

EXPORT COMPETITIVENESS AND PREMIUM POSITIONING OF FROZEN BERRIES IN THE GLOBAL TRADE

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ABSTRACT

Introduction. Frozen berries (HS 081110, HS 081120) are a growing category of global agricultural trade in which value creation increasingly depends on export-price positioning rather than volume growth alone. This positioning is shaped by both trade-side dynamics and production-side quality, yet while trade-side patterns are well documented, process-side quality factors remain comparatively underexplored in relation to trade outcomes.

Materials and methods. Annual UN Comtrade export series for HS 081110 and HS 081120 (2012–2025) were analysed using growth-rate and compound-annual-growth-rate (CAGR) analysis, quantity-weighted export unit value (EUV), paired and cross-sectional non-parametric tests, and binary logistic regression of persistent export-price premiums; this evidence was supplemented by a structured review of nine peer-reviewed food-science studies on freezing-related berry quality retention.

Results and discussion. Global export value rose from US\$1.564 billion to US\$3.136 billion (+100.44%, CAGR 5.49%), while quantity grew more modestly (+28.48%, CAGR 1.95%); EUV growth of 56.00% (CAGR 3.48%) therefore accounted for a substantial share of value expansion. EUV differed significantly by product group, with frozen raspberries, blackberries, and related berries commanding a higher unit value than frozen strawberries (paired t-test, $p = 0.00045$; Mann-Whitney $U = 92$, $p = 0.0017$). Among 115 exporter-product pairs, 58 (50.43%) showed a persistent price premium; logistic regression indicated that continuity of export participation was positively associated with premium status (OR = 1.683, 95% CI 1.144–2.478, $p = 0.0082$), while cumulative export scale was negatively associated (OR = 0.757, 95% CI 0.612–0.937, $p = 0.0105$), pseudo- $R^2 = 0.149$. The literature review of food-science studies indicated that controlled rapid freezing and stable cold storage likely support the physical and nutritional quality retention that could underlie such premiums, although a direct causal link cannot be established from trade data alone.

Conclusions. The global frozen-berry trade grew strongly in value, accompanied by rising export unit values and a positive association between continuity of export participation and premium positioning, while export volume grew at a slower rate.

KEYWORDS: frozen berries, export unit value, price premium, UN Comtrade, quality retention

Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

Ilakkya M: Conceptualization, data collection, statistical analysis and manuscript drafting.

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INTRODUCTION

Frozen berries occupy a growing niche within global fruit trade, combining a perishable, high-value raw material with a processing step – freezing, that is itself capable of preserving or eroding the attributes that determine commercial value. Global demand for convenient, shelf-stable, minimally processed fruit has expanded over the past decade, and frozen raspberries, blackberries and related berries (HS 081110) and frozen strawberries (HS 081120) have become an economically significant sub-category of world agricultural trade (Ivanov et al., 2021). Export performance in this category is not driven by volume growth alone. Trade evidence suggests that some exporters sustain higher per-kilogram export values than others over long periods, raising the question of which trade-related and process-related factors are associated with this differentiation. Existing food-science literature

has separately established that freezing rate, freezing method and storage conditions influence the physical and nutritional quality of berries (Kamiloglu, 2019; Žlabur et al., 2021; Stevanović et al., 2022; Da Silva et al., 2022), yet this evidence has rarely been connected to observed trade-price patterns for the same product category.

Frozen berries were selected as the focus of this study because they provide a relevant case for examining the transition from volume-based export growth to value-based market positioning. Unlike many agricultural commodities traded primarily on volume and relatively standardized characteristics, frozen berries combine perishability, freezing and processing requirements, quality preservation, and differentiated consumer demand. These characteristics make export unit value and premium positioning particularly relevant outcomes. In addition, the availability of consistent international trade data for major frozen-berry product groups over an extended period enables systematic comparison of export performance, competitiveness, and premium positioning across countries. Thus, frozen berries provide a suitable product context for examining whether market participation, export scale, product specialization, and destination-market characteristics are associated with persistent export price premiums.

The aim of this study was to characterise the global frozen-berry trade over 2012–2025 by following a single narrative arc from description to explanation, addressed through four sequential objectives: (1) establishing the overall trade trends, namely aggregate export performance and the relative contribution of value growth versus volume growth; (2) assessing competitiveness across exporters and product groups, namely differences in export unit value (EUV) among major exporters and between product groups; (3) identifying the trade-related factors associated with sustained premium positioning, namely persistent export price premiums and their correlates; and (4) considering possible explanations for that positioning, namely the food-science rationale of freezing-related quality retention as a supporting mechanism. Each aim is analysed with a method appropriate to its evidentiary target. Throughout, EUV is treated as a trade-value indicator rather than a transaction-level, and the link between trade-side premiums and freezing science is presented as a credible, literature-consistent mechanism rather than a demonstrated cause.

MATERIALS AND METHODS

Source of Data

Annual export data for frozen berries were obtained from the UN Comtrade Database (UN Comtrade, 2026) for HS 081110 (frozen strawberries) and HS 081120 (frozen raspberries, blackberries, mulberries, loganberries, black-, white- or redcurrants and gooseberries), for 2012–2025 (14 years). The reporting partner was set to World so that each exporter's series reflects total global exports rather than a single bilateral flow. The destination-augmented extension of the persistent-premium model additionally uses bilateral UN Comtrade export data (exporter, destination, product, year) for the same HS codes and period, combined with World Bank GDP per capita (World Bank, 2026) to construct a destination-income measure for each exporter-product pair.

Export Unit Value and Growth-Rate Analysis

Export unit value (EUV) was calculated as:

$$\text{EUV} = \text{Export Value} / \text{Export Quantity}$$

Annual growth rates and compound annual growth rates (CAGR) were computed for export value, export quantity and EUV using the exponential growth model:

$$Y = a \cdot b^t$$

Where Y is the variable being modeled (export value, export quantity, or EUV in a given year), a is a constant, b is the growth coefficient, and t is the year.

$$\text{CAGR (\%)} = [\text{Antilog}(b) - 1] \times 100$$

EUV is treated throughout as a trade-value indicator rather than a transaction-level price: it can reflect product mix, grade, destination markets, packaging, contractual terms, exchange-rate movements and re-export activity, in addition to underlying product quality.

Major-Exporter Identification and Weighted EUV

Major exporters were defined as the ten exporters with the highest cumulative export value within each product group over 2012–2025. For each exporter-product combination, weighted EUV was calculated as:

$$\text{Weighted EUV} = \text{Cumulative Export Value} / \text{Cumulative Export Quantity}$$

Observations with non-positive quantity were excluded. Differences in weighted EUV between product groups were tested using:

- i. A paired t-test and Wilcoxon signed-rank test (Wilcoxon, 1945) on the matched annual global series.
- ii. An exploratory two-sided Mann-Whitney U test (Mann and Whitney, 1947) on the cross-section of the ten major exporters per product group:

$$U = n_1 n_2 + [n_1(n_1+1)/2] - R_1$$

Where n_1 and n_2 are the sample sizes of the two groups and R_1 is the sum of ranks in group 1. A bootstrap 95% confidence interval (Efron and Tibshirani, 1993) was constructed for the median difference.

Persistent Export Price Premium and Logistic Regression

For each exporter-product-year observation, EUV was benchmarked against the quantity-weighted global EUV for the same product group and year:

$$\text{Premium (\%)} = [(\text{Exporter EUV} / \text{Global Product-Year EUV}) - 1] \times 100$$

A persistent premium was defined as an exporter-product combination whose EUV was at least 10% above the global benchmark in at least 8 of the 14 study years; this 10%-premium, 8-of-14-year rule was applied as the primary definition of persistent-premium status used throughout the results section, including Table 6 and the logistic regression.

To reduce the influence of very small trade flows, the model was estimated only for exporter-product combinations with at least US\$1 million in cumulative export value and at least five observed years. Exporter-product combinations were first enumerated from the full set of reporting exporters for HS 081110 and HS 081120 over 2012–2025, then retained for the regression sample only if they met both thresholds. This screening yielded a model sample of 115 exporter-product observations (57 for raspberries/blackberries/related berries and 58 for strawberries). As a robustness check, the persistence rule was also recomputed using a stricter 15% premium threshold, with the same 8-of-14-year requirement and the same 115-observation sample; this sensitivity analysis is reported alongside the primary findings in the corresponding results section.

A binary logistic regression (Hosmer et al., 2013) was fitted with persistent-premium status (1/0) as the dependent variable:

$$\text{Logit}(p) = \text{Log}[p / (1 - p)] = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4$$

Where p is the probability of persistent premium status, and X_1 – X_4 represent cumulative export scale (natural log of cumulative export value), years of active exporting, product specialisation within the exporter's frozen-berry portfolio, and export-value CAGR; product group was included as a control. The odds ratio for each predictor was calculated as:

$$\text{OR} = e^{\beta}$$

Odds ratios, 95% confidence intervals, Wald p -values, McFadden's pseudo- R^2 and a likelihood-ratio test were reported:

$$\text{Pseudo-}R^2 = 1 - (\text{Log } L_{\text{model}} / \text{Log } L_0)$$

A formal variance-inflation-factor (VIF) diagnostic, together with Pearson and Spearman correlation checks among the explanatory variables, was computed once the row-level predictor matrix became available:

$$\text{VIF} = 1 / (1 - R_i^2)$$

Where R_i^2 is the coefficient of determination from regressing the i^{th} explanatory variable on all other explanatory variables. This diagnostic is reported together with the destination-augmented model in the results section (Table 8).

Destination-Augmented Model

To test whether destination-market characteristics were also associated with persistent premium status, the logistic regression was extended to include a measure of destination-market income level:

$$\text{Logit}(p) = \text{Log}[p / (1 - p)] = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5$$

Where X_5 represents the GDP per capita (current US\$) of the exporter's destination market, sourced from the World Bank (World Bank, 2026) and assigned to each exporter-year observation using the corresponding calendar year. This variable was added to the base model alongside cumulative export scale, years of active exporting, product specialisation and export-value CAGR. The destination-augmented model was evaluated using the same odds-ratio, confidence-interval and pseudo- R^2 criteria as the base model, with the VIF diagnostic confirming no problematic multicollinearity between destination-market income and the other explanatory variables.

Production-Side Review: Freezing and Quality Retention

Because the trade dataset does not identify exporter-specific freezing equipment, freezing rate, cold-chain practice, cultivar or nutritional composition, this objective was addressed as an evidence-review exercise rather than a causal econometric test. A pool of literature on the pathway freezing conditions → ice-crystal formation and cellular integrity → nutritional and physical quality retention → potential product differentiation was screened for direct relevance to berries (strawberry, raspberry, blackberry, tayberry, blueberry). Nine core studies were retained, comparing quick/individual-quick-freezing (IQF), conventional/air-blast freezing, cryogenic freezing, and/or frozen-storage and thawing conditions, reporting outcomes for drip loss, texture, colour, and nutritional or antioxidant retention. The trade-side finding of persistent above-benchmark EUV positions was then interpreted as a possible market outcome compatible with differentiated quality, while explicitly recognising that the trade data cannot attribute any observed premium to freezing technology.

RESULTS AND DISCUSSION

Global export performance and trade dynamics, 2012–2025

Global frozen-berry trade expanded substantially between 2012 and 2025, although growth was uneven across the period (Table 1, Table 2, Figure 1). Total export value increased from US\$1.564 billion in 2012 to US\$3.136 billion in 2025 (+100.44%, CAGR 5.49%). Export quantity increased from 888.09 to 1141.04 million kg (+28.48%, CAGR 1.95%), while EUV increased from US\$1.762/kg to US\$2.748/kg (+56.00%, CAGR 3.48%). Export-value growth therefore substantially exceeded physical-volume growth, indicating that increase in value per kilogram made an important contribution to the expansion of global frozen-berry trade.

Table 1. Annual global export performance of frozen berries, 2012–2025

Year	Export value (US\$ bn)	Export quantity (million kg)	EUV (US\$/kg)	Value growth (%)	Quantity growth (%)	EUV growth (%)
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2012	1.56	888.09	1.76	—	—	—
2013	1.82	977.56	1.86	16.48	10.07	5.82
2014	1.91	948.12	2.02	4.96	-3.01	8.22
2015	1.91	1020.29	1.88	0.06	7.61	-7.02
2016	1.83	968.82	1.89	- 4.39	-5.04	0.69
2017	1.74	999.99	1.74	-4.71	3.22	-7.68
2018	1.95	1051.41	1.86	12.07	5.14	6.59
2019	1.98	1133.24	1.75	1.31	7.78	-6.01
2020	2.23	1143.14	1.95	12.45	0.87	11.48
2021	2.98	1206.02	2.47	33.97	5.50	26.99
2022	3.03	1119.73	2.71	1.73	-7.16	9.57
2023	2.50	1077.30	2.32	-17.71	-3.79	-14.47
2024	2.54	1150.60	2.21	1.83	6.80	-4.66
2025	3.14	1141.04	2.75	23.35	-0.83	24.39

Source: authors' calculation based on UN Comtrade (2026).

Table 2. Summary of global frozen-berry export performance, 2012 vs 2025

Indicator	2012	2025	Absolute change	Change (%)	CAGR (%)
Export value (US\$ bn)	1.564	3.136	+1.571 bn	+100.44	5.49
Export quantity (million kg)	888.086	1141.035	+252.949 m kg	+28.48	1.95
Export unit value (US\$/kg)	1.762	2.748	+0.987	+56.00	3.48

Source: authors' calculation based on UN Comtrade (2026).

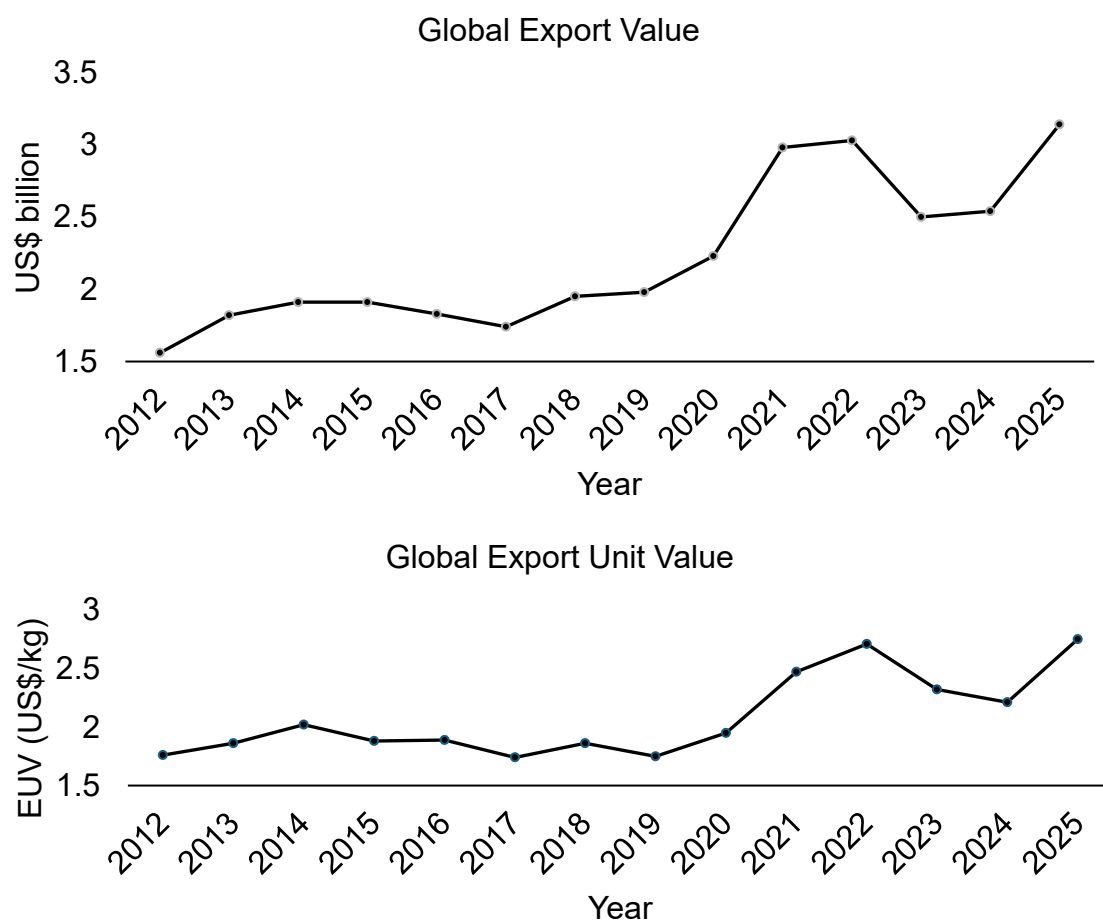




Figure 1. Global frozen-berry trade dynamics, 2012–2025: (a) export value, (b) export quantity, (c) export unit value

Source: authors' calculation based on UN Comtrade (2026).

Annual dynamics indicate distinct periods of expansion and contraction. Export value increased rapidly during 2020–2022, reaching US\$2.982 billion in 2021 and US\$3.034 billion in 2022. The strongest annual increase in EUV occurred in 2021 (+26.99%), accompanied by a 33.97% increase in export value. In contrast, 2023 recorded a marked contraction, with export value, quantity and EUV declining by 17.71%, 3.79% and 14.47%, respectively. Trade value recovered moderately in 2024 and increased by 23.35% in 2025; notably, the 2025 increase occurred despite a slight decline in export quantity (−0.83%), as EUV increased by 24.39%, indicating that the latest recovery in export value was strongly associated with higher value per kilogram rather than additional physical volume.

Overall, the global frozen-berry trade exhibited a combination of volume expansion and increasing export-value positioning during 2012–2025, with EUV growth (56.00%) exceeding quantity growth (28.48%) by a wide margin. Economically, this indicates that revenue growth in the sector has come to depend more on what exporters earn per kilogram shipped than on how much they ship - a shift toward value-based rather than volume-based competition that carries different strategic implications for exporters and policymakers (for example, favouring investment in quality, positioning and market access over capacity expansion alone). The next section examines whether this value positioning is shared broadly across exporters or concentrated among a subset of competitively differentiated suppliers.

Export unit value differences across major exporters and product groups

Major exporters are defined as the ten exporters with the highest cumulative export value within each product group over 2012–2025 (Table 3). This definition separates export scale from value positioning: an exporter can be a major supplier because of large trade volume while having a comparatively modest EUV.

Table 3. Major frozen-berry exporters by cumulative export value, 2012–2025

Rank	Product group	Exporter	Cumulative value (US\$ m)	Quantity (million kg)	Weighted EUV (US\$/kg)	Share of group trade (%)
1	Frozen Raspberries, blackberries and allied berries	Serbia	4436.98	1534.92	2.89	28.49
2		Poland	2903.77	1539.80	1.89	18.64
3		Chile	1923.46	604.99	3.18	12.35
4		Germany	746.03	262.60	2.84	4.79
5		Belgium	721.84	250.14	2.89	4.63
6		Netherlands	631.27	233.03	2.71	4.05
7		Ukraine	515.28	265.68	1.94	3.31
8		Bosnia and Herzegovina	449.71	175.71	2.56	2.89
9		Mexico	404.71	162.21	2.49	2.60
10		USA	401.82	107.44	3.74	2.58
1	Frozen Strawberries	Egypt	2605.91	1339.46	1.95	16.75
2		Mexico	2141.59	1162.40	1.84	13.76
3		Poland	2097.76	1173.51	1.79	13.48
4		China	1298.65	890.28	1.46	8.35
5		Morocco	1133.92	841.79	1.35	7.29
6		Chile	1103.51	484.71	2.28	7.09
7		Netherlands	800.35	455.31	1.76	5.14

8		USA	729.48	361.01	2.02	4.69
9		Spain	618.82	416.36	1.49	3.98
10		Belgium	572.60	275.41	2.08	3.68

Source: authors' calculation based on UN Comtrade (2026).

Major exporters are the top 10 by cumulative export value within each product group. The top 10 accounted for 84.32% of cumulative trade value in the raspberry/blackberry-related group and 84.20% in strawberries.

Table 4. Product-group export unit values and major-exporter EUV distribution

Measure	Raspberries, blackberries and allied berries	Strawberries
Global weighted EUV, 2012–2025 (US\$/kg)	2.508	1.807
Median weighted EUV among top 10 exporters (US\$/kg)	2.775	1.815
Mean weighted EUV among top 10 exporters (US\$/kg)	2.713	1.800
Minimum weighted EUV among top 10 (US\$/kg)	1.886	1.347
Maximum weighted EUV among top 10 (US\$/kg)	3.740	2.277

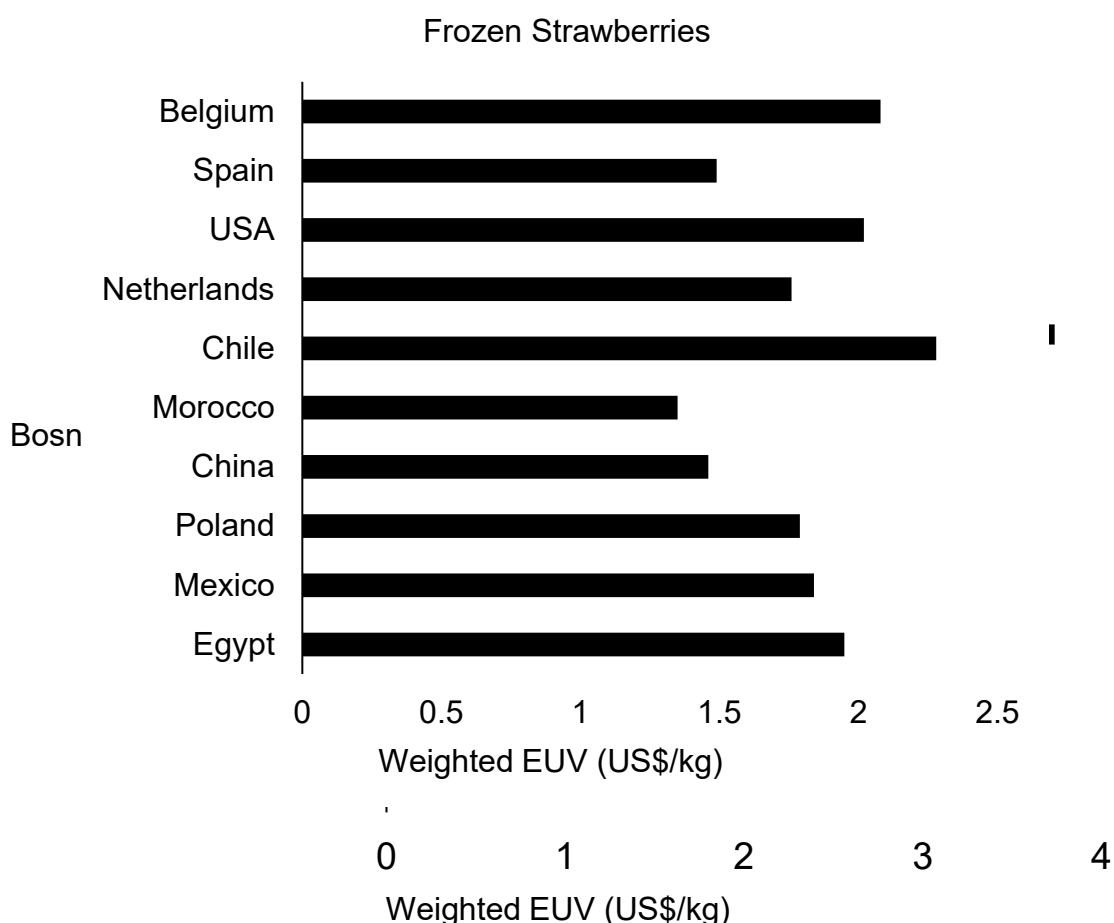


Figure 2. Weighted EUV of the ten major exporters by product group

Source: authors' calculation based on UN Comtrade (2026).

Among the ten major exporters in each product group, the distribution of weighted EUV was higher for frozen raspberries, blackberries, and related berries than for frozen strawberries. The median weighted EUV was US\$2.77/kg for the former and US\$1.81/kg for frozen strawberries, a median difference of US\$0.96/kg; a bootstrap 95% confidence interval for this median difference was US\$0.45 to US\$1.34/kg. An exploratory two-sided Mann-Whitney U test comparing the ten exporter-level weighted EUVs in each product group gave $U = 92$, $p = 0.0017$ (Mann and Whitney, 1947). This exporter-level comparison is treated as exploratory because the ten exporters were selected on the basis of cumulative export value and are therefore not a random sample of all

exporters. The primary evidence for a product-group difference is the matched annual comparison: the frozen raspberry/blackberry-related group had a mean annual EUV approximately US\$0.742/kg higher than frozen strawberries, with a paired t-test $p = 0.00045$ and a Wilcoxon signed-rank test $p = 0.00122$ (Wilcoxon, 1945). The product-group difference therefore appears in both the annual global series and the major-exporter cross-section. Serbia, Poland and Chile were the top three raspberry/blackberry-group exporters by value; the United States had the highest weighted EUV in that group (US\$3.74/kg) and Poland the lowest (US\$1.89/kg). Among strawberry exporters, Egypt, Mexico and Poland led by value, while Chile recorded the highest weighted EUV (US\$2.28/kg) and Morocco the lowest (US\$1.35/kg). The top ten exporters accounted for approximately 84% of cumulative trade value in each product group, indicating that the comparison captures the principal commercial exporters rather than isolated small trade flows.

These results demonstrate that export scale and export-value positioning are distinct dimensions of competitiveness in global frozen-berry trade: large cumulative exporters did not uniformly exhibit high EUVs, while some exporters with more moderate trade values recorded relatively high EUVs. Economically, this means that competitive advantage in this market is not simply a function of size - an exporter can be commercially significant through volume while ceding value-per-kilogram to smaller, more differentiated rivals, and vice versa. At the product level, the frozen raspberry/blackberry-related category consistently occupied a higher unit-value position than frozen strawberries, both in the global weighted series and among the selected major exporters, consistent with raspberries and blackberries occupying a more premium, less commoditised market segment. Because scale and value positioning diverge across exporters, the next section tells which exporter-level characteristics are systematically associated with sustaining a price premium over time.

Trade-related factors associated with persistent export price premiums

Previous sections establish that value positioning, not scale, differentiates exporters; this section identifies which trade-related characteristics are associated with sustaining that positioning over time, with destination-specific determinants examined separately below using supplementary bilateral trade data (Table 6B).

Table 5. Persistent premium prevalence among economically meaningful exporter-product pairs

Product group	Pairs in sample	model Persistent premium pairs	Persistent premium share (%)	Median premium (%)
Frozen Raspberries, blackberries and allied berries	57	28	49.12	13.46
Frozen Strawberries	58	30	51.72	18.55

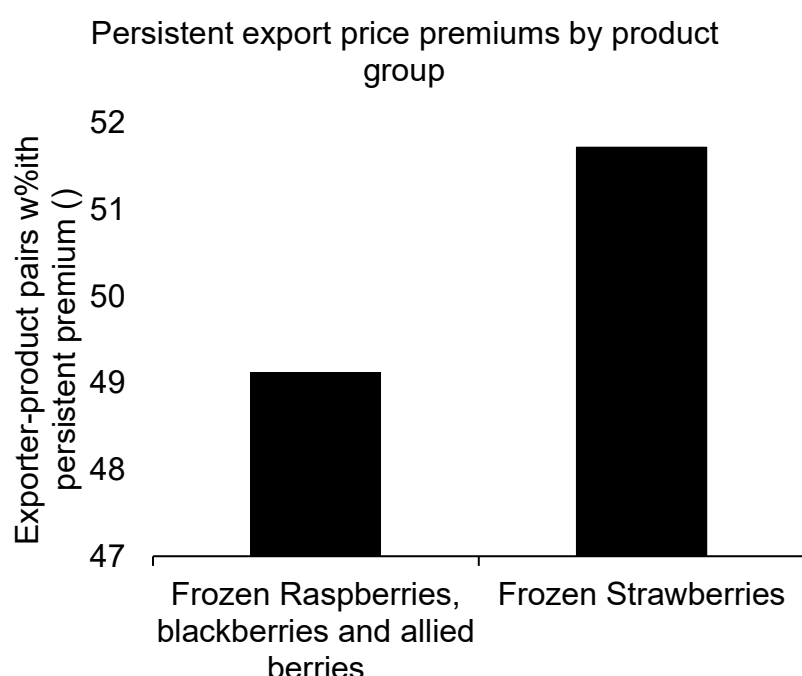


Figure 3. Persistent premium prevalence by product group

Logistic regression of persistent export price premiums

Variable	Odds ratio	95% CI	p-value	Association
Log cumulative export value	0.757	0.612–0.937	0.0105	Negative
Years active	1.683	1.144–2.478	0.0082	Positive
Product specialisation (%)	0.991	0.977–1.005	0.2073	Negative
Export-value CAGR (%)	0.989	0.971–1.008	0.2654	Negative

Strawberries (vs. other group)	1.102	0.486–2.497	0.8163	Positive
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Persistent above-benchmark export unit values were observed across a substantial share of economically meaningful exporter-product combinations. In the model sample, 58 of 115 exporter-product pairs (50.43%) met the persistence criterion; prevalence was 49.12% for raspberry/blackberry-related berries and 51.72% for strawberries (Table 6). The logistic regression (Table 7) indicates that trade persistence was positively associated with the probability of maintaining a persistent export price premium: the odds ratio for years active was 1.683 (95% CI 1.144–2.478, $p = 0.0082$), implying that each additional year of observed exporting was associated with approximately 68.3% higher odds of persistent premium status, conditional on the other variables in the model. In contrast, cumulative export scale showed a negative association: the odds ratio for log cumulative export value was 0.757 (95% CI 0.612–0.937, $p = 0.0105$), suggesting that persistent premiums were not simply a characteristic of the largest exporters. Economically, this pairing is consistent with a market in which durable buyer relationships, accumulated reputation and repeated dealings rather than sheer trade volume are what allow an exporter to sustain prices above the product-year benchmark; large-scale exporters may instead be competing more on price and availability to serve broad-based demand.

Product specialisation, export-value CAGR and product-group membership were not statistically significant at the 5% level ($p = 0.2073$, 0.2654 and 0.8163 , respectively), indicating that, once persistence and scale are accounted for, how specialised or fast-growing an exporter is, does not itself predict premium status. The overall likelihood-ratio test was significant ($p = 0.0002$), while the model explained a modest share of the variation (McFadden pseudo- $R^2 = 0.149$); economically, this modest fit indicates that trade persistence and scale offer only a partial explanation, and that buyer relationships, contract terms, quality investment and market access none of which are observable in aggregated trade data likely account for much of the remaining variation in premium status. A destination-augmented extension of this model, incorporating export-value-weighted destination GDP per capita, together with the accompanying collinearity diagnostics, is reported below (Tables 6B and 7).

Table 6B. Destination-augmented logistic regression of persistent export price premiums

Variable	Odds ratio	95% CI	p-value	Association
Log cumulative export value	0.685	0.542–0.866	0.0016	Negative
Years active	1.579	1.059–2.354	0.0249	Positive
Product specialisation (%)	0.994	0.980–1.008	0.4126	Negative
Export-value CAGR (%)	0.992	0.973–1.011	0.4013	Negative
Strawberries (vs. other group)	1.086	0.457–2.581	0.8503	Positive
Destination GDP per capita (per US\$10,000)	1.494	1.089–2.050	0.0129	Positive

Table 7. Collinearity diagnostics for the destination-augmented model

Predictor	VIF	Largest Pearson correlation (r)	Largest Spearman correlation (ρ)
Log cumulative export value	1.39	Destination GDP per capita: 0.374	Destination GDP per capita: 0.431
Years active	1.87	Log cumulative export value: 0.348	Log cumulative export value: 0.373
Product specialisation (%)	1.22	Export-value CAGR: –0.214	Export-value CAGR: –0.182
Export-value CAGR (%)	1.47	Years active: –0.214	Years active: –0.182
Strawberries (vs. other group)	1.04	All continuous predictors: $ r \leq 0.374$	All continuous predictors: $ \rho \leq 0.431$
Destination GDP per capita	1.23	Log cumulative export value: 0.374	Log cumulative export value: 0.431

Collinearity diagnostics were calculated from the complete 115-observation exporter-product predictor matrix, including the destination GDP-per-capita variable. Pearson and Spearman correlations among the continuous predictors were modest to moderate, with the largest correlation ($r = 0.374$, $\rho = 0.431$) occurring between log cumulative export value and destination GDP per capita. VIF values ranged from 1.04 to 1.87 across all predictors, indicating no concerning multicollinearity. These diagnostics support retaining all predictors, including destination GDP per capita, in the destination-augmented model, and resolve the limitation noted for the exporter-side-only model.

Sensitivity analysis using a stricter 15% premium threshold produced 48 persistent-premium cases (41.7%) versus 58 (50.4%) under the 10% threshold. The direction and statistical significance of the exporter-side associations were unchanged: log cumulative export value remained negative (OR = 0.649, 95% CI 0.511–0.825, $p = 0.0004$) and years active remained positive (OR = 1.592, 95% CI 1.079–2.349, $p = 0.0191$). The stricter-threshold model had McFadden pseudo- $R^2 = 0.196$, supporting the stability of the main associations to the premium cutoff.

An independent reconstruction of the sample, collinearity diagnostics and destination-GDP variable from raw UN Comtrade and World Bank records confirmed the reported sample composition, correlations and VIF values, with only minor differences attributable to variable-construction choices.

The positive association with destination GDP per capita is consistent with several complementary explanations: higher-income consumers place greater value on convenience, safety and perceived quality in frozen foods; higher-income markets often have stricter cold-chain and food-safety requirements that filter for exporters able to meet them consistently; and their retail channels more often carry branded or certified products sold at a premium. Because this association holds independently of exporter scale, persistence, specialisation and growth (Table 6B), it likely reflects a distinct, complementary factor rather than a restatement of exporter-side characteristics (association, not causation).

Freezing-related quality retention and differentiated export value positioning

Nine core studies were retained, covering the freezing-quality pathway outlined in Section 2.5 across strawberries, raspberries, blackberries, tayberry and blueberries (Table 8).

Table 8. Core evidence on freezing-related quality retention in berries

Study	Berry/material	Freezing comparison	Key quality outcomes
Kamiloglu (2019)	Strawberry	IQF vs conventional freezing; fresh vs frozen, in vitro digestion	Bioaccessible pelargonidin-3-glucoside 10.8–13.3 µg/g (frozen) vs 5.8 µg/g (fresh); increase independent of IQF vs conventional freezing
Stevanović et al. (2022)	Strawberry and raspberry	IQF vs conventional freezing; long-term frozen storage	Physicochemical properties, vitamin C and antioxidant activity strongly affected by storage; better retention after IQF; pronounced texture change after slow freezing
Žlabur et al. (2021)	Tayberry, raspberry and blackberry	Quick freezing –34 °C/25 min vs classical –18 °C/24 h; 3-month storage	Quick-frozen berries: less drip loss and colour change; ~28% higher ascorbic acid; better polyphenol, anthocyanin and antioxidant retention
Sahari et al. (2004)	Strawberry	Slow –20 °C vs quick –50 to –100 °C; storage at –12, –18, –24 °C	Early ascorbic-acid losses of 64.5%, 10.7% and 8.9% at –12, –18 and –24 °C, respectively; –18/–24 °C better preserved colour, texture and flavour
Van Buggenhout et al. (2006)	Strawberry	Different freezing conditions plus storage/thawing; pectin-related pretreatment	Slow freezing caused severe textural loss; rapid/cryogenic freezing produced better texture under tested pretreatment
Cao et al. (2018)	Blueberry	–20, –40, –80 °C and liquid-nitrogen freezing	Fastest (liquid-nitrogen) treatment not best overall; –80 °C gave better water-holding, drip-loss and pectin retention
Da Silva et al. (2022)	Strawberry	Forced-air conditions, –20 to –53 °C, 0.4–6.5 m/s	More intensive conditions increased hardness by 73% and reduced drip loss to ~5.5% of the original value
Holzwarth et al. (2012)	Strawberry	Conventional –20 °C vs liquid nitrogen; multiple thawing methods	Drip loss, colour, ascorbic acid and phenolics/anthocyanins measured across freezing and thawing treatments
Agnelli and Mascheroni (2002)	Strawberry and other foods	Conventional air-blast vs cryomechanical (liquid-nitrogen pre-freezing)	Cryomechanical processing formed a protective surface crust and reduced thawing losses relative to controls

Source: compiled by the authors from the cited studies (see References).

Coverage across the nine core studies is broad: all report on freezing-condition comparisons and berry-species-specific outcomes, with only Kamiloglu (2019) omitting physical-quality measures and Van Buggenhout et al. (2006) omitting nutrition/bioactive measures.

It is important to distinguish what this study's trade data can show from what the freezing-science literature separately reports. The trade analysis in the previous sections demonstrates from UN Comtrade records that value growth has exceeded volume growth and that persistent price premiums are associated with trade persistence, moderate scale and higher-income destination markets; it does not measure freezing technology, ice-crystal formation, drip loss or nutrient retention for any shipment. The findings below come instead from nine peer-reviewed experimental studies on berry freezing (Table 9), describing controlled laboratory comparisons, not the commercial shipments underlying Sections 3.1–3.3. The two evidence bases connect only at the level of plausibility, not direct measurement.

Berry tissue is a high-moisture cellular matrix; freezing rate through the critical ice-crystallisation zone governs crystal size and distribution. Rapid freezing produces smaller, more uniform crystals, while slow freezing favours

larger extracellular crystals that can damage membranes and cell walls, reducing water reabsorption on thawing and causing drip loss and turgor loss (Van Buggenhout et al., 2006). Cell-wall pectic substances are central to this: freezing-induced damage can compromise the mechanical integrity supporting firmness, and pectin-related pretreatment can improve outcomes (Van Buggenhout et al., 2006). Nutritional retention follows a related but distinct mechanism — freezing slows enzymatic and oxidative degradation, but concentration effects and membrane disruption can still alter measured vitamin, anthocyanin and phenolic content (Kamiloglu, 2019; Žlabur et al., 2021).

The relationship is not simply "faster is always better." Cao et al. (2018) found an intermediate -80°C treatment outperformed liquid nitrogen on several blueberry indicators, and cryogenic freezing shows no universal sensory advantage over air-blast freezing (Agnelli and Mascheroni, 2002; Holzwarth et al., 2012). IQF is a process format — rapid freezing of individual pieces, commonly via high-velocity cold air — where freezing rate through the critical range matters more than the IQF label itself; air-blast performance depends on temperature, velocity, humidity and product loading (Da Silva et al., 2022).

Across the nine studies, the consistent pattern is that controlled rapid freezing and stable storage reduce physical quality loss (especially drip loss and texture degradation) while often improving retention of vitamin C, anthocyanins and antioxidants — with notable exceptions: IQF is not superior for every nutritional endpoint (Kamiloglu, 2019), cryogenic freezing is not universally superior to optimised mechanical freezing (Cao et al., 2018), and storage/thawing can substantially modify quality after freezing (Sahari et al., 2004; Holzwarth et al., 2012). This offers a plausible mechanism for how processors could sustain the consistent physical and nutritional quality that supports differentiated positioning — but it remains a mechanism-based interpretation, not an identified causal effect, since the trade dataset does not observe freezing technology, certification or firm-level practices.

CONCLUSIONS

This study characterised the global frozen-berry trade over 2012–2025 by tracing trade trends, competitiveness, premium positioning and possible explanations in sequence. First, export-value growth was substantially higher than volume growth (CAGR 5.49% vs 1.95%), indicating that higher value captured per kilogram accompanied the expansion of the global frozen-berry trade. Second, frozen raspberries, blackberries, and related berries occupy a consistently higher value position than frozen strawberries, confirmed independently in both the matched annual series and the major-exporter cross-section (Tables 1 and 4). Third, persistent price premiums are positively associated with continuity of export participation and negatively associated with cumulative export scale (Table 6), a pattern that remained stable under a stricter premium threshold and after adding destination GDP per capita to the model (Tables 6B and 7); where a country sells its products, not only how long it has been selling them, is therefore also associated with sustained premium positioning. Peer-reviewed freezing science offers a plausible, literature-grounded explanation for how such premiums could arise on the production side, but this study does not test that mechanism directly against the trade data, and the association should not be read as a demonstrated causal pathway.

LIMITATIONS

These findings should be read alongside their limitations. EUV is a trade-value indicator rather than a transaction-level price or a direct quality measure, and can reflect product mix, grade, packaging, contractual terms, exchange-rate movements and re-export activity not observable in the aggregated exporter-to-World data used here. The logistic-regression sample is modest: 115 exporter-product pairs is a small base for a model with up to six predictors, which limits statistical power to detect smaller effects and means the reported odds ratios should be read as indicative rather than precise — the width of the 95% confidence intervals in Tables 7 and 7B reflects this. Most importantly, the study has no firm-level or shipment-level data on freezing technology, cold-chain investment or quality certification (for example, BRC, IFS, organic or fair-trade status); the link between persistent price premiums and freezing-related quality (Section 3.4) is therefore a plausible interpretation drawn from separate literature, not an estimated or tested relationship. The destination-level trade data used to construct the GDP-per-capita variable covers only the two HS codes and years analysed here and does not include importer distance, tariff rates or other market-specific demand factors. Future work pairing firm-level or shipment-level freezing and certification records with the existing trade and destination data would allow the mechanism proposed in Section 3.4 to be tested directly rather than inferred.

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