798544	0.07437855268750793	0.15174574584114625	0.152
L*	VD	-0.050218745	0.07293955804698696	0.52226076043949221	0.522
a*	FD	0.174322771	0.32952157612382754	0.62502131517713200	0.625
a*	HAD	0.420954309	0.32290063688896903	0.25017755440007333	0.250
a*	HYBRID	0.443177267	0.33148996517388130	0.23921977708293785	0.239
a*	MW	0.835624744	0.30915787483733881	0.04526569440120794	0.045
a*	VD	0.530979374	0.35703265500390785	0.19821788284378325	0.198
b*	FD	0.111611106	0.10638785448603941	0.34609806022108897	0.346
b*	HAD	0.025465190	0.10984020372989781	0.82591420297440565	0.826
b*	HYBRID	0.075531755	0.10720499033494037	0.51260705763258962	0.513
b*	MW	-0.044075206	0.10743995593679666	0.69894571240576275	0.699
b*	VD	0.068626056	0.11089128843562031	0.56328943976504431	0.563
ΔE	FD	85.995136660	66.18779067694968887	0.26392174190317158	0.264
ΔE	HAD	86.436549705	66.71444106988546707	0.26506493398925862	0.265
ΔE	HYBRID	113.017524899	67.87229680906558826	0.17117614785707821	0.171
ΔE	MW	86.870738657	66.42030354477159904	0.26125584455141243	0.261
ΔE	VD	80.978420737	67.52559516455228561	0.29679848062076863	0.297

CR2: cluster-robust variance estimation with small-sample correction. Robust inference analyses were conducted to account for dependence among effect sizes originating from the same study. Only Estimate_CR2, SE_CR2, and p_CR2 should be primarily interpreted.

Table S8. Adapted GRADE certainty-of-evidence assessment for the studied variables

Variable	Type_of_effect	k	N_studies	Risk of bias	Inconsistency	Imprecision	Indirectness	Publication_bias	Certainty
Vitamin C	logRR	47	6	Some concerns	Serious	Not serious	Not serious	Not serious	Moderate
TPC	logRR	108	8	Some concerns	Serious	Not serious	Not serious	Serious	Low
TFC	logRR	34	4	Some concerns	Serious	Serious	Not serious	Serious	Low
ABTS	logRR	6	1	Some concerns	Serious	Not serious	Not serious	Not assessable	Moderate
DPPH	logRR	48	6	Some concerns	Serious	Not serious	Not serious	Not serious	Moderate
FRAP	logRR	39	5	Some concerns	Serious	Not serious	Not serious	Not serious	Moderate
Hesperidin	logRR	22	2	Some concerns	Serious	Serious	Not serious	Not assessable	Low
Naringine	logRR	24	3	Some concerns	Serious	Serious	Not serious	Serious	Low
Narirutin	logRR	16	1	Some concerns	Serious	Not serious	Not serious	Not assessable	Moderate
Neohesperidin	logRR	8	2	Some concerns	Serious	Serious	Not serious	Not assessable	Low
L*	logRR	61	6	Some concerns	Serious	Not serious	Not serious	Serious	Low
a*	logRR	61	6	Some concerns	Serious	Serious	Not serious	Serious	Low
b*	logRR	61	6	Some concerns	Serious	Not serious	Not serious	Serious	Low
ΔE	SMD	54	5	Some concerns	Serious	Serious	Serious	Serious	Low

Certainty of evidence was adapted from the GRADE framework and evaluated according to risk of bias, inconsistency, imprecision, indirectness, and publication bias. Overall certainty levels were classified as moderate or low according to the available evidence.