Export Quality of Functional Materials in Japan: 2000–2023

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Abstract

This paper measures the quality of Japan's functional materials exports using detailed trade data and examines its characteristics. Specifically, assuming that export quality is reflected in export unit prices, we attempt to measure export quality by estimating gravity equations. This study focuses particularly on functional materials, measuring the quality of exports for each item based on detailed six-digit HIS code classifications. Japan's export competitiveness in functional materials maintains an exceptionally high global standard, representing one of the few sectors possessing the "ability to earn overseas" in the world market. In this sense, quantitative analysis of export quality for functional materials is highly significant. This study represents the first such attempt in Japan and holds considerable academic value.

Measurement results reveal that Japan maintains a top-tier global level of export quality, particularly for semiconductor materials and electronic components. Furthermore, the quality of exports for functional coating agents, paints, and inks, as well as functional films and sheets, has remained stable over time, maintaining a global ranking between 4th and 6th place. Considering that the quality of exports ranks highly globally and shows stable trends, functional materials play an extremely important role in Japan's export strategy.

Keywords: Export quality, Functional materials, Export price, Gravity equation, Semiconductor

JEL Codes: F14, F61

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1 Introduction

Functional materials are higher-value-added materials possessing properties and functions not found in conventional materials. Based on these superior characteristics, functional materials serve as core components in producing high-value-added products. For example, they function as the foundational materials for various components that make up end products like electric vehicles and smartphones. Many materials constituting semiconductors are precisely functional materials. Thus, functional materials are positioned as a core sector within the materials industry that creates particularly high added value. They go beyond merely supplying raw materials; they play a role as a source of industrial competitiveness, supporting technological innovation in downstream industries (automotive, electronics, medical, etc.). In other words, to enhance the international competitiveness of Japanese industry, it is necessary to improve the quality of functional material exports and further strengthen international competitiveness.

Measuring the quality of exports is not straightforward. Quality itself is an unobservable concept, and its definition is inherently ambiguous. Consequently, determining the analytical framework and data series to use for measurement presents significant challenges. Furthermore, since export quality varies by product, it is crucial to measure it at the most granular level possible, requiring sophisticated measurement methods. For these reasons, prior research on export quality within the field of international economics is scarce.

Japan's functional materials sector is one of the few areas where the country boasts a high global market share, and it is widely anticipated to serve as a key asset for Japan's international competitiveness in the global economy. Therefore, carefully examining the limitations of quantitative analysis and implementing various improvements to measurement methods to quantitatively assess the international competitiveness of Japan's functional materials should constitute research of significant value, both academically and for policy purposes. This paper, driven by this research question, measures the quality of Japan's functional materials exports since the 2000s through detailed product classification. This research represents a first-of-its-kind endeavor not only in Japan but globally.

The paper is organized as follows. Section 2 provides an overview of functional materials and confirms Japan's position within this field. Section 3 reviews prior research on measuring export quality. Section 4 explains the methodology for measuring export quality. The measurement results are presented in Sections 4 and 5. Section 6 summarizes the findings.

2 Functional Materials

2.1 The Role of Functional Materials

Functional materials are a general term for higher-value-added materials possessing properties and functions not found in conventional materials. The defining characteristic of functional materials is their high level of specific properties. Specific examples include photosensitivity in optical materials, ferromagnetism in magnetic materials, and high conductivity or insulation in conductive/insulating materials. high conductivity or insulation in conductive/insulating materials, and high heat shielding in heat transfer/heat shielding materials.[1]

Functional materials serve as core components in producing high-value-added products based on these superior properties. They function as the foundational materials for various components that make up end products like electric vehicles and smartphones. For instance, many materials constituting semiconductors are precisely functional materials.

Functional materials cover a wide range but can be broadly categorized into the following eight groups. Specifically: 1) Functional Resins (a general term for polymer mate-

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[1] Functional materials are artificially synthesized and processed through chemical reactions, so within the chemical industry they are commonly referred to as "functional chemicals" or "functional chemical products." For example, the Ministry of Economy, Trade and Industry defines functional chemicals as "a general term for high-value-added chemicals used with a focus on specific functional aspects such as photosensitivity, ferromagnetism, high conductivity, insulation, high heat shielding, and reaction promotion performance," making it nearly synonymous with functional materials.

rials imparted with specific superior functions such as gas barrier properties, heat resistance, conductivity, or biodegradability), 2) Functional Films & Sheets (materials such as plastic films that undergo coating, vapor deposition, lamination, printing, etc. on substrates like plastic film), 3) Electronic Components & Battery Materials (integrated circuits (ICs), printed circuit boards, etc., which constitute electronic devices like computers, smartphones, and displays; specific materials constituting batteries (primary and secondary batteries)), 4) Functional Coatings & Paints & Inks (materials applied to substrates (materials) to provide not only protection but also special functions and added value such as "water repellency," "anti-glare," "self-healing," "conductive," "anti-soiling," and other special functions or added value), 5) Functional Additives (materials imparting new functions such as weather resistance, impact resistance, flame retardancy, antistatic properties, and antibacterial properties), 6) Functional fillers & slurries (liquid dispersions of microparticles (fillers) engineered for specific functions like conductivity, insulation, rust prevention, transparency, flame retardancy, or enhanced mechanical properties), 7) Functional adhesives & Adhesives & Pressure-Sensitive Adhesives (high-performance materials possessing specific functions (heat resistance, conductivity, optical properties, repositionability, etc.) and combining the properties of both adhesives and pressure-sensitive adhesives (bonding and peel ability)), 8) Semiconductor-Related Materials (materials used throughout the entire semiconductor manufacturing process). Semiconductor-related materials are often utilized alongside functional materials from other groups. However, since semiconductors function as the core of all digital devices and the materials used throughout the entire manufacturing process are extremely diverse, it is appropriate to treat them as a separate group.

Japan once dominated the global market with various home appliances and semiconductors. However, its presence is now fading. Nevertheless, as discussed below, the functional materials that form the basis of these products remain highly significant globally and are an indispensable sector for Japan's sustained economic growth.

2.2 An Overview of Functional Materials Exports in Japan

Figure 1 shows the export share of functional materials in Japan since 2000 (as a percentage of total exports). As the figure indicates, the export share of functional materials has been on an upward trend since the 2000s, exceeding 10% in the latter half of the decade. Although growth subsequently leveled off, it began rising rapidly again in the late 2010s, reaching a share exceeding 14% in the 2020s. Considering that the share of automobiles (commodities under HS chapter 87), a major Japanese export, is 21.8%, and the share of machinery and mechanical appliances and parts thereof (commodities under HS chapter 84) is 17.5%, the export share of functional materials is comparable and can be positioned as one of Japan's primary export items. Figure 2 shows the share of exports by major destination for functional materials. In 2000, exports to China accounted for approximately 20% of the total, but this share gradually increased thereafter, reaching nearly 40% by the 2020s. South Korea also

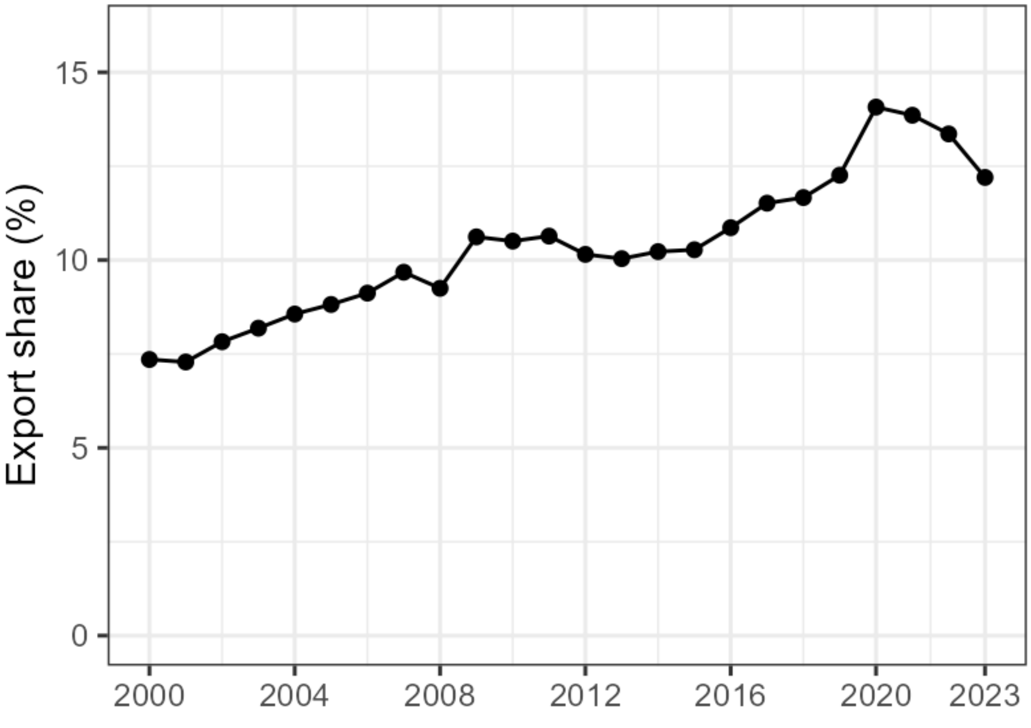

Figure 1. Changes in the export share of functional materials, 2000–2023.

expanded its export share after the 2000s, reaching nearly 20% in the early 2010s. However, it has been declining gradually since then. Combined, China, South Korea, and other Asian countries accounted for over 70% of the export share in the 2020s. In contrast, the export share to the United States and Europe remains generally low compared to Asian countries, failing to reach 20% in the 2020s. As these characteristics illustrate, Japan's global supply chain operates on a structure where functional materials produced in Japan are exported to Asian countries, primarily China and South Korea, and then processed into semi-finished goods and finished products within that region. Figure 3 shows the share of items within each functional material group that rank among the top 1 to 3 in global exports. For semiconductor-related functional materials (Figure 3a), the export share of items ranking among the top 1 to 3 was approximately 50% in 2000. Although it declined slightly thereafter, the share has stabilized at around 40%. Other functional material categories (Figures 3b–h) show generally stable trends, suggesting that Japan can expect stable exports for its world-leading functional materials.

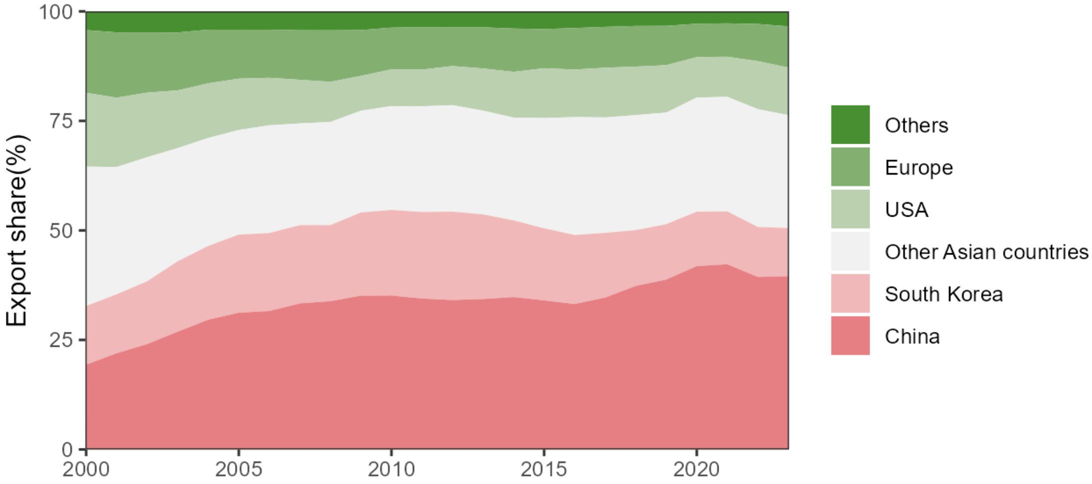

Figure 2. Export destinations for Japanese functional materials to selected destinations, 2000–2023.

Figure 4 shows the breakdown of functional material exports[2]. Within the 8 groups of

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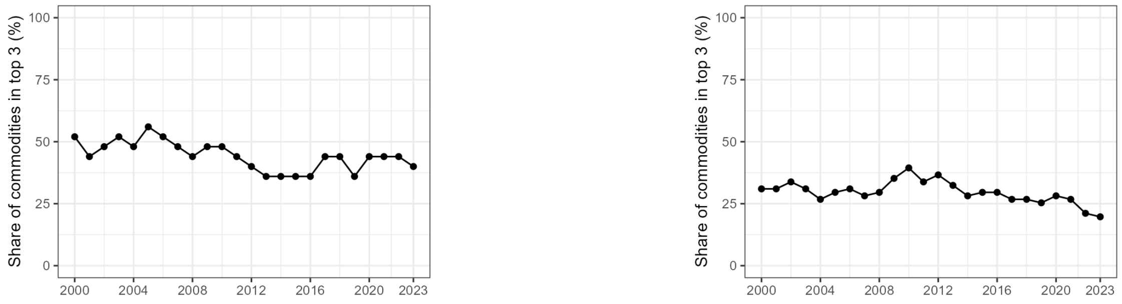
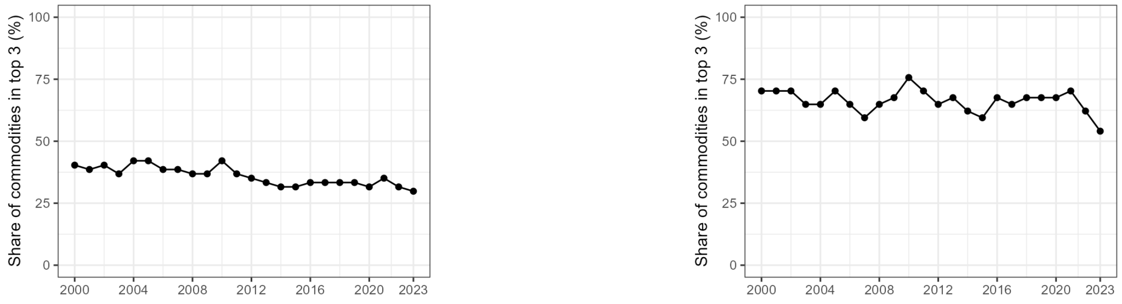


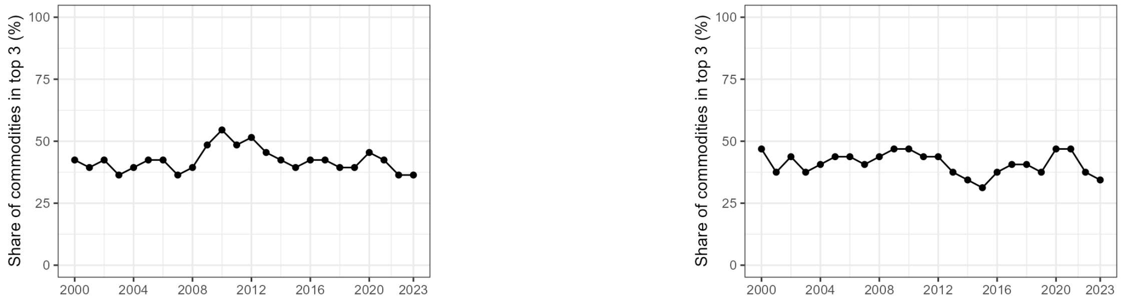
(a) Semiconductors

(b) Resins



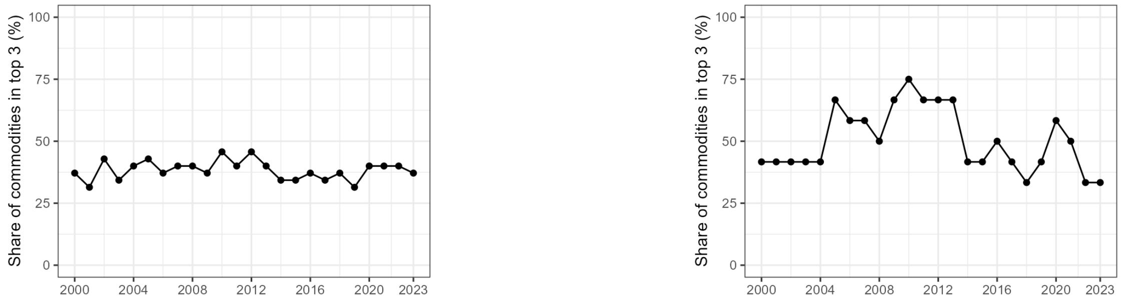
(c) Films & Sheets

(d) Electronics & Battery Materials



(e) Coating Agents, Paints & Inks

(f) Additives



(g) Fillers & Slurries

(h) Adhesives & Pressure-Sensitive Adhesives

Figure 3. Share of commodities ranked in the top three by export share within each functional material group in Japan.

functional materials[3], Functional Fesins hold the largest share (25%), followed by Electronic Components & Battery Materials (18%) and Semiconductor materials (17%). Functional Resins span a wide range of fields, from food packaging to medical, automotive, and aerospace applications, likely contributing to their high export share. Exports of materials used in Semiconductor manufacturing are also performing well.

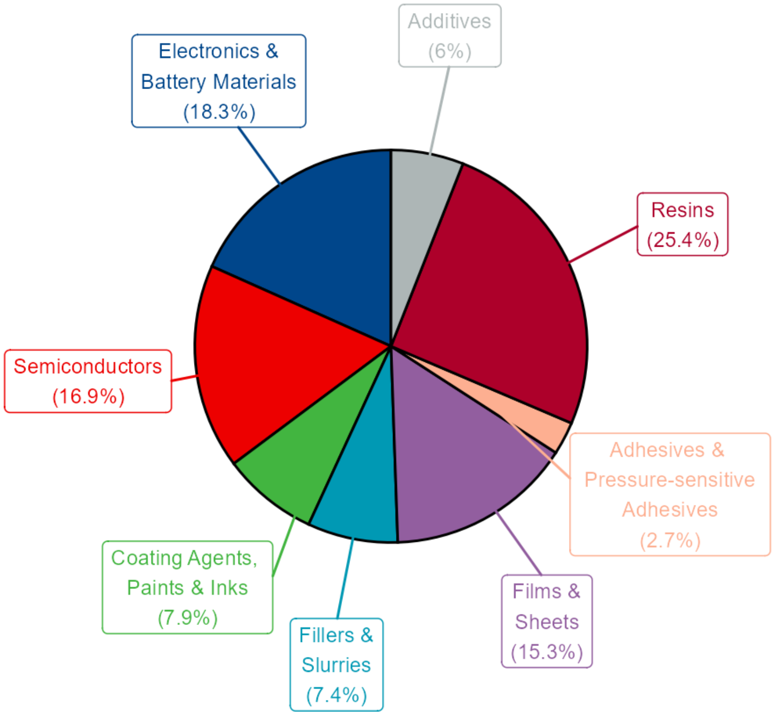


Figure 4. Export share of functional materials by group, 2023.

3 Literature Review

In determining and fluctuating exports, not only income and price factors but also the quality of export goods are significant. The concept of export quality is somewhat vague. Quality is

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For example, the Ministry of Economy, Trade and Industry defines functional chemicals as “a general term for high-value-added chemicals used with a focus on specific functional aspects such as photosensitivity, ferromagnetism, high conductivity, insulation, high heat shielding, and reaction promotion performance,” making it nearly synonymous with functional materials.

[3] Details are explained in the section Appendix

defined as “the totality of inherent properties and performance that serve as an evaluation to determine whether a product or service fulfills its intended purpose.”[4]

For example, automobiles with high technical performance are considered high-quality exports in overseas markets. However, it is not only technical performance that contributes to quality; elements that provide psychological satisfaction from ownership (such as brand) can also be regarded as high quality. Furthermore, high quality is crucial not only for goods but also for service exports. Japan’s famous castles are popular tourist destinations for foreign visitors. This popularity stems from the unique Japanese castle design and scenery meeting foreign demand with high quality.

Thus, while the factor of quality is extremely important in the export of goods and services, its quantitative measurement is not straightforward. Although the importance of export quality has long been pointed out, its theoretical background has not always been clear.[5]

In the 2000s, Melitz (2003) introduced a new development in trade theory, theoretically demonstrating that the existence of productivity is a crucial factor in a firm’s export behavior. However, the concept of export quality is broader and more abstract than productivity, making it difficult to claim that the new trade theory fully explains all aspects of export quality. Nevertheless, by providing an angle that export behavior is not solely determined by income and price factors, research on exports had begun to make steady progress.[6]

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[4] Interpreting the intended purpose as consumer demand, the quality of an export product can be understood as a concept encompassing the properties and performance of the export that satisfy the demands and needs of consumers in the export destination.

[5] For example, Ueda (1987) points out that when estimating the standard export function, income elasticity tends to take on quite high values (e.g., 3 or more), highlighting the importance of incorporating factors other than income and relative prices. He emphasizes non-price competitiveness factors, which can be interpreted as suggesting the role of quality in exports. The role of comparative competitiveness in postwar export growth was sharply noted by Kanamori (1987) and Sato (1977). Ueda (1987) further highlighted how Japan’s production and export structures adapted to changes in world demand growth, explaining that the quality of exports improved in response to demand at export destinations.

[6] Regarding product quality in international trade, Linder (1961)’s research is a long-standing contribution. While Linder did not explicitly address the quality of exports, he focused on the demand (or consumption preferences) of export destinations and proposed the Linder effect. His perspective can be said to have indirectly highlighted the role of quality in exports.

As the 2000s began, various data related to international trade also started to be published and organized. This development can be attributed to the expansion of market economies worldwide following the end of the Cold War in 1989, which created a need for the systematization of information concerning international trade in goods and services. Alongside this enrichment of data, combined with advances in information processing capabilities and statistical analysis methods, empirical analysis of international trade grew in both quality and quantity. Research on the quality of exports is no exception, with numerous studies conducted, primarily using empirical analysis.

The pioneering study on the quality of exports since the 2000s is Schott (2004) . This study uses U.S. industry-specific and importing-country-specific data to examine in detail the characteristics of export quality. Khandelwal (2010) and Amiti and Khandelwal (2013) measure the quality of export products in export decisions by estimating differentiated product-specific demand functions (Berry-type demand functions) in exporting countries (Matsuura (2015) provides an example of its application to Japan). These studies all focus on the export (supply) side. Feenstra and Romalis (2014) further explore the endogenous derivation of export quality

Hallak (2006) provides an analysis from the perspective of the demand side (importing countries).[7] Hallak (2006) assumes that export quality is reflected in export prices (using import prices as a proxy) and combines an import price determination equation with an import function (gravity equation) using export quality as an explanatory variable. The estimation uses cross-sectional data from 60 countries in 1995 at the three-digit HS code level. Henn et al. (2020) measure export quality using a richer dataset based on Hallak (2006)'s framework, analyzing 166 developed and developing countries over 1962–2014 using SITC 4-digit codes across more than 800 product categories.[8]

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[7] Khandelwal (2010), Amiti and Khandelwal (2013), and Hallak (2006) all utilize trade data. Analyses using firm-level data have also emerged. Examples include Bastos and Silva (2010), Manova and Zhang (2012), Martin (2012), Harrigan, Ma and Shlychkov (2015), Görg, Halpern and Muraközy (2017), Crozet, Head and Mayer (2012), and Piveteau and Smagghue (2019).

[8] Hallak and Schott (2011) improve the estimation of export quality by combining export prices and trade balances. Their approach judges products from countries achieving larger trade surpluses at the same

Hallak (2006) and Henn et al. (2020) developed a methodology that assumes export quality is reflected in export unit prices and attempts to measure export quality through estimation of import functions. This study adopts their methodology while introducing three novel aspects. First, it focuses on Japan's functional materials, measuring the export quality of items belonging to this category. As discussed in Section 1, enhancing the export quality of functional materials is essential for strengthening the international competitiveness of Japanese industries. Therefore, from a policy perspective, a quantitative understanding of the export quality of functional materials is highly significant. Second, the measurement is based on a more detailed product classification than previous studies.

Specifically, functional materials are subdivided at the HS 6-digit code level. This granular classification enables a more precise examination of the international competitiveness of Japan's functional materials. Third, the sample period is set from 2000 to 2023. Following the end of the Cold War, the world has intensified international competition amid the tide of globalization. Therefore, considering recent changes in the global economy, the sample period is set to the 2000s and beyond.

4 Derivation of Export Quality

4.1 Determinants of Export Price

Three factors determine export prices. The first is *product cost*, including production costs (influenced by labor productivity and capital intensity) and logistics costs (primarily transportation expenses, driven by distance). The second is *market trends and market size.* If consumption and investment are robust and the destination experiences an economic boom, export prices will rise. Conversely, if the economy deteriorates and demand stagnates, ex-

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price as being of "higher quality". Hallak (2010) reinterprets the Linder hypothesis—which states that trade flourishes between countries with similar income levels—in terms of the relationship between the "quality" of export products and "income.". Hallak and Sivadasan (2013) reveal a mechanism whereby highly productive firms produce high-quality, high-cost products and offset transportation costs to generate profits through exports.

port prices will fall. Furthermore, the larger the destination market size and the higher the income level of the country, the higher the price that can be set for the export goods The third is *export quality*. Generally, goods with high added value and superior quality tend to command higher unit prices, leading to increased export prices.

Empirical evidence on export price determinants is limited. Kamal (2021) uses Egyptian customs data to show: (i) highly productive firms produce high-quality products and set correspondingly high export prices; (ii) export prices are higher for more distant destinations and countries with higher income; and (iii) firms importing capital or intermediate goods set higher export prices. Harrigan, Ma and Shlychkov (2015) finds using U.S. firm data that firms with higher productivity and greater technological intensity set higher prices, while capital-intensive firms set lower prices. Manova and Zhang (2012) uses Chinese firm-level data to show: (i) higher-quality exports command higher prices; (ii) export prices increase with destination market size; and (iii) export prices rise with distance.

As these empirical studies demonstrate, the three determinants outlined earlier—cost, market trends and market size, and the quality of exports—all suggest they cannot be ignored. Therefore, we consider these three factors and specify the export price determination mechanism as shown in the Equation 1:

$$\ln p_{mx}^s = \beta_0^s + \beta_1^s \ln \theta_{mx}^s + \beta_2^s \,\mathrm{Dist}_{mx} + \beta_3^s \ln y_x + \beta_4^s \ln\left(\frac{K}{L}\right)_x + v_{mx}^s \tag{1}$$

where m, x, and s index importer, exporter, and sector. Cost factors are proxied by the exporting country's labor productivity (per capita income y_x), distance (Dist_{mx}), and the capital-labor ratio $(K/L)_x$. The quality of exports is θ_{mx}^s. This equation alone cannot identify the quality estimate as quality enters the equation as a dependent variable. In the next section, we combine 1 with the gravity equation to obtain the coefficients β.

4.2 Gravity Equation

Let $s = 1, \ldots, S$ index commodities, and the utility function of the representative consumer in country m is

$$u_m^s = \left[\sum_{k \in H_s} \left(\left(\theta_m^k \right)^{\delta_m^s} q_m^k \right)^{\alpha^s} \right]^{1/\alpha^s}, \quad 0 < \alpha^s,\, \delta_m^s < 1\, \forall\, s, k \tag{2}$$

where θ_m^k and q_m^k are the quality and quantity of variety k. The parameter δ_m^s captures the effect of income on the demand for quality. Thus, the utility function implies that if countries share the same quality preference $_m^k$, countries with higher income level tend to consume more high-quality commodities, and that countries with similar income levels can have different preference for quality. Different from Hallak (2006), where the representative consumer demands the same quality θ^k regardless of the exporter, we allow the consumer's demand for variety k to vary across exporters. This allows us to explore bilateral export quality and test whether an exporter adjusts quality based on destination. If an exporter does not adjust quality, $\theta^1 = \cdots = \theta^k$, $\forall k \in s$ and the model reduces to the one in Hallak (2006).

For a given expenditure allocation $E_m^1, \ldots, E_m^s$, expenditure on variety k is

$$p_m^k q_m^k = \frac{\left[\frac{p_m^k}{\left(\theta_m^k\right)^{\delta_m^s}} \right]^{1-\sigma^s}}{\sum_{j \in H_s} \left[\frac{p_m^j}{\left(\theta_m^j\right)^{\delta_m^s}} \right]^{1-\sigma^s}} E_m^s \tag{3}$$

where p_m^k is the price that a consumer in country m paid for a variety k and $\sigma^s = 1/(1-\alpha^s) > 1$ is the elasticity of substitution. Equation 3 expresses expenditure on a variety k as a fraction of total expenditure in commodity s.

We further assume that an exporter x produces N_x^s different varieties in commodity s and that varieties of the same commodity share the same quality and price. We then multiply Equation 3 with $N_m x^s$ to obtain the total imports from exporter x to country m for commodity s, and incorporate the iceberg trade cost $p_m x^s = p^s_x \tau_m x^s$ where $\tau_m x^s$ is the bilateral trade costs

$$\text{imp}^s_{mx} = N^s_x \frac{\left[\frac{p^s_x \tau^s_{mx}}{\left(\theta^s_{mx}\right)^{\delta^s_m}}\right]^{1-\sigma^s}}{\sum_{j \in H_s} \left[\frac{p^j_m}{\left(\theta^j_m\right)^{\delta^s_m}}\right]^{1-\sigma^s}} E^s_m \tag{4}$$

Define $\tilde{\sigma}^s = 1 - \sigma^s$ and take logs of equation (4):

$$\ln(\text{imp})^s_{mx} = \ln N^s_x - \tilde{\sigma}^s \ln p^s_x - \ln \sum_{j \in H_s} \left[\frac{p^j_m}{\left(\theta^j_m\right)^{\delta^s_m}}\right]^{-\tilde{\sigma}^s} + \ln E^s_m - \tilde{\sigma}^s \ln \tau^s_{mx} + \tilde{\sigma}^s \delta^s_m \ln \theta^s_{mx} \tag{5}$$

The first two terms are specific to exporter x, while the following two terms are specific to importer m. Thus, we can use commodity-specific exporter fixed effect and commodity-specific importer fixed effect two capture these four terms. Following the literature, bilateral trade costs τ^s_{mx} are captured using the bilateral physical distance $Dist_{mx}$ and a set of gravity variables G_{mx}, which includes common border, common colonizer, colonial relationship, common official language and the existence of a regional trade agreement.

$$\ln \tau^s_{mx} = \eta^s \ln \text{Dist}_{mx} + \tilde{\rho}^s G_{mx} + u^s_{mx} \tag{6}$$

The relationship between income and preference for quality is expressed as

$$\delta^s_m = \delta^s + \mu^s \ln y_m \tag{7}$$

Equations (6) and (7) are substituted into (5) to arrive at

$$\ln(imp)^s_{mx} = \mu^s \tilde{\sigma}^s \ln \theta^s_{mx} - \tilde{\sigma}^s \eta^s \ln Dist_m x + \rho^s G_{mx} + \Gamma^s_m + \Psi^s_x + \epsilon^s_{mx} \tag{8}$$

where $\rho^s = -\tilde{\sigma}^s \tilde{\sigma}^s$ and $\epsilon^s_{mx} = -\tilde{\sigma}^s u^s_{mx}$. Γ^s_m and Ψ^s_x are the import and exporter fixed effects, respectively.

Next, we solve Equation 1 for quality

$$\ln \theta^s_{mx} = -\frac{\beta^s_0}{\beta^s_1} + \frac{1}{\beta^s_1} \ln p^s_{mx} - \frac{\beta^s_2}{\beta^s_1} \ln Dist_{mx} - \frac{\beta^s_3}{\beta^s_1} \ln y_x - \frac{\beta^s_4}{\beta^s_1} \ln\left(\frac{K}{L}\right)_x - \frac{v^s_{mx}}{\beta^s_1} \tag{9}$$

Finally, Equation 9 is substituted into Equation 8 arrive at Equation 10 below. Note that we add the time index t, which has been dropped so far for brevity, into to make it clear that the function will be estimated using panel data.

$$\begin{aligned} \ln(\text{imp})^s_{mxt} = {} & \beta'_1 \ln p^s_{mxt} \ln y_{mt} + \beta'_2 \ln \text{Dist}_{mxt} \ln y_{mt} + \beta'_3 \ln y_{xt} \ln y_{mt} + \beta'_4 \ln\left(\frac{K}{L}\right)_{xt} \ln y_{mt} \\ & - \tilde{\sigma}^s \eta^s \ln \text{Dist}_{mx} + \rho^s G_{mx} + \Gamma^s_{mt} + \psi^s_{xt} + \varepsilon^s_{mxt} \end{aligned} \tag{10}$$

where ${\beta'_1}^s = \mu^s \tilde{\sigma}^s \frac{1}{\beta^s_1}$, ${\beta'_2}^s = -\mu^s \tilde{\sigma}^s \frac{\beta^s_2}{\beta^s_1}$, ${\beta'_3}^s = -\mu^s \tilde{\sigma}^s \frac{\beta^s_3}{\beta^s_1}$ and ${\beta'_4}^s = -\mu^s \tilde{\sigma}^s \frac{\beta^s_4}{\beta^s_1}$. Γ^s_m and Ψ^s_x will absorb time-invariant characteristics of the importer and exporter[9].

Equation (10) is estimated separately for each commodity. The error term ε_{mxt} is correlated with $\ln p^s_{mxt} \ln y_{mt}$ due to the included importer income. To address this endogeneity, $\ln(p_{mxt-1}) \ln(y_{mt})$ is used as an instrument for $\ln(p_{mxt}) \ln(y_{mt})$.

4.3 Data

Trade data are extracted at the 6-digit HS level for 2000–2023 from UN COMTRADE, using importer-reported data. Unit values are calculated by dividing import value by import quantity. Data at the 6-digit level contain missing quantity information and extreme values. Any series with 5 or more consecutive years of missing unit values is dropped. Missing unit values in the middle of a series are imputed using linear approximation; those at the endpoints are replaced by the nearest observed value, up to 5 years. Importer-reported

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[9] Adding the time index t to both fixed effects is necessary to control the first four unobservable variables in equation (5). This specification is also consistent with previous literature (Baldwin and Taglioni, 2006; Beverelli, 2022; French, 2016; Larch, Shikher and Yotov, 2025; Olivero and Yotov, 2012).

data are supplemented with exporter-reported data where the former are unavailable. For each importer-exporter-product series, extreme values—defined as values more than 1.5 × IQR above the third quartile or below the first quartile—are replaced by the series average. Gravity variables are from the CEPII database (Head and Mayer, 2013). GDP per capita is from the World Development Indicators. Capital per worker is calculated using the Penn World Tables 11.0 (Feenstra, Inklaar and Timmer, 2015).

The panel consists of 168 countries and 4,263 HS 6-digit commodities over 2000–2023, yielding over 34 million importer-exporter-commodity-year combinations.

4.4 Results

Table 1 summarizes the coefficients from estimating equation (10) separately for each commodity. Table 2 estimates the model using all commodities. In Table 1, model (1) is the base model, while models (2)–(8) test for model robustness using different specifications. Since displaying all individual coefficients is not feasible, we report only the median value, the ratio of positive and significant coefficients, and the ratio of negative and significant coefficients.

Model (1) yields expected signs overall for all variables. The results for $\ln(p^s_{mxt})\ln(y_{mt})$ indicate that for more than half of the commodities, quality demand does not increase—or even decreases—as a country becomes richer.[10]

Model (2) tests whether COVID-19 trade disruptions alter the results by estimating using only 2000–2019. Model (3) includes exporter-importer fixed effects and exporter-importer fixed effects. Model (4) fixes bilateral distance to its 2000 value. Models (5) and (6) use $\ln(p_{mxt-1})\ln(y_{mt-1})$ and $\ln(p_{mxt-2})\ln(y_{mt})$, respectively, as instruments. Models (7), (8), and (9) estimate equation (10) without IV. Model (9) uses Pseudo Poisson Maximum Likelihood (PPML).[11] Models (2) to (9) confirm that results do not change drastically; the

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[10] Since $\sigma > 0$ and $\beta_1 > 0$ (producing higher quality products requires higher production costs, reflected in price p_{mxt}), the sign of β_1' reflects the sign of α.

[11] PPML can be a preferred estimation method for gravity equations, especially with zero trade flows where taking logs drops observations (Santos Silva and Tenreyro, 2013). However, IV is our preferred method for estimating equation (10) because, in addition to addressing omitted variable bias, there are no zero trade

Table 1. Gravity Equation Estimation

	(1)			(2)			(3)		
	Median	Positive & significant	Negative & significant	Median	Positive & significant	Negative & significant	Median	Positive & significant	Negative & significant
$\ln(p^s_{mxt})\ln(y_{mt})$	−0.03	16.5	56.8	−0.03	15.6	55.0	−0.01	18.8	31.5
$\ln(K/L)_{xt}\ln(y_{mt})$	−0.25	16.3	43.3	−0.25	15.8	41.1	−0.02	17.4	18.8
$\ln(\text{dist}_{mx})\ln(y_{mt})$	0.06	39.4	23.6	0.07	38.7	22.2	0.17	35.5	12.8
$\ln(y_{xt})\ln(y_{mt})$	0.27	43.7	17.2	0.26	41.1	16.5	−0.06	16.2	21.2
$\ln(\text{dist}_{mx})$	−1.32	19.2	47.2	−1.37	17.6	46.4	−2.00	11.7	28.4
Common FTA	0.25	55.4	11.5	0.28	55.4	10.2	0.02	18.5	12.4
Colonial relationship	0.58	61.5	12.0	0.59	61.1	11.3	–	–	–
Common colonizer	0.29	45.5	22.5	0.28	44.2	22.8	–	–	–
Common official language	0.38	65.9	8.6	0.38	64.3	8.4	–	–	–
Common border	0.60	77.7	4.2	0.60	75.8	3.9	–	–	–
Period		2000–2023			2000–2019			2000–2023	
Exp.-Time + Imp.-Time FE		✓			✓			✓	
Exp.-Imp. FE								✓	
IV		✓			✓			✓	

Notes: Models (1)–(6) are estimated using IV. The IV for models (1)–(4) is $\ln(p_{mxt-1})\ln(y_{mt})$; for model (5) it is $\ln(p_{mxt-1})\ln(y_{mt-1})$; for model (6) it is $\ln(p_{mxt-2})\ln(y_{mt})$. Model (4) fixes bilateral distance to the 2000 value; all other models use distance data as provided by CEPII. Models (7) and (8) are estimated without IV (OLS); model (9) uses PPML. Heteroskedasticity-robust standard errors are in parentheses.

Table 1 (continued) Panel B: Models (4)–(6)

	(4)			**(5)**			**(6)**		
	Median	Positive & significant	Negative & significant	Median	Positive & significant	Negative & significant	Median	Positive & significant	Negative & significant
$\ln(p^s_{mxt})\ln(y_{mt})$	−0.03	16.5	56.8	−0.03	16.5	56.5	−0.03	14.8	55.1
$\ln(K/L)_{xt}\ln(y_{mt})$	−0.25	16.3	43.3	−0.24	16.4	42.6	−0.26	16.0	43.0
$\ln(\text{dist}_{mx})\ln(y_{mt})$	0.06	39.5	23.6	0.07	39.5	23.0	0.06	38.5	23.0
$\ln(y_{xt})\ln(y_{mt})$	0.27	43.5	17.2	0.26	42.6	17.3	0.28	43.4	16.8
$\ln(\text{dist}_{mx})$	−1.32	19.0	47.3	−1.33	18.7	47.2	−1.29	18.6	46.4
Common FTA	0.25	55.5	11.6	0.26	55.5	11.2	0.25	54.4	11.2
Colonial relationship	0.58	61.6	12.1	0.57	61.4	12.0	0.57	60.9	11.8
Common colonizer	0.27	44.7	23.1	0.28	45.2	22.8	0.29	45.1	22.5
Common official language	0.38	65.8	8.6	0.38	65.5	8.6	0.38	64.9	8.3
Common border	0.61	77.8	4.1	0.60	77.1	4.1	0.60	76.5	3.9
Period	2000–2023			2000–2019			2000–2023		
Exp.-Time + Imp.-Time FE	✓			✓			✓		
Exp.-Imp. FE									
IV	✓			✓			✓		

Notes: Models (1)–(6) are estimated using IV. The IV for models (1)–(4) is $\ln(p_{mxt-1})\ln(y_{mt})$; for model (5) it is $\ln(p_{mxt-1})\ln(y_{mt-1})$; for model (6) it is $\ln(p_{mxt-2})\ln(y_{mt})$. Model (4) fixes bilateral distance to the 2000 value; all other models use distance data as provided by CEPII. Models (7) and (8) are estimated without IV (OLS); model (9) uses PPML. Heteroskedasticity-robust standard errors are in parentheses.

Table 1 (continued) Panel C: Models (7)–(9)

	(7)			**(8)**			**(9)**		
	Median	Positive & significant	Negative & significant	Median	Positive & significant	Negative & significant	Median	Positive & significant	Negative & significant
$\ln(p^s_{mxt})\ln(y_{mt})$	−0.02	23.8	55.1	−0.02	23.3	53.9	−0.01	26.3	44.3
$\ln(K/L)_{xt}\ln(y_{mt})$	−0.25	16.7	44.1	−0.25	15.8	42.4	−0.20	21.3	39.2
$\ln(\text{dist}_{mx})\ln(y_{mt})$	0.06	40.5	24.3	0.07	40.7	22.6	0.02	33.7	30.4
$\ln(y_{xt})\ln(y_{mt})$	0.25	43.6	17.9	0.26	41.7	17.3	0.10	34.1	25.6
$\ln(\text{dist}_{mx})$	−1.34	19.3	48.7	−1.36	17.8	48.2	−0.68	25.7	39.2
Common FTA	0.27	57.6	11.2	0.29	57.8	10.4	0.36	58.2	12.1
Colonial relationship	0.59	62.8	12.0	0.60	61.9	11.4	0.35	50.0	19.9
Common colonizer	0.29	45.3	23.1	0.27	44.5	23.2	0.41	48.3	22.4
Common official language	0.38	66.9	8.9	0.39	65.0	8.9	0.22	51.3	18.5
Common border	0.62	79.2	4.3	0.62	77.5	4.1	0.53	71.4	7.7
Period		2000–2023			2000–2019			2000–2023	
Exp.-Time + Imp.-Time FE		✓			✓				
Exp.-Imp. FE								✓	
IV									

Notes: Models (1)–(6) are estimated using IV. The IV for models (1)–(4) is $\ln(p_{mxt-1})\ln(y_{mt})$; for model (5) it is $\ln(p_{mxt-1})\ln(y_{mt-1})$; for model (6) it is $\ln(p_{mxt-2})\ln(y_{mt})$. Model (4) fixes bilateral distance to the 2000 value; all other models use distance data as provided by CEPII. Models (7) and (8) are estimated without IV (OLS); model (9) uses PPML. Heteroskedasticity-robust standard errors are in parentheses.

estimates are therefore robust.

We also estimate the model by aggregating all commodities, with fixed effects modified to importer-year-commodity and exporter-year-commodity. Table 2 further confirms the overall trends in Table 1. While the coefficient for $\ln(p_{mxt})\ln(y_{mt})$ in PPML has the reverse sign, the PPML model is estimated without IV and may therefore be biased. While the coefficient for $ln(p_mxt)ln(y_mt)$ in PPML has reverse sign, the PPML model is estimated without using IV and, thus, might be biased. Nevertheless, we believe that these estimate results are robust.

4.5 Quality Estimates

To obtain quality estimates for each exporter-importer-product-year combination, we rewrite equation (9) as[12]

$$\mu^s \tilde{\sigma}^s \ln \theta^s_{mxt} + \mu^s \tilde{\sigma}^s \frac{\beta_0}{\beta_1} = \beta'_1 \ln p^s_{mxt} + \beta'_2 \ln \mathrm{Dist}_{mx} + \beta'_3 \ln y_{xt} + \beta'_4 \ln\left(\frac{K}{L}\right)_{xt} \tag{11}$$

We define the left-hand side as the bilateral quality$Q^1_{mxt} = \mu^s \tilde{\sigma}^s \ln \theta^s_{mxt} + \mu^s \tilde{\sigma}^s \frac{\beta_0}{\beta_1}$. The right-hand side is calculated using estimated coefficients from equation (10). We shift Q^1_{mxt} by a constant so the minimum quality value in the panel equals zero. Q^1_{mxt} is then aggregated to represent the overall export quality of an exporter to all destinations via weighted average:

$$Q^2_{xt} = \sum_m w_{mxt}\, Q^1_{mxt}, \quad w_{mxt} = \frac{\mathrm{Export}_{mxt}}{\sum_m \mathrm{Export}_{mxt}} \tag{12}$$

We also propose Q^3_{xt}, which uses a world-export-share weighting scheme:

$$Q^3_{xt} = \sum_m \omega_{mxt}\, Q^1_{mxt}, \quad \omega_{mxt} = \frac{\mathrm{Export}_{mxt}}{\sum_x \sum_m \mathrm{Export}_{mxt}} \tag{13}$$

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observations in our data.

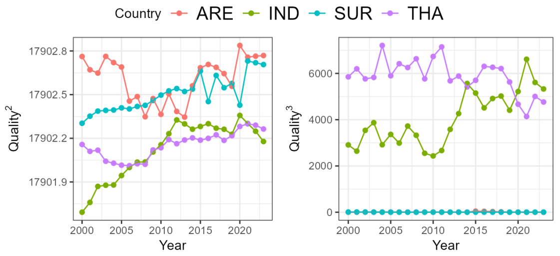
[12] The term $-\mu^s \tilde{\sigma}^s \frac{1}{\beta_1} v_{mxt}$ reflects factors that are exporter-importer specific but unobservable. We set this term to zero when calculating the quality estimates.

Table 2. Gravity Estimation Using All Commodities

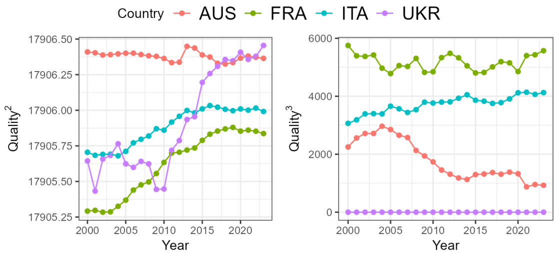
	IV	OLS	PPML
$\ln(p^s_{mxt})\ln(y_{mt})$	-0.020^{***}	-0.009^{***}	0.008^{***}
	(0.0001)	(0.0001)	(0.0002)
$\ln(K/L)_{xt}\ln(y_{mt})$	-0.251^{***}	-0.252^{***}	-0.170^{***}
	(0.002)	(0.002)	(0.016)
$\ln(\text{dist}_{mx})\ln(y_{mt})$	0.146^{***}	0.146^{***}	-0.004
	(0.001)	(0.001)	(0.004)
$\ln(y_{xt})\ln(y_{mt})$	0.297^{***}	0.289^{***}	0.084^{***}
	(0.002)	(0.002)	(0.020)
$\ln(\text{dist}_{mx})$	-2.324^{***}	-2.344^{***}	-0.553^{***}
	(0.006)	(0.006)	(0.042)
Common FTA	0.263^{***}	0.275^{***}	0.503^{***}
	(0.001)	(0.001)	(0.005)
Colonial relationship	0.761^{***}	0.777^{***}	0.325^{***}
	(0.002)	(0.002)	(0.016)
Common colonizer	0.429^{***}	0.428^{***}	0.243^{***}
	(0.003)	(0.003)	(0.018)
Common official language	0.426^{***}	0.433^{***}	0.100^{***}
	(0.001)	(0.001)	(0.007)
Common border	0.628^{***}	0.640^{***}	0.537^{***}
	(0.001)	(0.001)	(0.006)
N	30,846,680	32,187,840	32,187,840

Notes: ***, **, * Significant at the 1%, 5%, and 10% level, respectively. Heteroskedasticity-robust standard errors in parentheses. The IV model uses $\ln(p_{mxt-1})\ln(y_{mt})$ as the instrument for $\ln(p_{mxt})\ln(y_{mt})$. Fixed effects are importer-year-commodity and exporter-year-commodity.

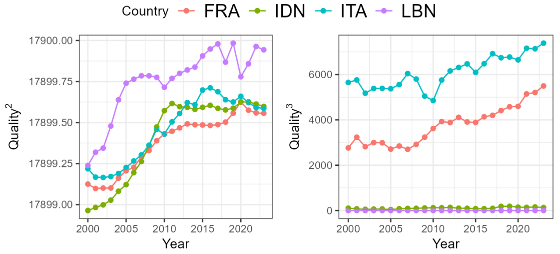
Figure 5 compares Q^2_{xt} and Q^3_{xt} for six commodities chosen because their exporters are well known.



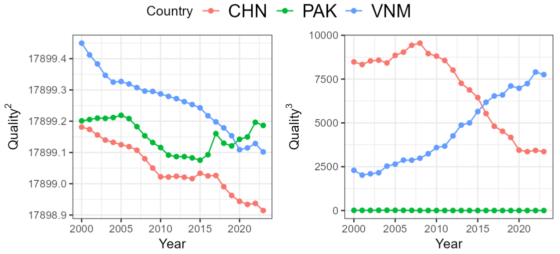
(a) Rice (HS: 100630)



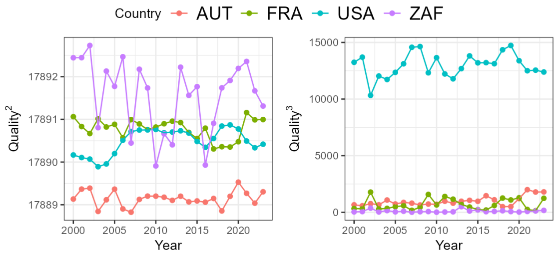
(b) Wine, 2 litres or less (HS: 220421)



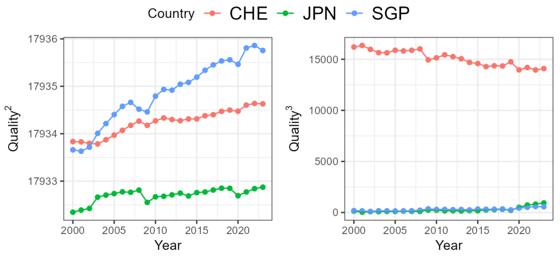
(c) Leather handbag (HS: 420221)



(d) Sports footwear (HS: 640411)



(e) Aircraft engines (HS: 840710)



(f) Wrist-watches (HS: 910121)

Figure 5. Estimated Q^2_{xt} and Q^3_{xt} over time for specific commodities. Left panels show Q^2_{xt}; right panels show Q^3_{xt}.

For rice (HS 100630), Q^2_{xt} places the United Arab Emirates (UAE) and Suriname (SUR) at the top. Q^3_{xt} instead assigns the highest quality to India (IND) and Thailand (THA). In our data, in 2023, Suriname exports rice only to France with the quality value of 4.4, while the United Arab Emirates exports rice to 8 countries with quality ranging from 4.4 to 4.7. Thailand exports to 74 countries around the world with quality ranging from 3.6 to 4.2, while India exports to 51 countries with quality ranging from 3.5 to 4.1. Thus, Q^2_{xt} will result in the United Arab Emirates has higher export quality in rice than Thailand. On the other hand, Q^3_{xt} adjusts for demand by incorporating world export share as weights.

For wine (HS 220421), France (FRA) and Italy (ITA) export to 116 and 88 destinations, respectively; Ukraine (URK) exports to only 3. After adjusting for demand, France and Italy have the highest Q^3_{xt}.

For leather handbags (HS 420221), Italy, France, India and Lebanon (LBN) export to 89, 77, 21 and 3 destinations, respectively. Q^3_{xt} captures the higher global demand for goods from Italy and France.

For sports footwear (HS 640411), China exports to 92 destinations, Vietnam to 58, and Pakistan to 4. Q^3_{xt} is higher for Vietnam than China, possibly reflecting improvements in Vietnamese production quality.

For aircraft engines (HS 840710), the USA exports with the highest quality to 31 destinations. Austria (AUT), France and South Africa (ZAF) exports to 13, 4, and 3 destinations, respectively.

For wrist-watches (HS 910121), Switzerland (CHE) exports to 76 destinations; Japan (JPN) to 8 and Singapore (SGP) to 4. Q^3_{xt} places Switzerland first in export quality.

These examples confirm that Q^3_{xt} better captures overall export quality by accounting for both estimated bilateral quality and world demand information.

5 Discussion

5.1 Standardized Quality of Functional Materials

The previous section establishes that Q^3_{xt} is our best indicator of export quality, but it is comparable only within a given commodity. We cannot state whether quality in one commodity is higher or lower than in another. This is because equation (10) is estimated separately for each commodity. Furthermore, the sign of Q^3_{xt} carries no intrinsic meaning.

We overcome these problems by standardizing Q^3_{xt} to have mean 0 and standard deviation 1 within each commodity:

$$Q_{xt}^{4} = \frac{Q_{xt}^{3} - \mathbb{E}[Q_{xt}^{3}]}{\mathrm{sd}[Q_{xt}^{3}]} \tag{14}$$

A positive (negative) value of Q_{xt}^{4} indicates export quality above (below) the world average. The magnitude of Q_{xt}^{s} indicates how far from the world average.

Let G index a group of functional materials (e.g., semiconductors). We calculate the weighted average quality for each group as

$$Q_{xt}^{5(G)} = \sum_{g \in G} \lambda_{xt}^{g} \times Q_{xt}^{4(g)}, \quad \lambda_{xt}^{g} = \frac{\mathrm{Export}_{xt}^{g}}{\sum_{g \in G} \mathrm{Export}_{xt}^{g}} \tag{15}$$

where λ_{xt}^{g} is the export to total export ratio for each exporter x in each functional material group g. Thus, $Q_{xt}^{5(G)}$ measures average quality within a functional material group in terms of standard deviations from the world average.

Table 3 shows the normalized quality $Q_{xt}^{5(G)}$, world export share, and normalized revealed comparative advantage (NRCA) for each functional material group. NRCA is calculated as

$$\mathrm{NRCA}_{xt}^{g} = \frac{\mathrm{Export}_{xt}^{g}}{\sum_{g} \sum_{x} \mathrm{Export}_{xt}^{g}} - \frac{\left(\sum_{g} \mathrm{Export}_{xt}^{g}\right) \left(\sum_{x} \mathrm{Export}_{xt}^{g}\right)}{\left(\sum_{g} \sum_{x} \mathrm{Export}_{xt}^{g}\right)^{2}} \tag{16}$$

Overall, China possesses the highest $Q_{xt}^{5(G)}$ for many functional groups, including Films & Sheets, Electronics & Battery Materials, Coating Agents Paints & Inks, Additives, and Fillers & Slurries. For the Semiconductor group, the USA ranks first in quality for 7 out of 25 commodities, and China for 8 out of 25. Japan tops the Semiconductor group overall despite possessing the highest quality for only 4 out of 25 commodities, indicating it specializes in a small number of critical semiconductor materials in which it dominates globally. For Electronics & Battery Materials, China ranks first (14 out of 36 commodities with the highest quality), while Japan ranks second (8 out of 36).

The next few sections will shed light on the export quality of Japan in Semiconductor

Table 3. Normalized Quality for 8 Functional Materials Groups among G20 Countries (2023)

	Semiconductors			**Resins**			**Films & Sheets**			**Electronics & Battery Materials**		
Country	NQ	ES (%)	NRCA	NQ	ES (%)	NRCA	NQ	ES (%)	NRCA	NQ	ES (%)	NRCA
ARG	−0.37	0.01	−0.00001	−1.00	0.15	−0.00008	−0.77	0.13	−0.00005	−0.72	0.03	−0.00004
AUS	1.28	5.05	0.00015	−0.98	0.21	−0.00096	−0.79	0.11	−0.00062	−0.82	0.03	−0.00039
BRA	0.11	0.77	−0.00005	−0.92	0.54	−0.00035	−0.66	0.43	−0.00024	−0.70	0.22	−0.00016
CAN	0.88	1.93	−0.00018	−0.44	2.82	−0.00050	−0.33	2.49	−0.00036	−0.58	0.55	−0.00042
CHN	2.91	9.53	−0.00030	2.04	8.35	−0.00135	2.87	23.33	0.00201	4.55	36.12	0.00215
DEU	2.37	11.00	0.00030	0.89	10.75	0.00124	0.69	11.41	0.00071	0.95	7.82	0.00021
FRA	0.24	2.67	−0.00010	1.16	8.15	0.00110	−0.23	3.30	−0.00016	−0.35	1.52	−0.00027
GBR	0.03	1.01	−0.00009	−0.52	2.43	0.00011	−0.45	1.98	−0.00003	−0.36	1.28	−0.00005
IDN	0.10	0.27	−0.00004	−0.91	0.32	−0.00033	−0.64	0.45	−0.00018	−0.68	0.17	−0.00013
IND	−0.28	0.06	−0.00012	−0.02	0.48	−0.00036	−0.57	0.95	−0.00014	−0.51	0.66	−0.00010
ITA	0.33	2.14	−0.00012	−0.27	3.99	0.00020	0.00	5.13	0.00029	0.04	2.70	0.00003
JPN	3.75	12.24	0.00074	0.17	5.61	0.00065	1.68	6.13	0.00054	1.45	10.96	0.00091
KOR	0.83	3.16	0.00015	0.91	7.30	0.00164	1.26	5.00	0.00063	1.40	10.41	0.00095
MEX	0.64	0.56	−0.00025	−0.61	1.26	−0.00092	−0.45	2.16	−0.00039	−0.61	0.57	−0.00043
RUS	−0.23	0.05	−0.00006	−0.68	0.28	−0.00029	−0.81	0.04	−0.00023	−0.81	0.01	−0.00013
SAU	−0.36	0.00	−0.00006	0.99	3.21	0.00050	−0.77	0.07	−0.00027	−0.64	0.16	−0.00010
TUR	1.17	0.55	0.00002	−0.77	0.46	−0.00006	−0.44	1.48	0.00012	−0.36	0.47	0.00000
USA	3.56	17.88	0.00082	1.14	14.27	0.00170	0.52	9.71	0.00029	0.88	6.33	−0.00009
ZAF	−0.26	0.09	−0.00004	−0.98	0.23	−0.00020	−0.79	0.14	−0.00015	−0.81	0.05	−0.00010

Table 3 (continued)

	Coating Agents, Paints & Inks			**Additives**			**Fillers & Slurries**			**Adhesives & Pressure-Sensitive Adhesives**		
Country	NQ	ES (%)	NRCA	NQ	ES (%)	NRCA	NQ	ES (%)	NRCA	NQ	ES (%)	NRCA
ARG	−0.85	0.04	−0.00005	−0.92	0.08	−0.00004	−0.86	0.17	−0.00001	−0.87	0.10	−0.00002
AUS	−0.59	0.32	−0.00045	−0.93	0.16	−0.00041	−0.46	0.80	−0.00015	−0.87	0.12	−0.00022
BRA	−0.74	0.44	−0.00018	−0.17	0.61	−0.00014	−0.86	0.32	−0.00007	−0.80	0.55	−0.00007
CAN	−0.53	1.53	−0.00041	−0.68	1.48	−0.00036	−0.37	2.27	−0.00013	−0.53	1.96	−0.00016
CHN	2.67	14.38	0.00032	3.31	17.29	0.00051	5.54	28.57	0.00056	1.52	9.77	−0.00029
DEU	1.92	15.92	0.00116	1.51	15.25	0.00091	0.78	10.73	0.00026	1.91	14.51	0.00047
FRA	0.20	4.62	0.00008	−0.22	4.30	0.00006	−0.02	2.87	−0.00002	−0.21	3.69	−0.00002
GBR	−0.26	2.95	0.00013	−0.45	2.71	0.00007	−0.55	2.25	0.00004	−0.35	2.54	0.00003
IDN	−0.76	0.20	−0.00016	−0.89	0.24	−0.00016	−0.89	0.12	−0.00005	−0.84	0.17	−0.00008
IND	−0.50	0.51	−0.00019	−0.39	0.80	−0.00016	0.39	1.44	−0.00002	−0.60	1.01	−0.00006
ITA	0.20	4.85	0.00017	−0.29	4.00	0.00003	−0.41	2.46	−0.00005	0.32	5.48	0.00014
JPN	1.13	7.57	0.00064	0.59	6.26	0.00038	2.21	9.82	0.00048	0.71	7.09	0.00031
KOR	0.23	3.70	0.00031	0.14	4.65	0.00040	0.18	4.84	0.00026	0.49	6.93	0.00037
MEX	−0.49	1.32	−0.00037	−0.62	1.44	−0.00033	−0.24	1.37	−0.00017	−0.70	0.65	−0.00025
RUS	−0.57	0.06	−0.00018	−0.89	0.10	−0.00016	0.74	1.64	0.00001	−0.80	0.19	−0.00007
SAU	−0.73	0.06	−0.00023	1.40	1.94	0.00009	−0.91	0.16	−0.00005	2.05	4.79	0.00020
TUR	−0.41	0.58	−0.00003	−0.65	0.55	−0.00005	−0.39	0.40	−0.00001	−0.53	0.62	−0.00002
USA	1.70	14.64	0.00083	1.19	13.08	0.00054	0.67	10.89	0.00019	1.54	13.36	0.00036
ZAF	−0.82	0.16	−0.00010	−0.82	0.33	−0.00007	−0.96	0.08	−0.00004	−0.79	0.33	−0.00004

and Electronics Battery Materials.

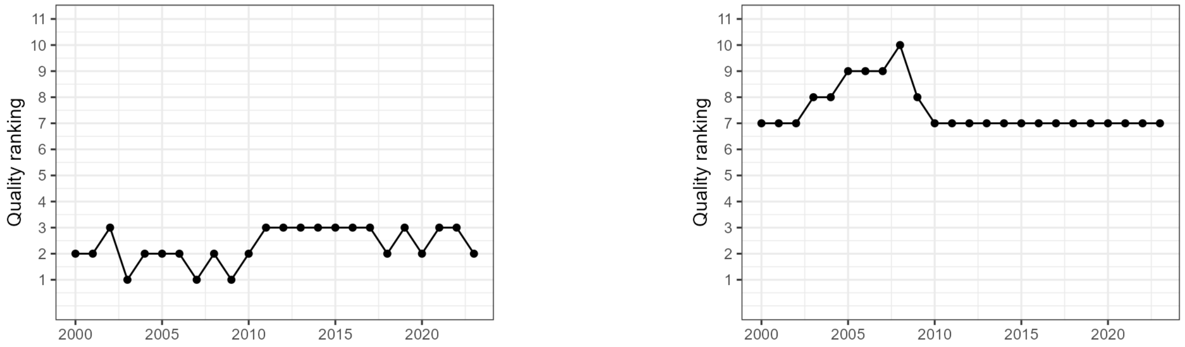
5.2 World Ranking of 8 Categories

Figure 6 shows the global ranking of export quality for each of the eight functional material groups. Semiconductor materials consistently maintained either first or second place throughout the period. Electronics components & battery materials generally maintained high quality, though the ranking has recently declined slightly. For functional coating agents, paints and inks; functional films and sheets; functional adhesives; and functional additives, all categories remained stable over time, consistently ranking between fourth and sixth globally. The stability and high global standing of these functional materials confirms their crucial role in Japan's export strategy.

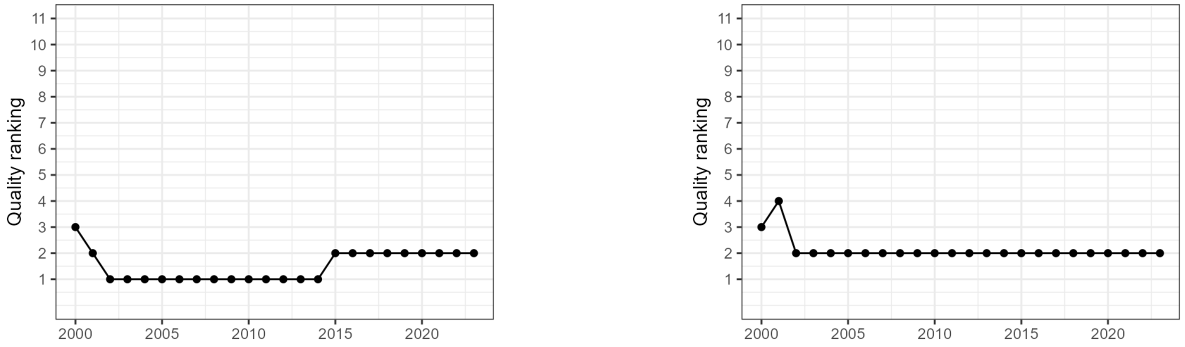
5.3 Semiconductor and Electronics & Battery Materials

Japan's semiconductor materials have consistently ranked first since 2004, showing minimal fluctuation and high stability. As of 2023, the United States ranks second. While the U.S. held the top position in 2000, it subsequently declined before recovering around 2010. China has steadily increased its quality since 2000, ranking third as of 2023. Germany shows stable trends but remains below Japan, the U.S., and China.

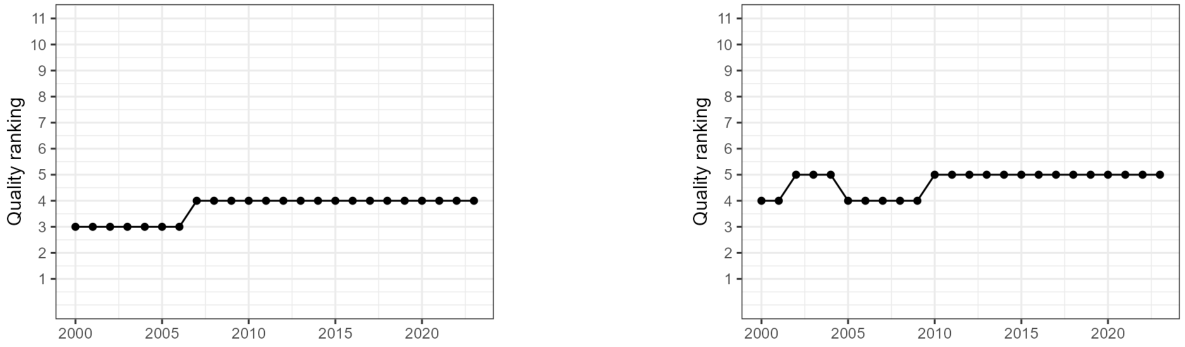
For electronics components and battery materials, Japan maintained a stable world's second-highest position from 2000 to 2016 and reached first place in 2017 but has since declined. Germany and the United States started at high levels in 2000 but gradually declined. China has steadily risen, surpassing Japan and Germany to take the top position since 2000.



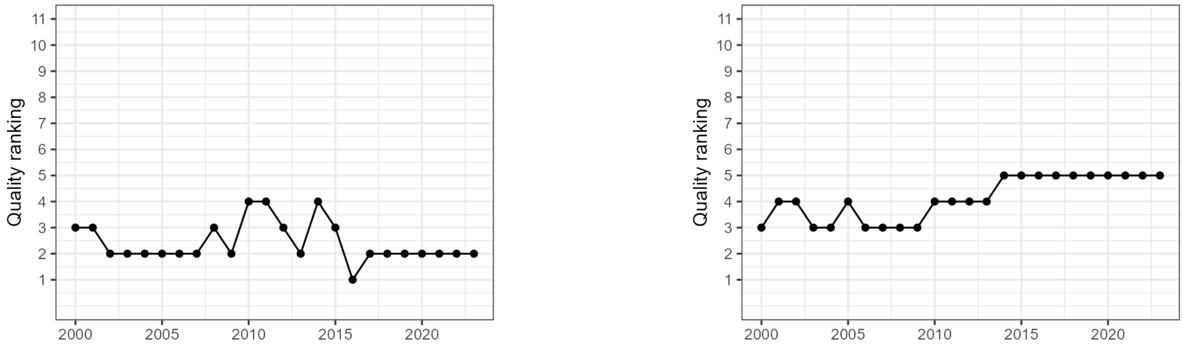
(a) Semiconductors **(b)** Resins



(c) Films & Sheets **(d)** Electronics & Battery Materials

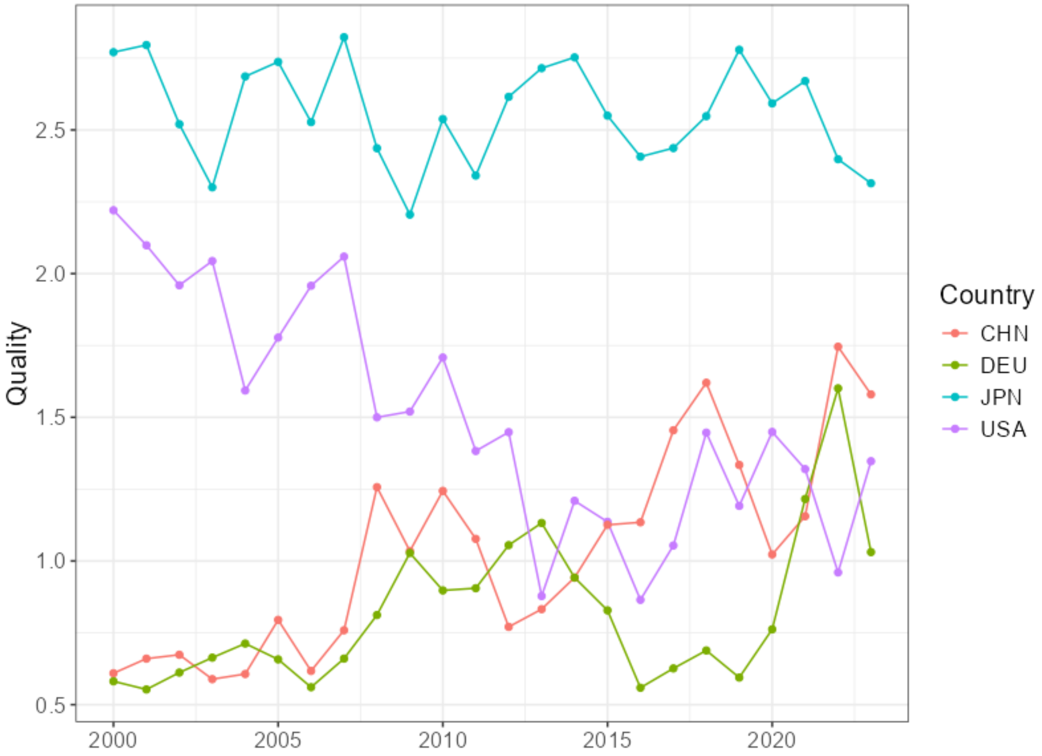


(e) Coating Agents, Paints & Inks **(f)** Additives

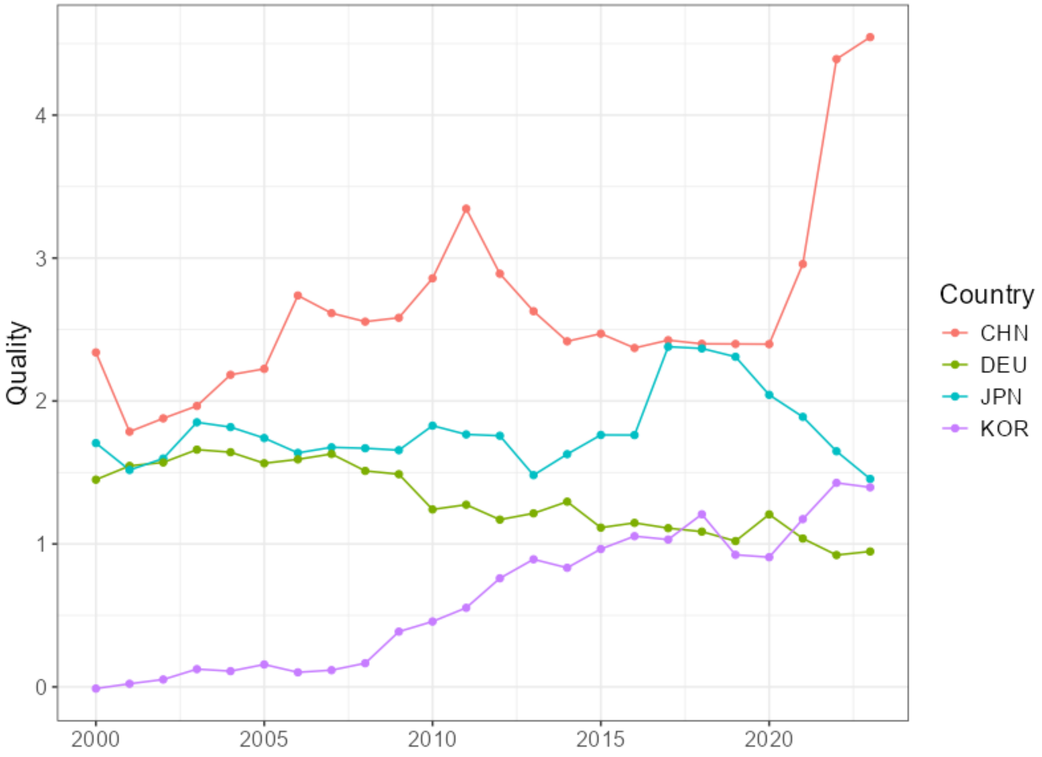


(g) Fillers & Slurries **(h)** Adhesives & Pressure-Sensitive Adhesives

Figure 6. Global ranking of export quality for each functional material group, Japan, 2000–2023.



(a) Semiconductors



(b) Electronics & Battery Materials

Figure 7. Quality estimate of Semiconductor and Electronics & Battery Materials for selected countries, 2000–2023.

5.4 Semiconductor Materials and Electronic Components and Battery Materials

As we have seen, the quality of exports in Japan's functional materials sector has been confirmed to be high for semiconductor materials, electronic components, and battery materials. Therefore, to examine the characteristics of these two categories more closely, we will select particularly distinctive items from each category and provide detailed explanations.

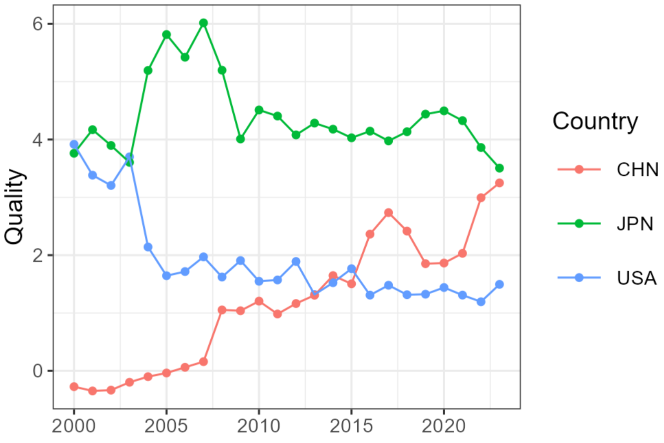
(a) Silicon Wafers (HS: 381800)

A silicon wafer is a thin, circular high-purity silicon plate that serves as the substrate for semiconductor chips. Silicon wafers themselves have poor electrical conductivity in their pure state, but adding specific substances (ions) enables electrical control. Utilizing this property, complex electrical circuits are etched onto the wafer, enabling it to function as a "semiconductor chip" that processes and stores information.

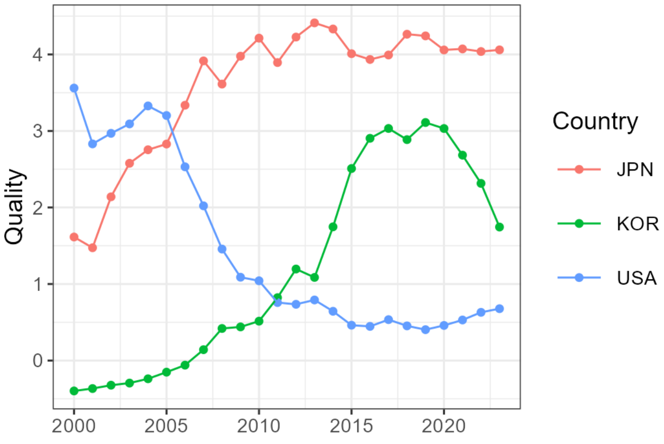
Japanese companies hold a very high global market share in the manufacturing of these silicon wafers, with the top two companies alone accounting for approximately 60% of the market. Japanese companies supply high-purity, high-flatness wafers essential for cutting-edge semiconductor manufacturing, where miniaturization continues to advance. This is evident from the trend in export quality shown in Figure 8a. Japan's silicon wafer exports consistently maintain a quality level more than twice that of China and the United States. This demonstrates the deep trust placed in Japanese suppliers by global semiconductor manufacturers and their ability to sustain high market share through long-term contracts.

(b) Photoresist (HS: 370710)

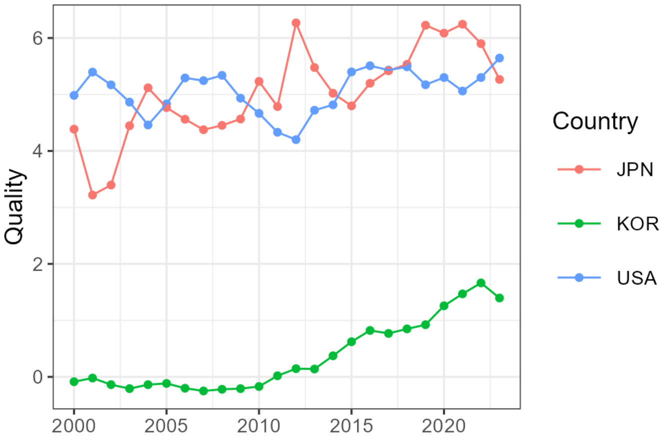
Figure 8b shows the quality of photo-resist exports. Japan's photoresist exports consistently maintain a quality level more than twice that of South Korea and the United States. Photoresist is a photosensitive liquid resin essential for the "photolithography process" in semiconductor manufacturing. After being applied to a silicon wafer, light is directed at



(a) Silicon Wafers (HS: 381800)



(b) Photoresist (HS: 370710)



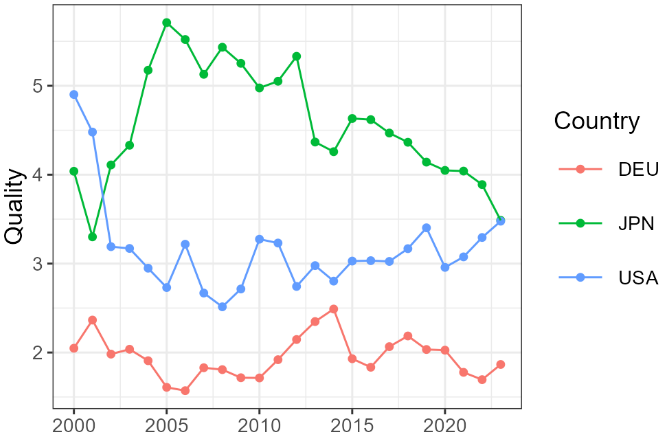
(c) Slurry (HS: 340590)

Figure 8. Quality of selected semiconductor materials for the top 3 countries.

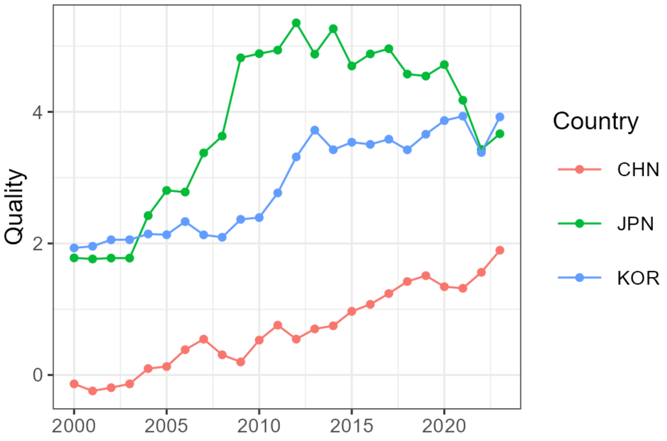
specific areas to induce a chemical reaction, and the circuit pattern is formed through a development process. Japanese companies dominate the photoresist market, with the top five firms holding approximately 90% (70-90%) of the global share. Their strength can be summarized in four key points. First, Japanese companies excel at close collaboration with their customers, the device manufacturers, achieving highly customized solutions (fine-tuning) to meet demands for nano-level miniaturization. Second, Japanese chemical manufacturers possess long-accumulated expertise in "ultra-high purity" processes that eliminate impurities to the utmost extent and in synthesis technologies for designing complex molecular structures. Third, companies supplying the main raw materials for photoresists—photosensitizers and polymers—are concentrated domestically, forming a robust "ecosystem." This depth of the supply chain enables stable high quality and rapid improvements. Fourth, photoresist development requires substantial investment and many years. Once adopted, switching to another company's product becomes difficult. Japanese companies have maintained top market share from the outset, creating high barriers to entry that prevent other countries from catching up.

(c) Slurry (HS: 340590)

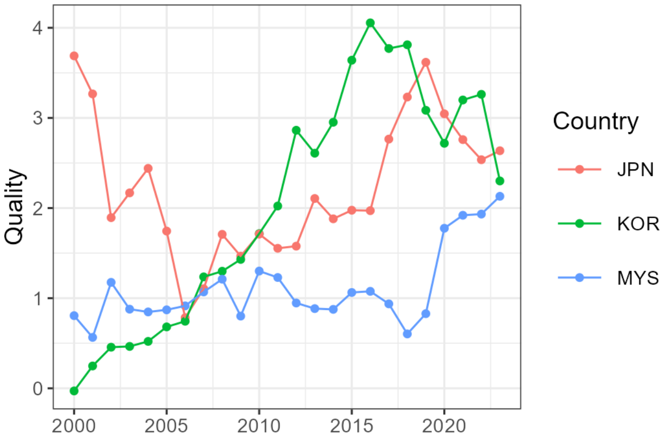
Japan's slurry exports maintain world-leading quality, competing with the United States (Figure 8c). Slurry is a complex mixture of abrasive particles and chemicals, requiring advanced "integral" technology to achieve flat, targeted removal at specific rates for particular films (copper, tungsten, oxide films, etc.). Japanese manufacturers possess long-standing expertise in this precise chemical control, supplying the world with slurries of exceptionally high quality.



(a) Metal-Coated Powder (HS: 381010)



(b) Insulating Film (HS: 392062)



(c) Flexible PCB Copper Foil (HS: 741011)

Figure 9. Quality of selected Electronic Components & Battery Materials for the top 3 countries.

5.5 Electronic Components and Battery Materials

(a) Metal-Coated Powder (HS: 381010)

Although the quality of Japan's metal-coated powder exports has gradually declined, it remains at a world-leading level (Figure 9a). Metal-coated powders are functional materials created by uniformly coating the surfaces of fine particles—such as resins, ceramics, and glass—with metals like copper, nickel, gold, or silver. In the metal-coated powder (conductive particles/fillers) market, Japanese companies have established a very strong position in global market share, backed by their high technological capabilities. This dominance stems from Japanese companies' advanced microfabrication technologies and Japan's unique collaborative manufacturing approach, which meticulously addresses customer requirements.

(b) Insulating Film for Electronic Materials (HS: 392062)

Japan holds the top position globally for insulating films used in electronic materials (Figure 9b). These thin-film materials primarily serve to insulate and protect between fine wiring in semiconductor packages and electronic substrates. As Figure 9(b) indicates, Japan holds the top position globally. Key factors include the presence of advanced chemical synthesis technologies accumulated over many years and close coordination with customers (customization capabilities).

(c) Flexible Printed Circuit Board Copper Foil (HS: 741011)

Figure 9c shows the export quality of rolled copper foil for flexible printed circuit boards (FPC). This material is a copper foil with high flexibility and durability, produced by thinly stretching copper ingots using rolling mills. It serves as wiring for FPCs (flexible printed circuits), particularly in automotive and mobile devices requiring bending and vibration, where it prevents cracking. As Figure 9(c) also shows, Japan has steadily increased its export volume and boasts an overwhelmingly dominant position globally. Three key factors underpin this: First, the presence of advanced metal processing technology. Rolled copper foil is manufactured by repeatedly thinning copper ingots using rollers. Japanese companies maintain unmatched precision in this process. Second, overwhelmingly superior high-purity technology. Japanese companies dominate overseas competitors in the technology to push the purity of raw copper to its absolute limits. Third is reliability built through years of research and development. Japanese companies closely collaborate with customers in cutting-edge fields like automobiles (electrification) and communications (5G/6G), continuously and steadily conducting R&D aligned with next-generation needs. This has resulted in establishing high barriers to entry while ensuring high reliability.

6 Conclusion

This paper examined the quality of Japan's exports of functional materials using detailed trade data. The findings from this study can be summarized in three points. First, the quality of exports measured based on export unit prices is generally consistent with the actual global market share of each product category. Second, Japan maintains a top-tier level globally in the quality of its exports, particularly for semiconductor materials and electronic components. Third, the export quality of other functional materials (coating agents & paints & inks, functional films & sheets, etc.) has remained stable over time and continues to hold high global rankings. Based on these analytical results, functional materials in Japan possess strong international competitiveness. To enhance the global competitiveness of Japanese industry, it is necessary to further improve export quality and strengthen international competitiveness. Several challenges remain in this research. The first is to conduct a more detailed examination of semiconductor materials, which boast world-leading quality among functional materials. The manufacturing process for semiconductor products is broadly divided into front-end and back-end processes, with numerous materials and equipment used in each stage. Scrutinizing the quality of Japan's exports of semiconductor materials and manufacturing equipment in each process, and how this compares internationally, is critically important for deeply considering the future of the semiconductor industry, positioned as a strategic material from a security perspective. The second is to reaffirm Japan's earning power by measuring the quality of exports across various industries. It is highly interesting to examine how well Japan maintains its international competitiveness in industries traditionally considered its strengths—such as transportation machinery, machine tools, and the chemical industry—and to identify promising product categories within each sector. Third, applying the analytical framework used in this study to the quality of exports in the service sector. While Japan has a significant import surplus in digital-related services, it has substantially increased exports in travel transactions (so-called inbound demand) and content transactions. Measuring the quality of exports in these areas implies exploring potential areas of comparative advantage for Japan and is highly significant.

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Appendix

The method for identifying specific functional materials is explained below. In this study, specific items were collected based on the "Compendium of Functional Materials 2011" (Processing Technology Research Society, 2011) (hereinafter referred to as "Compendium 2011")[13].

In the Compendium 2011, functional materials are categorized as: 1) Functional Resins, 2) Functional Films & Sheets, 3) Electronics components & Battery materials, 4) Functional Coatings, Paint & Inks, 5) Functional Additives, 6) Functional Fillers & Slurries, and 7) Functional Adhesives & Pressure-sensitive Adhesives and provides detailed introductions to the materials falling under each category. Furthermore, considering recent developments, this study establishes Semiconductor materials as an independent eighth category[14].

The number of materials in each category is as follows: 1) Functional Resins (67 commodities), 2) Functional Films & Sheets (160 commodities), 3) Electronics Components & Battery Materials (38 commodities), 4) Functional Coatings, Paints & Inks (47 commodities), 5) Functional Additives (46 commodities), 6) Functional Fillers & Slurries (27 commodities), 7) Functional Adhesives & Adhesive Agents (21 commodities), and 8) Semiconductor Materials (25 commodities).

Next, we use AI to search for the HS codes corresponding to each material. In some cases, multiple HS codes may be detected for a single material. Table A1 lists the corresponding HS codes for each category.

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[13] Compedium 2011 has not been revised since 2011.

[14] Some semiconductor materials overlap with items in the seven categories mentioned earlier.

Table A1. Functional Materials and Their Corresponding HS 6-Digit Codes

Group	HS 6-Digit Codes										
Semiconductors	280110	280130	280461	281111	281122	281290	283531	284700	284920	285219	285290
	290314	290346	290348	320790	340311	340590	350691	370710	370790	381400	381800
	382499	390750	391910	391990	392310	690990	710813	740819	760529	848690	854442
	902780										
Resins	285210	290250	291512	291612	291614	292390	292419	293190	293499	294200	320810
	320820	320890	320910	320990	321000	321410	330499	340241	340242	340290	350691
	380991	381230	381239	382499	390110	390120	390130	390140	390190	390210	390230
	390290	390311	390319	390320	390330	390390	390410	390421	390422	390430	390440
	390450	390469	390610	390690	390720	390729	390730	390760	390761	390770	390790
	390791	390799	390810	390890	390910	390920	390950	391000	391190	391390	391400
	391690	391990	392010	392020	392043	392049	392059	392063	392069	392092	392099
	392113	392190	392310	392620	392690	400219	400299	401693	540231	590210	701990
	854159										
Films & Sheets	321000	321200	321210	340250	382499	390330	391000	391400	391910	391990	392010
	392020	392030	392043	392049	392051	392060	392061	392062	392063	392069	392071
	392073	392079	392090	392092	392099	392112	392113	392119	392190	392321	392329
	392330	392350	392610	392690	480640	480890	481159	481930	481940	482110	482190
	482360	540231	540248	540263	540742	540743	550320	550390	551449	560310	560311
	560312	560313	560390	560391	560392	560691	580640	700530	760711	760719	760720
	761699	850511	854370	900120	900190	900290	940599				
Electronics & Battery Materials	250410	280530	280590	284190	321200	321511	321519	321590	350691	350699	380110
	381010	382499	390740	390791	390799	391000	391910	391990	392020	392043	392049
	392062	392069	392092	392093	392094	392190	702000	722090	741011	741012	741021
	741022	750610	760320	760711	760719	760720	850690	850790			

Table A1 (continued)

Group	HS 6-Digit Codes										
Coating Agents, Paints & Inks	290522	290619	320820	320890	320910	320990	321000	321410	321511	321519	321590
	340250	340391	340399	350400	350610	350691	350699	381231	381500	382490	382499
	390461	390469	390690	390730	390790	390791	390890	390950	391000	391400	391910
	391990	392020	392061	392099	392690	481099	481160				
Additives	281122	283327	290549	291439	291512	293190	293369	293399	293499	320649	320820
	320890	321000	340213	340219	340231	340239	340241	340250	340290	340311	340391
	340399	350610	350691	350699	380891	380894	380991	381111	381190	381220	381230
	381231	381239	382490	382499	390210	390490	390690	390720	390770	390950	391000
	391990	392690	540761	701400	854370						
Fillers & Slurries	250810	280300	281700	281810	282300	282590	283911	283919	283990	284190	284210
	284610	292690	320611	320890	320990	321000	321200	321290	350610	382490	382499
	390311	390610	390690	390720	390799	390920	392099	681510	690310	690390	700600
	701810	701820	701890	710610	900190						
Adhesives & Pressure-Sensitive Adhesives	320990	350610	350691	350699	382499	390210	390799	391000	391190	391910	391990
	392190										