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The effect of maximum residue limit standards on China's agri-food exports: A health perspective

Bo Chen | **Yiming Chen** | **Siqi Zhang**

School of Economics, Huazhong University of Science and Technology, Wuhan, China

Correspondence
Siqi Zhang, School of Economics, Huazhong University of Science and Technology, Wuhan, China.
Email: zhangsiqi@hust.edu.cn

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Abstract

This paper investigates the impact of maximum residue limit (MRL) standards of 2692 chemical substances regulated by 44 importing countries on China's agri-food exports, disaggregated at HS 8-digit product level over 2005–2021. We find that MRL standards for health-threatening chemical substances facilitate China's exports of agri-food products, while low-hazard MRLs impede trade. Furthermore, stricter MRL standards for health-threatening substances reduce the probability of exporting (extensive margin) while generating larger export values conditional on exporting (intensive margin). We also identify that the adjustments of fixed and variable compliance costs resulting from changes in health-threatening and low-hazard MRLs contribute to the heterogeneous responses on the extensive and intensive margins of exports.

KEYWORDS
agri-food trade, extensive margin, intensive margin, maximum residue limit

JEL CLASSIFICATION
F14, Q17, Q18

1 | INTRODUCTION

The impacts of agri-food standards on trade have become a focal point of a growing body of literature. Particularly, the maximum residue limit (MRL) of chemical substances is one of the most widely concerned agri-food standards (Ferro et al., 2015; Traoré & Tamini, 2022; Hejazi et al., 2022). MRL standards are mandatory public standards set by governments, stipulating the maximum allowable concentrations of chemical substances tested from imported and domestic agricultural products. Unlike the number of country-specific notifications to the World Trade Organization (WTO) on Sanitary and Phyto-Sanitary (SPS) and Technical Barriers to Trade (TBT) measures, MRL standards not only capture the prevalence of standards but also precisely measure their strictness (Fiankor et al., 2021). The numerical stringency of MRL standards has been utilized to gauge the impacts of agri-food standards on trade. While trade protectionism due to stringent MRL standards has been widely discussed, the potential trade-enhancing effect resulting from tightening health-threatening chemical substances has not received sufficient attention.[1]

The distinction between protectionism and necessary MRL standards that safeguard human health is intricate and inconclusive. The WTO recommends that member states defer to MRL standards set by Codex Alimentarius (hereafter Codex), a standard-setting organization jointly administered by the WTO and the World Health Organization (WHO). The Codex MRL standards serve as internationally recognized science-based guidelines for food safety. However, it is important to note that the implementation of these Codex MRL standards is not compulsory. Each country retains its sovereignty in establishing its own MRL standards based on risk assessment and the precautionary principle.[2]

Li and Beghin (2014) define that MRL standards stricter than the Codex as protectionist, while MRL standards less stringent than the Codex standard are viewed as anti-protectionist. Carrére et al. (2018) and Karemera et al. (2022) highlight that directly comparing the average MRL stringency at the product-substance level to the Codex standards is not an informative measurement for protectionism. Instead, they suggest that the emphasis should be placed on jointly considering the significance of chemical substances that entail long-term toxicological risks.[3]

In this study, we redefine the measurement of protectionism and necessary MRL standards by mapping two pieces of information: (i) whether specific chemical substances have been banned (smaller than 0.01 parts per million) by the European Union (EU) during the period of study (2005–2021); (ii) the acute toxicological risk effects classified by the WHO (2019 guideline).[4] The acute toxicological risk effects reported by the WHO are the scientific benchmark on which the Codex MRL standard is based. Due to the difference between the EU and WHO, there are four scenarios for a chemical substance: (i) both the EU bans the substance, and WHO classifies it as extremely/highly hazardous or moderately/slightly hazardous in the WHO guideline; (ii) the EU bans the substance, while WHO treats it as low-hazard; (iii) the EU does not ban the substance, and WHO treats it as low-hazard; (iv) the EU does not ban the substance, while WHO treats it as extremely/highly or moderately/slightly hazardous. The chemical substances in scenario (i) are undoubtedly health-threatening. Those in scenarios (ii) and (iii) are low-hazard substances because the WHO treated the substance as a low hazard to human health. Despite the EU prohibition, there is insufficient evidence to support that such prohibition is solely aimed at protecting human health rather than being influenced by protectionist motives (e.g., see Baylis et al., 2022). Additionally, we treat the chemical substances in scenario (iv) as low-hazard, which significantly differs from Li and Beghin (2014), who rely on the Codex standard based on the WHO classification.

Previous literature finds that importing countries with comparative advantages and higher tariffs on agri-food imports are inclined to adopt more lenient MRL standards (Carrére et al., 2018; Karemera et al., 2022). As such, chemical substances regarded as extremely/highly or moderately/slightly hazardous by the WHO while not banned by the EU are very likely to be low-hazard substances. In sum, in this paper, we treat the chemical substances in scenario (i) as health-threatening substances while the rest in the other scenarios are low-hazard ones.

This study investigates the impact of MRL standards on China's agri-food exports disaggregated at the HS 8-digit product level from 2005 to 2021. We manually match MRL standards for 2692 chemical substances across 44 importing countries with China's export data at the HS 8-digit level of 1459 agri-food products (HS chapters 02–24). The MRL database records MRL standards at the country-product-substance level and uses product descriptions to identify products. Therefore, we carefully screen and code product descriptions into China's HS 8-digit product code.[5] Our analysis addresses two issues: (i) assessing the impact of MRL standards for health-threatening and low-hazard chemical substances on China's agri-food exports, respectively; (ii) measuring the extensive margin of trade (probability of exporting) and intensive margin of trade (export values condition on trade occurrence) of health-threatening and low-hazard MRLs.

According to the report from the Food and Agriculture Organization of the United Nations (FAO), China is the second-largest developing country in terms of agricultural exports in 2020 ($76 billion).[6] In contrast, the MRL standards regulated by the Chinese government are relatively more lenient than the EU (Li & Beghin, 2014). The number of chemical substances applied to agri-food products in China is 78 in 2005, amounting to 511 in 2021 (Figure 1). As a comparison, the EU regulated MRL standards for 524 kinds of chemical substances in 2008, experiencing a 110% growth rate during 2014–2015 and reaching 1301 in 2021. Consumers' growing concern about food safety prompts the EU, which has been an agri-food standard leader for decades, to regulate more stringent MRL standards for health-threatening chemical substances.[7]

Consensus has not been reached regarding the impacts of MRL standards on extensive and intensive margins of trade, and differentiated chemical substances are considered as one of the sources that triggered the heterogeneous impacts to trade margins. Chen et al. (2008) find that a 10% decrease in Chlorpyrifos[8] MRL results in a decline of 3.2%, 2.1%, and 10% exports for garlic, onion, and spinach, respectively. Tran et al. (2012) posit that more stringent MRL standards for Chloramphenicol (CAP)[9] have negative effects on both the extensive and intensive margin of crustacean imports to the United States, Canada, Japan, and the EU-15 member countries. Xiong and Beghin (2012) investigated the impacts of the MRL standard for aflatoxin[10] on bilateral trade between fourteen European countries and nine African countries, concluding that neither extensive nor intensive margins were affected by the aflatoxin standard. Hejazi et al. (2022) find that more restrictive MRL standards for insecticides (herbicides) would negatively (positively) impact the US exports of fruits and vegetables to the EU and CPTPP member countries; tougher fungicides MRLs inhibit the United States from exporting fruits and vegetables to the EU while not significantly affecting US-CPTPP trade.

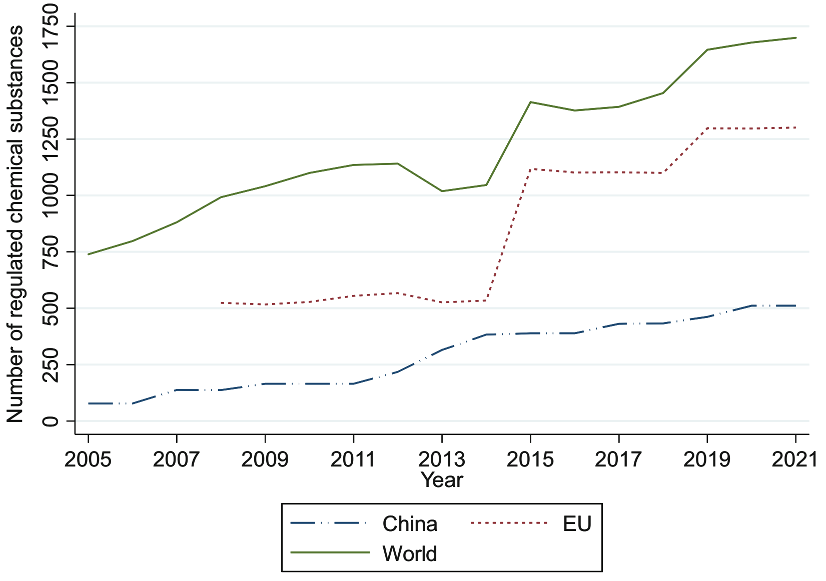

FIGURE 1 The number of chemical substances regulated by China, the European Union (EU), and the World during the period 2005–2021. [Colour figure can be viewed at wileyonlinelibrary.com]

To better understand the impacts of MRL on agri-food exports, we investigate the heterogeneous effects of health-threatening MRLs and low-hazard MRLs on the intensive and extensive margins of Chinese agri-food exports. Our analysis is based on China's export data at the HS-8 level and the corresponding MRL data. Our empirical findings reveal that health-threatening MRL standards increase the intensive margin but decrease the extensive margin. Conversely, low-hazard MRLs have the opposite effect on the intensive and extensive margins. We propose a theoretical interpretation using a heterogeneous firm model with endogenous fixed costs (referred to as the "spillover effect"), suggesting that MRL standards may impact fixed compliance costs and variable compliance costs differently, leading to heterogeneous effects on extensive and intensive margins.

Our contributions are threefold. First of all, we contribute to the existing literature by decomposing MRLs into health-threatening and low-hazard MRLs and investigating the heterogeneous impacts of China's agri-food exports. Our results reveal both a trade protectionism effect (mainly from low-hazard MRLs) and a trade-enhancing effect (mainly from health-threatening MRLs). Second, we manually create a unique dataset by matching MRLs with highly disaggregated HS-8 agri-food exports, allowing us to investigate the heterogeneous impacts of different types of MRLs on both extensive and intensive margins of exports. Third, we identify the channel through which the heterogeneous impacts on the intensive and extensive margins of exports result from changes in health-threatening and low-hazard MRL standards, that is, the heterogeneous effects on fixed and variable compliance costs induced by stricter health-threatening and low-hazard MRLs.

This article is structured as follows. Section 2 introduces the background. Section 3 specifies an econometric model to investigate the impact of MRL standards on China's agri-food exports and describes the data. Results are discussed in Section 4, along with heterogeneous analysis. Sensitivity of fixed and variable compliance costs to MRL standards are examined in Section 5. Section 6 concludes.

2 | BACKGROUND: CLASSIFICATION OF CHEMICAL SUBSTANCES BY THE EU AND WHO

The European Union and the World Health Organization regulate and classify chemical substances by evaluating various information concerning food safety standards. Generally, the WHO categorizes chemical substances into extremely/highly hazardous, moderately/slightly hazardous, and low-hazard substances based on acute toxicology to human health.[11] In addition to the scientific information regarding acute toxicology that poses a threat to human health, EU policymakers also consider the chronic and long-term toxicity on consumers' health.

The European Commission evaluates the effects of residues of chemical substances by collecting information on the Acceptable Daily Intake (ADI) and the Acute Reference Dose (ARfD).[12] The ADI index contributes to measuring chronic toxicity, and the ARfD value serves as a reference for acute toxicity with long and short-term intake. The European Food Safety Authority (EFSA) reiterated in its report submitted to the European Commission that the EFSA Pesticide Residues Intake Model (PRIMo) estimates both short-term and long-term consumer exposure to pesticide residues and identifies potential risks to consumers' health.[13]

Although the numerical stringency of MRL standards has been regulated by the EU and adjusted over time, restricting MRLs to 0.01 ppm (referred to as a "ban") is considered a strong signal of a substance's threat to human health. For example, in 2019, the EFSA reported that Chlorpyrifos, a widely-used pesticide, could potentially endanger children's neuron development due to its toxicology.[14] Consequently, the EU began to ban the use of Chlorpyrifos (tightening MRL for Chlorpyrifos to 0.01 ppm) in EU Regulation 2020/1085, which came into effect in July 2020.

Table 1 lists the four scenarios we used to classify chemical substances as health-threatening and low-hazard substances. The number of chemical substances in each of the four scenarios is provided, along with three examples of specific substances in each scenario. The salient distinction between our classification and that of Li and Beghin (2014) lies in the last scenario: the EU did not ban the substance, while the WHO treated it as either extremely/highly hazardous or moderately/slightly hazardous. The total number of chemical substances in the fourth scenario is 591.

Let's take bentazone, an herbicide applied to crops such as wheat, rice, and beans, as an example. The WHO classified bentazone as moderately hazardous, citing the potential for serious eye irritation and skin sensitization.[15] However, the EFSA reported that bentazone did not present genotoxic, carcinogenic, or neurotoxic potential, leading to no further scientific evidence on the long-term risk to human health.[16] Consequently, the EU adopted a relatively tolerant MRL standard for bentazone at 0.1 ppm on wheat, rice, and beans since 2008.

In addition, the Common Agricultural Policy (CAP) of the EU has subsidized wheat exporters since the 1980s with the primary objective of supporting farm income (Barassi & Ghoshray, 2007). The broadening of the CAP's objectives in recent decades has resulted in an average annual expenditure of 60 billion euros by the EU through a variety of measures (Biagini et al., 2020).[17] In 2021, the EU remains the largest producer of wheat in the world, with a production of 1.39 billion tons. This finding is consistent with the results reported by Biagini et al. (2023), which indicate that EU subsidies have increased farm productivity. The comparative advantage of wheat production, combined with remarkable subsidies for farmers, contributes to explaining the lenient MRL standard for bentazone regulated by the EU.

TABLE 1 Classification of chemical substances.

MRL types in this study	Four scenarios	Regulation by the EU	Classification by WHO based on acute toxicology	Decomposing health-threatening MRLs	Number and examples of chemical substances
Health-threatening MRLs	**Scenario 1**	Ban	Extremely/highly hazardous	**High-hazard MRLs**	39 (e.g., diphacinone, pentachlorophenol, and strychnine)
		Ban	Moderately/slightly hazardous	**Moderate-hazard MRLs**	131 (e.g., chlorpyrifos, lindane, and naled)
Low-hazard MRLs	**Scenario 2**	Ban	Low hazardous	**Low-hazard MRLs**	577 (e.g., bromacil, ethalfluralin, and zineb)
	Scenario 3	Not ban	Low hazardous		1354 (e.g., folpet, lenacil, and picloram)
	Scenario 4	Not ban	Extremely/highly hazardous; moderately/slightly hazardous		591 (e.g., bentazone, cypermethrin, and dicamba)

3 | METHODOLOGY

3.1 | Baseline specification

Following Anderson and van Wincoop (2003) and Anderson and Yotov (2016), we use a gravity model to estimate the impacts of MRL standards for health-threatening chemical substances and MRL standards for low-hazard substances on China's agri-food exports. The sector-level baseline specification is given as:

$$\begin{aligned} lnY_{jkt} &= \beta_0 + \beta_1 HealthThreatening_{jkt-1} + \beta_2 LowHazard_{jkt-1} \\ &\quad + \beta_3 \ln\left(1 + Number_{jkt-1}\right) + \beta_4 \ln\left(1 + Tariff_{jkt}\right) + \alpha_{jk} + \alpha_{kt} + \alpha_{jt} + \varepsilon_{jkt}, \end{aligned} \tag{1}$$

where ε_{jkt} is the error term.

where lnY_{jkt} is the logarithm value of China's annual exports of agri-food product k at HS 8-digit (under HS chapters 02–24) shipped to importing country j at time t.[18] $HealthThreatening_{jkt-1}$ and $LowHazard_{jkt-1}$ represent the average intensity of MRL stringency for health-threatening and low-hazard chemical substances regulated on agri-food product k at HS 8-digit level imposed by importing country j in the last year, respectively. In addition, we further control for the number of chemical substances with tougher-than-China MRL standards regulated on agri-food product k by importing country j at time $t-1$ (i.e., $\ln\left(1 + Number_{jkt-1}\right)$). This newly added control variable takes the advantage of our unique dataset with abundant categories of chemical substances and captures the time-varying MRL strictness at the importer-product level in the dimension of the number of restricted categories. The effectively applied tariff imposed by importing country j at the time t on agri-food product k is defined by $Tariff_{jkt}$.

Ferro et al. (2015) point out that importing considerable value of agri-food products from China and thereby intensifying the competition on domestic farmers might prompt importing countries to tighten the MRL standard and expand the number of tougher-than-China chemical substances. We used 1-year lagged values of three variables of interest ($HealthThreatening_{jkt-1}$, $LowHazard_{jkt-1}$, $\ln\left(1 + Number_{jkt-1}\right)$) to address the endogeneity issue resulting from reverse causality. Fiankor et al. (2021) posit that the omission of unobserved factors, such as demand for protectionism and food safety as well as shocks related to the domestic supply chain, that might simultaneously correlate with agri-food standards and China's agricultural exports leads to biased estimates. We address the omitted-variable-bias concern by using importer-product (α_{jk}), product-year (α_{kt}), and importer-year (α_{jt}) fixed effects to capture the unobserved confounding factors.

Following Li and Beghin (2014), we employ the nonlinear exponential index of MRL restrictiveness as the following:

$$\begin{aligned} HealthThreatening_{jkt-1} &= \frac{1}{N_s}\left(\sum_{s \epsilon N_{kt-1}} \exp\left(\frac{MRL\_CHINA_{skt-1} - MRL\_IMPORTER_{skt-1}}{MRL\_CHINA_{skt-1}}\right)\right), \\ LowHazard_{jkt-1} &= \frac{1}{N_{s'}}\left(\sum_{s' \epsilon N_{kt-1}} \exp\left(\frac{MRL\_CHINA_{s'kt-1} - MRL\_IMPORTER_{s'kt-1}}{MRL\_CHINA_{s'kt-1}}\right)\right) \end{aligned} \tag{2}$$

where MRL_CHINA_{skt-1} and $MRL\_IMPORTER_{skt-1}$ refer to the MRL standard for health-threatening chemical substances regulated on agri-food product k by the exporter (i.e. China) and the importer j at time $t-1$, respectively. N_{kt-1} denotes the set of health-threatening chemical substances at the product-year level; N_s is the number of health-threatening chemical substances and $N_{s'}$ is the number of low-hazard chemical substances. At the domain $(0, e \approx 2.718]$, the restrictiveness index captures the average intensity of the importer's MRL stringency over health-threatening (low-hazard) chemical substances regulated on the agri-food product k at time $t-1$ relative to exporter China.[19]

The prevalence of consumer awareness of agri-food safety in developed and developing countries underscores the common understanding that the use of extremely or highly hazardous substances in agricultural production should be minimized. To further identify heterogeneous trade effects of MRL standards, we decompose the health-threatening MRLs into high-hazard (extremely or highly hazardous substances classified by the WHO and simultaneously banned by the EU) and moderate-hazard (moderately or slightly hazardous substances classified by the WHO and simultaneously banned by the EU) MRLs.[20] The baseline regression can be revised as:

$$lnY_{jkt} = \beta_0 + \beta_1 HighHazard_{jkt-1} + \beta_2 ModerateHazard_{jkt-1} + \beta_3 LowHazard_{jkt-1} + \beta_4 \ln\left(1 + Number_{jkt-1}\right) + \beta_5 \ln\left(1 + Tariff_{jkt}\right) + \alpha_{jk} + \alpha_{kt} + \alpha_{jt} + \varepsilon_{jkt}, \quad (3)$$

where $HighHazard_{jkt-1}$, $ModerateHazard_{jkt-1}$, and $LowHazard_{jkt-1}$ represent the average intensity of MRL stringency for high-hazard (extremely or highly deleterious), moderate-hazard (moderately or slightly pernicious), and low-hazard chemical substances regulated on agri-food product k imposed by importing country j at time $t-1$, respectively.[21]

The estimations of Equations (1) and (3) are implemented by Poisson pseudo-maximum likelihood (PPML). PPML estimation provides unbiased estimates of heteroskedasticity by modeling the disturbance term as generated from a Poisson distribution.[22] Santos Silva and Tenreyro (2011) demonstrate that the PPML method applies well to trade data dominated by zero values.

3.2 | Data

To capture the impacts of MRL standards on China's agri-food exports, we utilize the MRL database sourced from Homologa.[23] The Homologa MRL database offers MRL standards for 2692 chemical substances across 75 importing economies applied to 1459 agri-food products (HS chapters 02–24). However, agri-food products in the Homologa database are described in the text and have not been coded into HS 8-digit product codes. We manually match product descriptions with HS 8-digit codes, and the importer-product-substance level of MRL standards is then matched with China's export data at the HS 8-digit product level.[24]

The total number of observations after matching is 5,505,110, and the missing values account for 0.1%. We replace the missing values with default values adopted by each government in real practice.[25] If there are no default values regulated by that government, we substitute the most tolerant MRL standard regulated by other importing countries for the missing MRL standards.[26] We focus on the trade effects of MRL standards for health-threatening and low-hazard chemical substances, indicating that not all of the agri-food products would be investigated. The agri-food products at HS 8-digit level are selected if MRL standards have been regulated by at least 30% of importing countries and at least one MRL standard for health-threatening chemical substances was regulated on the agri-food product.[27] After applying these two selection standards, we obtained 520 agri-food products across 44 importing countries, with 170 kinds of health-threatening substances and 2522 kinds of low-hazard substances. Notably, the export values of the agri-food products under investigation from these 44 importing countries account for 68.3% of exports of these products shipped from China to the world. Finally, our final sample includes 85,874 observations, of which 75.9% observations are zero trade flow. Decomposing the health-threatening MRLs into high-hazard and moderate-hazard MRLs results in a dataset with 476 agri-food products across 42 importing countries.[28] The export values of these agri-food products account for 58.2% of the total exports of these products shipped from China to the world. This sample data consists of 63,238 observations, with 77.8% of zeros.

Tariff data are sourced from the UNCTAD Trade Analysis Information System (TRAINS) and the WTO's Integrated Database (IDB). Real GDP per capita is extracted from the World Bank's World Development Indicator (WDI) database. Gravity variables such as distance, contiguity, and common language are taken from the Centre d'Etudes Prospective et d'Informations Internationales (CEPII). Table 2 presents the descriptions of independent variables and summary statistics.

The mean value of the restrictiveness index for health-threatening MRLs and low-hazard MRLs are 1.43 and 1.22, respectively. Values higher than one suggest that MRL standards regulated by importing countries are on average more stringent than China, and health-threatening MRLs are on average stricter than low-hazard MRLs within the same product.[29]

4 | RESULTS

4.1 | The impacts of MRL standards on China's agri-food exports

Table 3 reports the estimated impacts of MRL standards for health-threatening and low-hazard chemical substances on China's agri-food exports. Column (1) and Column (2) show the results of Model 1 based on Equation (1) and the results of Model 2 based on Equation (3), respectively. In Column (1), we find that the coefficient of $HealthThreatening_{jkt-1}$ is 0.247, implying that the export values of China's agricultural exports would increase by 24.7% if the MRL restrictiveness index for health-threatening substances was tightened by one unit in the last period. Alternatively speaking, a 10% increase in the importer's average MRL stringency for health-threatening chemical substances at the mean in last year[30] would induce a 3.53% $\left(\frac{24.7\%}{(1/1.43)*100\%} * 10\%\right)$ increase in current-year export values of China's agri-food products. The estimate of the MRL restrictiveness index for low-hazard substances is not significant, suggesting that MRL standards for low-hazard substances do not significantly affect China's agri-food exports. The negative and significant estimation of $\ln(1 + Number_{jkt-1})$ indicates that the 10% increase in the number of tougher-than-China MRL standards in the last period at the mean is associated with a 2.1% reduction in China's agri-food exports in the current period. The coefficient of $\ln(1 + Tariff_{jkt})$ is negative and significant, suggesting that a 1% increase in tariff reduces the export values of China's agri-food products by 11.6%.

Results in column (2) show that stricter MRL standards for high-hazard substances have no significant effects on trade in the following period, which is consistent with our expectation due to the common acknowledgment of protecting human health by exporters and importers. A 10% more stringent MRL standard for moderate-hazard substances increased export values of China's agri-food products in the following period by 4.37%[31]; while a 10% tougher MRL standard for low-hazard substances last year reduced China's agri-food exports this year by 2.73%.[32]

TABLE 2 Description of independent variables and summary statistics.

Variable	Description	Obs	Mean	SD	Min	Max
$HealthThreatening_{jkt-1}$	The average intensity of MRL stringency for health-threatening substances regulated on product k by country j at time $t-1$	85,874	1.430	0.356	0	2.709
$HighHazard_{jkt-1}$	The average intensity of MRL stringency for high-hazard substances regulated on product k by country j at time $t-1$	65,471	1.308	0.384	0	2.718
$ModerateHazard_{jkt-1}$	The average intensity of MRL stringency for moderate-hazard substances regulated on product k by country j at time $t-1$	83,641	1.475	0.390	0	2.709
$LowHazard_{jkt-1}$	The average intensity of MRL stringency for low-hazard substances regulated on product k by country j at time $t-1$	85,874	1.218	0.528	0	2.718
$Number_{jkt-1}$	The number of substances with tougher-than-China MRLs regulated on product k by country j at time $t-1$	85,874	138.662	146.612	0	525.000
$Tariff_{jkt}$	The effectively applied tariff imposed by country j applied to product k at time t (%)	85,874	10.732	47.966	0	3000.000
$GDPPC_{jt}$	The GDP per capita in country j at time t in constant 2015 U.S. dollars	85,874	34649.616	23180.026	1087.583	108351.45
$Dist_j$	The distance between China and importing country j	85,874	7933.005	3357.374	955.651	19297.500
$Contig_j$	Dummy variable equal to 1 if China and country j are contiguous	85,874	0.049	0.216	0	1
$ComLang_j$	Dummy variable equal to 1 if China and country j share a common language	85,874	0.034	0.182	0	1

TABLE 3 Impacts of MRL standards on China's agri-food exports: PPML.

	(1) model 1	(2) model 2	(3) developed	(4) developing	(5) developed	(6) developing	(7) exclude EU	(8) exclude EU	(9) 2008–2021	(10) 2008–2021
$HealthThreatening_{jkt-1}$	0.247** (0.101)		−0.007 (0.095)	−0.048 (0.153)			0.225** (0.111)		0.324*** (0.105)	
$HighHazard_{jkt-1}$		−0.169 (0.153)			−0.054 (0.194)	0.111 (0.693)		−0.160 (0.202)		−0.154 (0.169)
$ModerateHazard_{jkt-1}$		0.296* (0.159)			0.370** (0.175)	0.785 (1.939)		0.012 (0.220)		0.418** (0.169)
$LowHazard_{jkt-1}$	−0.056 (0.059)	−0.224*** (0.062)	−0.110*** (0.036)	0.097 (0.161)	−0.194*** (0.067)	−0.508*** (0.143)	−0.045 (0.067)	−0.220*** (0.075)	−0.054 (0.063)	−0.247*** (0.069)
$\ln\left(1 + Number_{jkt-1}\right)$	−0.211*** (0.079)	−0.407*** (0.092)	−0.110*** (0.036)	0.097 (0.161)	−0.571*** (0.097)	2.210*** (0.365)	−0.230** (0.092)	−0.413*** (0.117)	−0.217** (0.086)	−0.408*** (0.098)
$\ln\left(1 + Tariff_{jkt}\right)$	−0.116*** (0.032)	−0.065 (0.063)	−0.405*** (0.068)	0.449* (0.248)	−0.068 (0.070)	0.162 (0.248)	−0.101*** (0.034)	−0.013 (0.071)	−0.118*** (0.032)	−0.053 (0.064)
Observations	38,023	26,052	31,628	5276	23,726	1314	20,382	10,175	34,731	23,984
R-squared	.887	.886	.892	.869	.880	.900	.883	.883	.886	.884
Importer-product FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Product-year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Importer-year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: The dependent variable in Columns (1)–(2) is the logarithm of China's annual export value of agri-food product k shipped to importer j at time t. Model 1 measures the impact of health-threatening and low-hazard MRLs on China's agri-food exports. In Model 2, we decompose health-threatening MRLs into high-hazard and moderate-hazard MRLs. The dependent variable in Columns (3) and (5) is the logarithm of China's agri-food exports shipped to developed countries; the dependent variable in Columns (4) and (6) is the logarithm of China's export values of agri-food products shipped to developing countries. Columns (7)–(8) exclude the EU market from China's destination markets; Columns (9), (10) focus on the period of study from 2008 to 2021 during which the EU harmonized MRLs. Importer-product (HS-6), product-year, and importer-year fixed effects are included. Standard errors are in parentheses and are clustered by importer-product-year. *, **, and *** denote $p < .10$, $p < .05$, and $p < .01$, respectively.

This finding is novel because existing literature finds either a negative impact of MRL standards on trade (Wei et al., 2012; Winchester et al., 2012) or a positive or insignificant trade effect of MRL standards (Shingal et al., 2021; Xiong & Beghin, 2012).[33] By decomposing chemical substances into health-threatening (i.e., high-hazard, moderate-hazard), and low-hazard substances, we identify the positive trade effects of tightening moderate-hazard MRLs and the negative trade effects of more restrictive low-hazard MRLs. The coefficient of $\ln\left(1 + Number_{jkt-1}\right)$ in Model 2 is negative and significant with a greater magnitude relative to the estimate in Model 1. The estimates of $\ln\left(1 + Tariff_{jkt}\right)$ in Model 2 show that the tariff did not significantly impact China's agri-food exports, which is not consistent with the estimate shown in Model 1. Carrére et al. (2018) and Karemera et al. (2022) find that lower tariff is highly likely to coexist with more restrictive MRL standards. As such, lower tariffs might be highly correlated with stricter high- and moderate-hazard MRLs, and the coefficient of tariff is thereby absorbed by changes in high- and moderate-hazard MRLs.

In Columns (3)–(6) of Table 3, we present the results when the importers are developed countries and developing countries, respectively. We find that more stringent MRL standards for health-threatening substances do not significantly affect China's agri-food exports shipped to either developed or developing countries. Tightening low-hazard MRLs by developed countries induces a trade-impeding effect on China's agri-food exports; while no significant effect has been found from developing countries. When decomposing health-threatening MRLs into high- and moderate-hazard MRLs, we find that developed countries would expand import values of agri-food products from China resulting from more restrictive MRL standards for moderate-hazard substances. Developing countries are not sensitive to changes in either high- or moderate-hazard MRLs whereas are keener on low-hazard MRLs relative to developed countries. The magnitude of the trade-impeding effect of low-hazard MRLs is 5.11% larger for developing countries relative to developed countries.[34]

We examine the impacts of health-threatening (high- and moderate-hazard) MRL standards on China's agri-food exports under two specific situations: (i) we exclude the EU market from China's destination markets and merely focus on the impacts of MRLs on China's exports to non-EU countries; (ii) we focus on the period of study from 2008 to 2021 since the EU harmonized MRL standards in 2008. Columns (7)–(8) in Table 3 show the results under the first situation, suggesting that non-EU importing countries are not sensitive to the changes in high- and moderate-hazard MRLs while shrinking import values of agri-food products from China induced by stricter MRL standards for low-hazard substances. The magnitudes of coefficients are similar to the results shown in Column (2). Results of Columns (9)–(10) indicate that whether the starting year of the period of study is before or after the EU's harmonization of MRL standards does not make a big difference, we also find a trade-facilitating effect of tightening moderate-hazard MRLs and a trade-impeding effect of a more stringent low-hazard MRLs. The magnitudes of the trade effects are slightly greater than those shown in Column (2).

In Table 4 we report the results when using the WHO classification of MRL standards for health-threatening (high-hazard, moderate-hazard) and low-hazard chemical substances. Unlike the classification used in Table 3, the health-threatening substances in Columns (1)–(2) of Table 4 include the substances recognized as high- or moderate hazards by the WHO while not forbidden by the EU. Results of Column (1) show that MRL standards for both health-threatening and low-hazard substances defined by WHO impede China's agri-food exports, and the magnitude of negative coefficients is larger for health-threatening substances relative to low-hazard substances. In Column (2), we find that the trade-restricting effect is the largest for moderate-hazard

TABLE 4 Impacts of MRL standards classified by WHO or EU on China's agri-food exports: PPML.

	MRLs classified by WHO Model 1 (1)	MRLs classified by WHO Model 2 (2)	MRLs banned (or not banned) under EU regulation Model 1 (3)	MRLs banned (or not banned) under EU regulation Model 1 China – EU (4)
$HealthThreatening_{jkt-1}$	−1.078*** (0.180)		1.146*** (0.409)	−0.340 (0.306)
$HighHazard_{jkt-1}$		−0.206** (0.082)		
$ModerateHazard_{jkt-1}$		−1.534*** (0.291)		
$LowHazard_{jkt-1}$	−0.168*** (0.047)	−0.195*** (0.039)	−3.868*** (0.525)	1.762*** (0.618)
$\ln\left(1 + Number_{jkt-1}\right)$	0.138 (0.088)	0.280*** (0.090)	0.330*** (0.114)	−0.140 (0.095)
$\ln\left(1 + Tariff_{jkt}\right)$	−0.069** (0.029)	−0.112*** (0.037)	−0.084** (0.040)	−1.753*** (0.453)
Observations	46,928	40,015	48,289	14,990
R-squared	.885	.881	.883	.865
Importer-product FE	Yes	Yes	Yes	Yes
Product-year FE	Yes	Yes	Yes	Yes
Importer-year FE	Yes	Yes	Yes	Yes

Note: The dependent variable in columns (1)–(3) is the logarithm of China's annual export value of agri-food product k shipped to importer j at time t. The dependent variable in column (4) is the logarithm of China's annual export value of agri-food product k shipped to EU member countries at time t. Model 1 measures the impact of health-threatening and low-hazard MRLs on China's agri-food exports. In model 2, we decompose health-threatening MRLs into high-hazard and moderate-hazard MRLs. Columns (1)–(2) uses WHO classification to identify health-threatening and low-hazard MRLs. Columns (3)–(4) classify chemical substances into two groups identified by whether the substances have been banned or not banned by the EU. Importer-product (HS-6), product-year, and importer-year fixed effects have been included. Standard errors are in parentheses and are clustered by importer-product-year. *, **, and *** denote $p < .10$, $p < .05$, and $p < .01$, respectively.

substances, followed by high-hazard and low-hazard substances. The discrepancies of the corresponding results in Table 3 and Table 4 imply that the high- and moderate-hazard substances classified by the WHO while not prohibited by the EU contribute to the trade-reducing effect of health-threatening MRLs.

We also classify chemical substances into health-threatening and low-hazard groups identified by whether the substances have been banned by the EU. We assume the motivation for the EU's ban on specific chemical substances applied to agri-food products to protecting human health not to conducting protectionism. In Table 4, Column (3) applies to China's agri-food exports to all the trading partners, and Column (4) focuses merely on China–EU trade. We find that MRL standards for EU-banned substances ("health-threatening" MRLs here) encourage more agri-food exports from China to the importing countries, while stricter MRL standards for substances that have not been prohibited by the EU ("low-hazard" MRLs here) reduce China's exports of agri-food products. The results are similar to those in Table 3 with a greater magnitude of trade effects. Results in Column (4) suggest that MRL standards for EU-banned substances do not significantly affect China's exports to the EU, and stricter MRL standards for substances that have not been prohibited by the EU generate more EU imports from China. These results are consistent with our argument that China's producers have exerted more concern on food safety in recent decades. For example, Sun et al. (2021) find that China's evolving food safety standards have a negative impact on import values from countries with lower food safety standards, and trade-impeding effects are mainly attributed to import refusals due to safety and hygiene reasons.

4.2 | Extensive and intensive margin of trade

Table 5 reports the results of the Heckman selection model (Heckman, 1979; detailed in Appendix A).[35] The results of Columns (1)–(2) in Table 5 imply that tightening MRL standards for health-threatening substances decreases the extensive margin of exports while increasing the intensive margin of exports. On the contrary, stricter MRL standards for low-hazard substances improve the likelihood of China's exporting agri-food products to international markets; while reducing export values conditional on producers' export decisions.

The different changes in fixed and variable compliance costs induced by more stringent MRLs might help explain the opposite effects on the extensive and intensive margin of exports resulting from stricter health-threatening and low-hazard MRL standards. The propositions in Chaney (2008) and Krautheim (2012) suggest that the intensive margin of trade is negatively associated with the changes in variable compliance costs and the extensive margin of trade is negatively affected by the changes in both variable and fixed compliance costs. Therefore, we posit the empirical results of the Heckman selection model that the positive and significant impacts of health-threatening MRLs on the intensive margin of exports are associated with a decrease in variable compliance costs, and the significantly negative impacts of low-hazard MRLs on the intensive margin of exports are attributed to increase in variable compliance costs. The negative impacts of health-threatening MRLs on the extensive margin of exports indicate that more restrictive MRL standards of health-threatening substances are highly likely to generate higher fixed compliance costs. On the contrary, the positive impacts of low-hazard MRLs on the extensive margin of exports imply that tougher low-hazard MRL standards are supposed to give rise to lower fixed compliance costs.

The fixed compliance costs that are related to MRLs consist of investment in new production techniques or adjustments and employee training expenses; the variable compliance costs are

TABLE 5 Extensive and intensive margin of trade: Heckman selection model.

	Model 1		Model 2		Model 1		Model 1		Model 2		Model 2	
					Developed		Developing		Developed		Developing	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	EM	IM	EM	IM	EM	IM	EM	IM	EM	IM	EM	IM
Health Threatening $_{jkt-1}$	−0.058***	0.333***			−0.099***	0.197**	0.196***	0.498***				
	(0.016)	(0.062)			(0.020)	(0.079)	(0.026)	(0.143)				
$HighHazard_{jkt-1}$			0.068***	0.211***					0.135***	0.298***	−0.157***	−0.483**
			(0.017)	(0.076)					(0.020)	(0.098)	(0.039)	(0.205)
Moderate Hazard $_{jkt-1}$			−0.050**	0.140					−0.031	0.175**	0.328***	0.500
			(0.021)	(0.085)					(0.023)	(0.088)	(0.058)	(0.355)
$LowHazard_{jkt-1}$	0.054***	−0.124***	0.034**	−0.040	0.046***	−0.179***	−0.020	0.118	−0.035**	−0.173***	0.031	0.534***
	(0.010)	(0.040)	(0.014)	(0.051)	(0.013)	(0.046)	(0.017)	(0.073)	(0.016)	(0.059)	(0.029)	(0.112)
$\ln\left(1+Number_{jkt-1}\right)$	−0.127***	0.092**	−0.043***	0.294***	−0.134***	0.061	−0.136***	0.020	−0.071***	0.265***	−0.071**	0.514***
	(0.005)	(0.038)	(0.008)	(0.033)	(0.006)	(0.049)	(0.012)	(0.085)	(0.008)	(0.043)	(0.028)	(0.137)
$\ln\left(1+Tariff_{jkt}\right)$	−0.058***	−0.017	−0.067***	−0.105***	−0.035***	−0.036	−0.128***	−0.204***	−0.065***	−0.107***	−0.103***	−0.310***
	(0.005)	(0.025)	(0.006)	(0.035)	(0.006)	(0.027)	(0.010)	(0.074)	(0.007)	(0.040)	(0.019)	(0.098)
$\ln\left(GDPPC_{jt}\right)$	0.210***	−0.111*	0.198***	0.158*	0.186***	0.250***	0.655***	0.209	0.157***	0.215**	0.693***	0.904*
	(0.007)	(0.065)	(0.010)	(0.088)	(0.011)	(0.088)	(0.023)	(0.371)	(0.012)	(0.094)	(0.039)	(0.526)
$\ln\left(Dist_j\right)$	−0.405***	−0.552***	−0.437***	−0.789***	−0.353***	−0.735***	−0.922***	−0.664	−0.459***	−0.787***	−0.227***	−2.252***
	(0.010)	(0.112)	(0.012)	(0.160)	(0.011)	(0.122)	(0.029)	(0.513)	(0.013)	(0.193)	(0.086)	(0.456)
$Contig_j$	0.511***	0.327*	0.644***	1.195***	*Omitted*	*Omitted*	0.191***	0.409**	*Omitted*	*Omitted*	0.848***	1.654**
	(0.027)	(0.170)	(0.038)	(0.278)			(0.033)	(0.169)			(0.073)	(0.680)
$ComLang_j$	0.881***	−0.382***	1.140***	−0.452*	0.652***	−0.730***	1.056***	0.125	0.891***	−0.671***	2.484***	1.349
	(0.059)	(0.129)	(0.083)	(0.249)	(0.066)	(0.128)	(0.138)	(0.242)	(0.089)	(0.231)	(0.274)	(1.001)
$ComLang_j * Product_k$	−0.057***		−0.060***		−0.046***		−0.089***		−0.051***		−0.126***	
	(0.006)		(0.008)		(0.006)		(0.014)		(0.009)		(0.022)	
IMR_{jkt}		−1.241***		−1.012**		−0.625		−0.919		−1.025*		0.689
		(0.380)		(0.501)		(0.478)		(0.727)		(0.586)		(0.954
Observations	85,874	20,658	63,238	14,026	70,444	17,114	15,430	3544	57,597	12,748	5641	1278
Product-year FE	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	No

Note: The dependent variable in the EM equation is a binary variable, taking the value of one if positive exports of agri-food product k at HS 8-digit level from China to importing country j at time t is observed; zero otherwise. The dependent variable in the IM equation is the logarithm of the positive export value of agri-food product k shipped from China to importing country j at time t. Model 1 refers to the specification used to measure the impact of health-threatening and low-hazard MRLs on China's agri-food exports. In Model 2, we decompose MRLs into high-hazard, moderate-hazard, and low-hazard MRLs. The dependent variables in Columns (5), (6) and (9), (10) are dependent variables in the EM and IM equations shipped to developed countries, respectively. The dependent variables in Columns (7), (8) and (11), (12) are dependent variables in the EM and IM equations shipped to developing countries, respectively. We interact HS 2-digit chapters with the indicator for common language between country pairs to construct an exclusion restriction that accounts for heterogeneity in products. The product-year fixed effects are included in Columns (1)–(6), and Columns (9), (10), whereas not included in the model of developing countries due to data limitations. The product fixed effects are defined for each two-digit product category of k to avoid multicollinearity. Standard errors are in parentheses. *, **, and *** denote $p < .10$, $p < .05$, and $p < .01$, respectively.

composed of input costs, costs related to quality control, and testing techniques in the wake of changes in MRL standards.

The negative relationship between distance and extensive as well as intensive margin of exports has been confirmed. Sharing a common border and common language encourages more producers to participate international agri-food market, consistent with our predictions. The estimates of real GDP per capita in Columns (1)–(2) indicate that the probability of exporting agri-food products from China to a large economy is higher while the values of exports are relatively smaller than those shipped to a small economy.

Results of Columns (5)–(8) show the extensive and intensive margins of exports resulting from more restrictive MRL standards for health-threatening and low-hazard substances in developed and developing countries. The results in Columns (5)–(6) are similar to those reported in Columns (1)–(2). The extensive and intensive margin of exports in developing countries seems sensitive to stricter health-threatening MRLs.

In Model 2, we decompose the health-threatening MRLs into high- and moderate-hazard MRLs, results are shown in Columns (3)–(4). We find that stricter moderate-hazard MRLs induce negative impacts on the extensive margin of exports, while more restrictive MRL standards for low-hazard substances lead to positive impacts on the extensive margin. We posit that the negative impacts of health-threatening MRLs on the extensive margin of exports are mainly attributed to the tougher moderate-hazard MRLs. Not surprisingly, we find positive and significant impacts of high-hazard MRLs on both extensive and intensive margins. This finding confirms our conjecture that as the high-hazard substances are tightened both exporters and importers might reduce the uncertainty[36] facing them and therefore increase both the likelihood of exporting and the value of exports due to tougher high-hazard MRLs.

Columns (9)–(12) show the results of Model 2 in developed and developing countries. It is interesting to find that both extensive and intensive margins of exports declined when the developed countries tightened low-hazard MRLs. On the contrary, tightening high-hazard MRLs entailed a decrease in both the extensive and intensive margins of exports to developing countries. This finding is consistent with the predictions of Li and Beghin (2014) who conclude that four out of the top five economies in terms of protectionism are developed countries and regions.

5 | SENSITIVITY OF FIXED AND VARIABLE COMPLIANCE COSTS TO MRL STANDARDS

In Section 4.2 we argue that the changes in health-threatening and low-hazard MRL standards would have heterogeneous effects on the intensive and extensive margins thanks to the different impacts of those changes on fixed and variable costs. To support our argument, we further explore whether more stringent health-threatening and low-hazard MRL standards impact the extensive and intensive margins through the changes in MRL-related fixed and variable compliance costs. We extract the data concerning Chinese farmers' adjustment of fixed and variable compliance costs related to MRL standards from a Chinese nationwide survey of costs and revenues of agricultural products published by China Statistics Press. On the basis of this new data set, we compared the results of two empirical specifications: (i) 2SLS regressions on health-threatening and low-hazard MRL standards using Chinese farmers' fixed and variable compliance costs as dependent variables; and then investigate the impacts of fixed and variable compliance costs on the probability of exporting (EM) and export value conditional on export decision (IM); (ii)

Replicating Table 5 using Heckman selection model to explore the impacts of MRLs on EM and IM, and predicting the changes in fixed and variable compliance costs induced by stricter health-threatening and low-hazard MRL standards.

The Chinese nationwide survey of costs and revenues of agricultural products (CRAP) is a series of annual-published books edited by the Price and Cost Investigation Center under the National Development and Reform Commission of China. The CRAP data contains Chinese farmers' average costs and revenues for each unit of agricultural land,[37] based on more than 80 agricultural products and surveyed 66,000 farmers across 1553 counties and 312 cities in China. The data regarding fixed costs of farmers available in the CRAP survey includes depreciation of fixed assets, insurance fees, management fees, financial fees, sales fees, and land transfer fees. The CRAP survey data pertinent to variable costs of farmers are costs of seeds, fertilizers, agricultural chemical fees, agricultural film, rental of operation service, and labor costs. In view of remarkable missing values at the product-year level during the period 2005–2021, we selected two proxy variables for fixed and variable compliance costs. The proxy variables for Chinese farmers' adjustments of fixed compliance costs due to changes in the MRL standards are the depreciation of fixed assets; the proxy variables for the variable compliance costs resulting from the changes of MRLs are the agricultural chemical fees. Considering the number of missing values, we select 18 agricultural products for the empirical analysis.[38]

Columns (1)–(2) of Table 6 show the results from the Heckman selection model, and Columns (3)–(6) show the results of two-step 2SLS regressions based on the specific 18 agri-food products. The instrumental variables of the health-threatening MRL stringency, low-hazard MRL restrictiveness index, and the number of tougher-than-China chemical substances are the average value of the same variables for the agri-food products set by the same importer under the same HS-6 heading whereas not belonging to the specified 18 agri-food products, respectively.[39] The instrumental variables of fixed and variable compliance costs are the average value of the same variables for the agri-food products under the same HS-4 heading while not belonging to the specified 18 agri-food products, respectively.[40] Weak IV tests and overidentification tests of instrumental variables are shown in Table A3. Results of weak IV tests show that all the IVs are positively correlated with the endogenous variables,[41] and the overidentification tests suggest that IVs are uncorrelated with the predicted error term of the 2SLS estimations.

The results of the Heckman selection model based on specified 18 agri-food products show that stricter health-threatening MRLs entail lower extensive margins and higher intensive margins of exports, and more restrictive low-hazard MRLs lead to higher extensive margins of exports. The results suggest that tightening health-threatening MRLs induces lower variable compliance costs and higher fixed compliance costs, while tougher low-hazard MRLs generate lower fixed compliance costs and higher variable compliance costs.[42]

We also find consistent results from two-step 2SLS regressions. In Table 6, the coefficients of health-threatening MRLs in Columns (3)–(4) indicate that more stringent health-threatening MRLs are associated with higher fixed compliance costs and lower variable compliance costs. Combined with the significantly negative coefficient of fixed compliance costs in Column (5) and significantly negative estimates of variable compliance costs in Column (6), we conclude that higher fixed compliance costs and lower variable compliance costs resulting from tougher health-threatening MRLs would generate lower extensive margins and higher intensive margins. The coefficients of variable compliance costs in Column (5) and fixed compliance costs in Column (6) are not significant, suggesting that fixed compliance costs would not significantly impact the intensive margins, and variable compliance costs hardly influence the extensive margins. Likewise, the results in Columns (3) and (5), together with those in Columns (4) and (6), suggest that

TABLE 6 Fixed and variable compliance costs as channel: Impacts of MRL standards on EM and IM.

	Heckman selection model		2SLS regression			
	(1)	(2)	(3)	(4)	(5)	(6)
	EM	IM	Fixed compliance costs	Variable compliance costs	EM	IM
$HealthThreatening_{jkt-1}$	−0.532*** (0.066)	1.633*** (0.320)	0.025* (0.013)	−0.266*** (0.043)		
$LowHazard_{jkt-1}$	0.104*** (0.037)	0.126 (0.150)	−0.043*** (0.007)	0.055*** (0.019)		
$\ln\left(1 + Number_{jkt-1}\right)$	−0.160*** (0.025)	−0.170 (0.123)	0.022** (0.010)	−0.115*** (0.033)		
$\ln\left(1 + Tariff_{jkt}\right)$	−0.078*** (0.019)	−0.081 (0.091)	0.014*** (0.003)	0.061*** (0.009)		
$\ln\left(GDPPC_{jt}\right)$	0.293*** (0.032)	−0.565*** (0.162)				
$\ln\left(Dist_j\right)$	−0.597*** (0.037)	−0.404 (0.278)				
$Contig_j$	1.221*** (0.098)	0.514 (0.542)				
$ComLang_j$	4.822*** (0.387)	−2.153*** (0.569)				
$ComLang_j * Product_k$	−0.496*** (0.049)					
IMR_{jkt}		−2.947*** (0.564)				
FC_{kt}					−0.135*** (0.044)	3.419 (3.026)
VC_{kt}					−0.017 (0.012)	−3.650*** (0.637)
Observations	7383	1249	7383	7383	7383	1249
R-squared			.739	.587	.386	.422
Product-year FE	Yes	Yes	Yes	Yes	Yes	Yes
Importer-year FE	No	No	Yes	Yes	Yes	Yes

Note: Columns (1), (2) are results of Heckman selection model on specific 18 agri-food products. The dependent variable in the EM equation is a binary variable, taking the value of one if positive exports of agri-food product k at HS 8-digit level from China to importing country j at time t is observed; zero otherwise. The dependent variable in the IM equation is the logarithm of the positive export value of agri-food product k shipped from China to importing country j at time t. Columns (3)–(6) show results of 2SLS regressions on specific 18 agri-food products. The dependent variable in Column (3) is proxy variable for fixed compliance costs; the dependent variable in Column (4) is proxy variable for variable compliance costs. The proxy variable for Chinese farmers' adjustments of fixed compliance costs concerning changes in MRL standards is depreciation of farmers' fixed costs; the proxy variable for variable compliance costs related to MRL standards is agricultural chemical fees. The dependent variable in Column (5) is the probability of exporting (EM), and the dependent variable in Column (6) is the export value conditional on export decision (IM). The instrumental variables of health-threatening MRL stringency, low-hazard MRL restrictiveness index, and the number of tougher-than-China chemical substances are the average value of the same variables for the agri-food products set by the same importer under the same HS-6 heading whereas not belonging to the specified eighteen agri-food products, respectively. For missing values for IVs, we instead use the average value of the same variables for the agri-food products set by the same importer under the same HS-4 heading whereas not belonging to the specified eighteen agri-food products, respectively. The instrumental variables of fixed and variable compliance costs are the average value of the same variables for the agri-food products under the same HS-4 heading while not belonging to the specified eighteen agri-food products, respectively. IVs for several agri-food products are the average value of the fixed and variable compliance costs for the remaining agri-food products under the same HS-2 heading due to data limitations, they are: potatoes, tomatoes, turnips, cucumbers, long beans, apples, maize, rape or colza seeds. The total number of observations for 2SLS regressions of specific eighteen agri-food products is 7383 at product-year level. The eighteen agri-food products are potatoes, tomatoes, cabbages, cauliflowers, turnips, cucumbers, aubergines, capsicum, long beans, mandarins, apples, wheat, maize, rice, ground-nuts, rape or colza seeds, sugar beet, and sugar cane. We interact HS 2-digit chapters with the indicator for common language between country pairs to construct an exclusion restriction that accounts for heterogeneity in products. Product-year fixed effect is included in the Heckman selection model, and the product fixed effects are defined for each two-digit product category of k to avoid multicollinearity. Product-year fixed effect and importer-year fixed effect are included in 2SLS estimations. Standard errors are in parentheses and are clustered by importer-product-year at the HS-6 level in 2SLS estimations. *, **, and *** denote $p < .10$, $p < .05$, and $p < .01$, respectively.

tightening low-hazard MRLs would increase the extensive margin of exports through lower fixed compliance costs and would generate higher variable compliance costs and further reduce the intensive margin of exports.

6 | CONCLUSIONS

The debate on whether MRL standards act as barriers to agri-food trade has been evaluated through country-product case studies, emphasizing the importance of distinguishing the trade effects of health-threatening (necessary) MRLs from low-hazard (protectionism) MRLs. In this paper, we conduct further empirical analyses on the impacts of MRL standards for health-threatening chemical substances and low-hazard substances based on China's agri-food exports. We compile unique data that utilizes China's export data at the HS 8-digit level with respect to 520 agri-food products subject to MRL standards for 2692 chemical substances across 44 importing countries during the period 2005–2021 within a structural gravity framework.

We find that MRL standards for health-threatening chemical substances facilitate China's exports of agri-food products, while low-hazard MRLs impede them. A 10% increase in the importer's average MRL stringency for health-threatening chemical substances in the previous year would generate 3.53% more export values. A 10% tougher MRL standard for low-hazard substances in the previous year reduces China's agri-food exports by 2.73%. The trade-impeding effect of low-hazard MRLs is 5.11% larger for developing countries relative to developed countries. In addition, we introduce the number of MRLs tougher than China's standards as a control variable to analyze the effects of the numerical stringency of MRL standards on China's exports of agri-food products. We find that a 10% increase in the number of tougher-than-China MRL standards in the previous year is associated with a 2.10% reduction in China's agri-food exports. This new finding validates our hypothesis that both the number of stricter MRLs compared to the exporter and the numerical values of MRLs impact China's agri-food export patterns. Failing to consider the number of more stringent MRL standards would lead to an overestimation of the effect of MRLs on agri-food exports.

Furthermore, we also find that stricter health-threatening MRLs reduce extensive margin while increasing intensive margin. On the contrary, tightening low-hazard MRLs increases the probability of exporting while decreasing the intensive margin. Based on detailed survey data on Chinese farmers, we offer significant evidence regarding the shifts in fixed and variable compliance costs related to health-threatening (necessary) and low-hazard (protectionist) MRLs. Tightening health-threatening MRLs are linked to decreased variable compliance costs and increased fixed compliance costs, whereas stricter low-hazard MRLs would result in reduced fixed compliance costs and increased variable compliance costs.

We observe that the average variable compliance costs (agricultural chemical fees) per unit of farmland in China increased from 64 RMB (Chinese currency, approx. 8.9 USD) to 167 RMB (approx. 23.1 USD) from 2005 to 2021. The average fixed compliance costs (depreciation of fixed assets) per unit of farmland was 13 RMB (approx. 1.8 USD) in 2005 and 50 RMB (approx. 6.9 USD) in 2021. The fast-growing increase in the average variable compliance costs suggests that Chinese farmers have encountered barriers to assessing the international market due to more restrictive low-hazard MRL standards regulated by importing countries. Chinese fruit farmers suffer most from the increase of both fixed and variable compliance costs, suggesting that importing countries tightened both the health-threatening and low-hazard MRLs for fruits during the period 2005–2021. These findings contribute to the nascent literature on exploring the relationship between MRLs and farmers' adjustment of fixed and variable compliance costs, offering policy implications such as trade patterns, trade barriers for farmers cultivating different product categories, and a guide for improving international opportunities.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest to disclose.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Siqi Zhang https://orcid.org/0009-0003-8823-3115

ENDNOTES

[1] Protectionist MRLs represent a more restrictive MRL standard imposed by the government to alleviate the competition confronted by domestic farmers and producers. The necessary MRLs refer to MRL standards for chemical substances that threaten human health and might induce illness or inconvertible health loss.

[2] The WTO declares that SPS measures should be based on international standards such as the Codex, risk assessment based on science, and applying the principle of precaution in the absence of international standards and scientific evidence.

[3] The data on long-term toxicological risk effects are provided by the Quebec Ministries of Agriculture and Environment and the National Institute of Public Health of Quebec on the SAgE pesticide website: http://www.sagepesticides.qc.ca/Default.aspx.

[4] The full name of the 2019 WHO guideline is "The WHO Recommended Classification of Pesticides by Hazard and Guidelines to Classification 2019," which can be retrieved from: http://www.who.int/publications/i/item/9789240005662.

[5] Report table of the matching is available upon request.

[6] FAOSTAT data source: https://www.fao.org/faostat/en/#data/TCL.

[7] In July 2020, the European Union published Reg. (EU) 2020/1085 in which the MRL for Chlorpyrifos (a pesticide widely used in fruits and vegetable cultivation) was set at the lowest level (0.01 parts per million), banning Chlorpyrifos as a pesticide. European Food Safety Authority (EFSA) reported that Chlorpyrifos is potentially genotoxic and would cause neurodevelopmental damage to children.

[8] Chlorpyrifos is a classic pesticide applied in fruits and vegetable production.

[9] Chloramphenicol (CAP) is an antibiotic that was used as a veterinary drug in crustacean products.

[10] Aflatoxin is a saprophytic fungi that damages human health.

[11] More information based on which the WHO classifies risks of substances to human health can be found on the WHO website. https://www.who.int/publications/i/item/9789240005662.

[12] Information regarding how the EU sets regulations on MRL standards also includes: (i) the use of a substance including quantity, frequency, and growth stage of the plant suggested by Good Agricultural Practice (GAP) standards; (ii) experimental data on the expected residues when the pesticide is applied according to GAP. Details are available at: https://food.ec.europa.eu/plants/pesticides/maximum-residue-levels/how-are-eu-mrls-set_en.

[13] The EFSA report can be retrieved from: https://pubmed.ncbi.nlm.nih.gov/32625691/.

[14] The EFSA 2019 report can be accessed from: https://efsa.onlinelibrary.wiley.com/doi/full/10.2903/j.efsa.2019.5809.

[15] Relevant explanations concerning the acute toxicity of bentazone can be retrieved from WHO's website: https://www.inchem.org/documents/icsc/icsc/eics0828.htm.

[16] The relevant EFSA report is available at: https://efsa.onlinelibrary.wiley.com/doi/abs/10.2903/j.efsa.2015.4077

[17] The CAP measures are coupled direct payments, decoupled direct payments, agri-environmental payments, on-farm investments, and other measures (Biagini et al., 2020).

[18] We focus on the agri-food products on which MRL standards have been regulated by at least 30% of importing countries at the time t and at least one health-threatening MRL has been regulated. The agri-food product categories under investigation are detailed in Table A1.

[19] The index would take the value of one (exp(0)) if China and the importer set the same level of MRL standards for health-threatening chemical substances at the product-year level. The upper limit of this index is $\exp(1) = e \approx 2.718$ where importer j set the MRL standard at zero (strictest level); the lower limit of this index is $\exp(-\infty) \approx 0$ where importer j imposes a very large (lax) MRL standard. Li and Beghin (2014) propose that the exponential function aims at putting more weight on the MRLs that are relatively more stringent.

[20] To capture the heterogeneous effects of MRL standards for high-hazard, moderate-hazard, and low-hazard substances on China's agricultural exports, we require that at least 30% of importing countries set MRLs for at least one high-hazard and one moderate-hazard substance. The agri-food product categories under investigation are also detailed in Table A1.

[21] We presume that high-hazard substances are more likely to be prohibited by both exporters and importers while the moderate-hazard substances are regulated more seriously in developed countries than developing countries.

[22] Santos Silva and Tenreyro (2006) point out that log-linearization of the gravity equation and then applying OLS leads to inconsistent estimation since the expected values of the log linearized error term will be correlated with the covariates of the regression and thereby violates the normal distribution assumption.

[23] Homologa is a global regulatory database on registrations of crop protection products, collecting information on maximum residue limits from credible government sources.

[24] If HS 8-digit trade data cannot be matched to MRL standards from the Homologa database, we use the most lenient MRL standard under the same HS 6-digit or 4-digit headings.

[25] References of rules that are commonly used to deal with missing values are Drogué and DeMaria (2012), Fiankor et al. (2021), Shingal et al. (2021), and Traoré and Tamini (2022). We listed this procedure with references in Table A2.

[26] References that used this method are Drogué and DeMaria (2012), Ferro et al. (2015), and Fiankor et al. (2021). We cannot replace missing values with zero since the zero value of the MRLs implies the most stringent standard.

[27] Ferro et al. (2015) keep the product if at least 50% of importing countries regulate MRL standards. We accommodate this ratio to 30% as a response to our data characteristics.

[28] The agri-food products at HS 8-digit level are selected if MRL standards have been regulated by at least 30% of importing countries and MRL standard for at least one high-hazard and one moderate-hazard chemical substance was regulated on the agri-food products.

[29] The average value of MRL standards for high-hazard and moderate-hazard substances are 1.31 and 1.48, respectively, suggesting that the average intensity of MRL stringency for moderate-hazard substances is more dissimilar between China and importing countries than high-hazard MRLs.

[30] The 10% increase in the MRL restrictiveness index implies that the ratio denoted by $\frac{MRL\_CHINA_{skt-1} - MRL\_IMPORTER_{skt-1}}{MRL\_CHINA_{skt-1}}$ would rise by 0.0414 (log(110%) = 0.0414). Alternatively speaking, $\frac{MRL\_IMPORTER_{skt-1}}{MRL\_CHINA_{skt-1}}$ would fall by 0.0414. If we assume that MRL standards regulated by China keep constant, then the 10% increase in the MRL restrictiveness index indicates that the MRL standard imposed by the importing country would be tightened by 4.14% of China's MRL standards ($4.14\% * MRL\_CHINA_{skt-1}$).

[31] One unit value of changes in the MRL restrictiveness index is associated with 29.6% changes in the export values of China's agricultural products, then 10% increase in the MRL restrictiveness index leads to a change in the export values by: $\frac{29.6\%}{(1/1.475)*100\%} * 10\% = 4.37\%$.

[32] $\frac{22.4\%}{(1/1.218)*100\%} * 10\% = 2.73\%$.

[33] The inconclusive empirical findings in the previous literature are attributed to various products, countries, and chemical substances.

[34] One unit value of changes in the low-hazard MRLs set by developed and developing countries is associated with 19.4% and 50.8% reduction in the export values of China's agricultural products, respectively. In other words, 10% increase in the MRLs leads to a decrease in the export values by: $\frac{19.4\%}{(1/1.167)*100\%} * 10\% = 2.26\%$; $\frac{50.8\%}{(1/1.451)*100\%} * 10\% = 7.37\%$. Therefore, the gap of trade-impeding effect of low-hazard MRLs between developed and developing countries is 7.37%–2.26% = 5.11%.

[35] We interact HS 2-digit chapters with the indicator for common language between country pairs to construct an exclusion restriction that accounts for heterogeneity in products. The exclusion variable only affects the fixed costs of trade without affecting the variable costs of trade. Similar methods for creating the exclusion variable can be found in Xiong and Beghin (2014), and Ferro et al. (2015).

[36] The main uncertainty facing exporters is the trade barriers resulted from MRLs whereas the main uncertainty facing importers (consumers) is the food safety of exporting source (i.e., China).

[37] The unit of agricultural land in China is mu, equivalent to 0.067 hectares.

[38] The 18 agricultural products are potatoes, tomatoes, cabbages, cauliflowers, turnips, cucumbers, aubergines, capsicum, long beans, mandarins, apples, wheat, maize, rice, ground-nuts, rape or colza seeds, sugar beet, and sugar cane.

[39] For missing values for IVs, we instead use the average value of the same variables for the agri-food products set by the same importer under the same HS-4 heading whereas not belonging to the specified 18 agri-food products, respectively.

[40] IVs for several agri-food products are the average value of the fixed and variable compliance costs for the agri-food products under the same HS-2 heading while not belonging to the specified 18 agri-food products due to data limitations, they are potatoes, tomatoes, turnips, cucumbers, long beans, apples, maize, rape or colza seeds.

[41] In Table A3, the Cragg-Donald Wald F statistics are higher than the critical value of 10, suggesting that the null hypothesis that IVs are not significantly correlated with the endogenous variables should be rejected. In the overidentification tests, the IVs are not significantly correlated with the predicted error term of 2SLS estimations. We implemented the Sargan test to jointly test the validity of IVs, and the *p*-values of the Sargan test suggest that we cannot reject the null hypothesis that IVs are exogenous.

[42] Though the coefficient of low-hazard MRLs in Column (2) is insignificant, it is in line with the results in Table 5 and also supported by the following 2SLS result (which is significant).

[43] Similar methods for creating the exclusion variable can be found in Xiong and Beghin (2014), and Ferro et al. (2015).

[44] The inverse Mills ratio is the ratio of the probability density function to the cumulative distribution function. $IMR_{jkt} = \frac{\phi(Z_{jkt}\gamma)}{\Phi(Z_{jkt}\gamma)}$, where Z_{jkt} is a vector of explanatory variables influencing the true value of latent variable observed in the selection equation, γ is a vector of parameters (Greene, 2008).

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APPENDIX A

A.1. EXTENSIVE AND INTENSIVE MARGINS OF TRADE

To further explore the impacts of MRL standards for health-threatening and low-hazard chemical substances on the probability of export (extensive margin) and the volume of export conditional on export decisions (intensive margin), we implement the Heckman selection model (Heckman, 1979). The Heckman selection model includes two procedures: a selection equation and an outcome equation.

The selection equation which estimates the impacts of MRL standards on the probability of exporting is given by:

$$P_{jkt} = \beta_0 + \beta_1 HealthThreatening_{jkt-1} + \beta_2 LowHazard_{jkt-1} + \beta_3 \ln\left(1 + Number_{jkt-1}\right) + \beta_4 \ln\left(1 + Tariff_{jkt}\right) + \beta_5 lnGDPPC_{jt} + \beta_6 lnDist_j + \beta_7 Contig_j + \beta_8 ComLang_j + \beta_9 ComLang_j * Product_k + \alpha_{kt} + \varepsilon_{jkt}, \tag{A1}$$

where P_{jkt} is a binary variable, taking the value of one if positive exports of agri-food product k from China to importing country j at time t is observed, zero otherwise; $lnGDPPC_{jt}$ is the logarithm of real GDP per capita in country j at time t; $lnDist_j$ is the logarithm of the distance between China and importing country j; $Contig_j$ and $ComLang_j$ are indicators for importing country j which shares a common border and common language with China. We interact HS 2-digit chapters with the indicator for common language between country pairs ($ComLang_j * Product_k$) to construct an exclusion restriction that accounts for heterogeneity in products. α_{kt} is product-year fixed effects, and ε_{jkt} is the error term.

The intensive margin equation that estimates the impact of MRL standards on export values conditional on exporting is specified as the following:

$$lnM_{jkt} = \beta_0 + \beta_1 HealthThreatening_{jkt-1} + \beta_2 LowHazard_{jkt-1} + \beta_3 \ln\left(1 + Number_{jkt-1}\right) + \beta_4 \ln\left(1 + Tariff_{jkt}\right) + \beta_5 lnGDPPC_{jt} + \beta_6 lnDist_j + \beta_7 Contig_j + +\beta_8 ComLang_j + \beta_9 IMR_{jkt} + \alpha_{kt} + \varepsilon_{jkt}, \tag{A2}$$

Where lnM_{jkt} is the logarithm of the export value of agri-food product k shipped from China to importing country j at time t. The interaction term $ComLang_j * Product_k$ is selected as the exclusion restriction due to the fact that it only affects the fixed cost of trade while not affecting the variable cost of trade in our sample.[43] We compute the inverse Mills ratio (IMR_{jkt})[44] from the selection equation and include the inverse Mills ratio in the intensity equation to correct for sample selection bias.

TABLE A1 HS chapters in China's agricultural export data.

HS2	Product description	Number of HS 8-digit products under HS 2-digit sectors	Share of HS 2-digit sectors to the total number of observations (%)	Number of HS 8-digit products under HS 2-digit sectors	Share of HS 2-digit sectors to the total number of observations (%)
		Sample of Model 1		Sample of Model 2	
02	Meat and edible meat offal	58	0.90%	57	0.66%
03	Fish and crustaceans and aquatic invertebrates	32	0.07%	32	0.10%
04	Dairy produce; birds' eggs; natural honey; edible products of animal origin, not elsewhere specified or included	18	0.27%	16	0.17%
06	Live trees and other plants; bulbs, roots, and the like; cut flowers and ornamental foliage	8	0.19%	6	0.21%
07	Edible vegetables and certain roots and tubers	97	28.14%	92	28.00%
08	Edible fruit and nuts; peel of citrus fruit or melons	80	26.55%	79	28.39%
09	Coffee, tea, mate, and spices	45	11.98%	45	11.95%
10	Cereals	20	5.72%	19	5.13%
11	Products of the milling industry; malt; starches; inulin; wheat gluten	13	1.32%	10	0.88%
12	Oil seeds and oleaginous fruits; miscellaneous grains, seeds, and fruit; industrial or medicinal plants; straw and fodder	52	11.19%	50	11.68%
14	Vegetable plaiting materials; vegetable products not elsewhere specified or included	2	0.05%	2	0.02%
15	Animal or vegetable fats and oils and their cleavage products; prepared edible fats; animal or vegetable waxes	18	0.76%	10	0.29%

(Continues)

TABLE A1 (Continued)

HS2	Product description	Number of HS 8-digit products under HS 2-digit sectors	Share of HS 2-digit sectors to the total number of observations (%)	Number of HS 8-digit products under HS 2-digit sectors	Share of HS 2-digit sectors to the total number of observations (%)
16	Preparations of meat, fish or crustaceans, or aquatic invertebrates	10	0.14%	10	0.13%
17	Sugars and sugar confectionery	3	0.02%	0	0.00%
19	Preparations of cereals, flour, starch, or milk; pastrycooks' products	4	0.49%	4	0.39%
20	Preparations of vegetables, fruit, nuts, or other parts of plants	41	10.26%	28	10.38%
21	Miscellaneous edible preparations	2	0.03%	1	0%
22	Beverages, spirits, and vinegar	6	1.27%	6	1.14%
23	Residues and waste from the food industries; prepared animal fodder	3	0.38%	2	0.38%
24	Tobacco and manufactured tobacco substitutes	8	0.28%	7	0.09%
Total		520	100%	476	100%

TABLE A2 Rules applied to missing values of MRLs.

Country	The first rule applied	If the first rule does not apply, the second rule is applied	Reference
Argentina	CODEX	0.01	Shingal et al. (2021)
Australia	0.01		Shingal et al. (2021)
Brazil	CODEX		Shingal et al. (2021)
Canada	0.1		Drogué and DeMaria (2012), Fiankor et al. (2021), Traoré and Tamini (2022)
Chile	CODEX		Shingal et al. (2021)
China	CODEX		Shingal et al. (2021)
Egypt	CODEX	EU	Shingal et al. (2021), Fiankor et al. (2021), Traoré and Tamini (2022)
EU	0.01		Shingal et al. (2021)
India	CODEX		Shingal et al. (2021)
Israel	CODEX		Shingal et al. (2021)
Japan	0.01		Shingal et al. (2021)
Korea	CODEX		Shingal et al. (2021)
Malaysia	CODEX	0.01	Shingal et al. (2021)
Mexico	0.01		Shingal et al. (2021)
New Zealand	CODEX	0.1	Drogué and DeMaria (2012), Traoré and Tamini (2022)
Norway	0.01		Shingal et al. (2021)
Russia	CODEX		Shingal et al. (2021)
Singapore	CODEX		Shingal et al. (2021)
South Africa	CODEX	EU	Shingal et al. (2021), Fiankor et al. (2021), Traoré and Tamini (2022)
Switzerland	EU	0.01	Shingal et al. (2021)
Thailand	CODEX		Shingal et al. (2021)
Turkey	CODEX	0.01	Shingal et al. (2021), Fiankor et al. (2021), Traoré and Tamini (2022)
Ukraine	CODEX		Shingal et al. (2021)
USA	0.01		Shingal et al. (2021)
Vietnam	CODEX		Shingal et al. (2021)

TABLE A3 Weak IV test and overidentification test of IVs.

	Weak IV test			Overidentification test			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent variable	$HealthThreatening_{jkt-1}$ $LowHazard_{jkt-1}$ $ln\left(1+Number_{jkt-1}\right)$ Endogenous variables in Table 6, Columns (3), (4)	FC_{kt}, VC_{kt} Endogenous variables in Table 6, Column (5)	FC_{kt}, VC_{kt} Endogenous variables in Table 6, Column (6)	Predicted error term from 2SLS estimation in Table 6, Column (3)	Predicted error term from 2SLS estimation in Table 6, Column (4)	Predicted error term from 2SLS estimation in Table 6, Column (5)	Predicted error term from 2SLS estimation in Table 6, Column (6)
$IV\_HealthThreatening_{jkt-1}$	0.799*** (0.015)			−0.000 (0.011)	0.000 (0.036)		
$IV\_LowHazard_{jkt-1}$	0.912*** (0.009)			0.000 (0.007)	0.000 (0.018)		
$IV\_\ln\left(1+Number_{jkt-1}\right)$	0.640*** (0.018)			0.000 (0.007)	0.000 (0.022)		
IV_FC_{kt}		0.737*** (0.047)	0.347*** (0.067)			0.000 (0.035)	−0.000 (1.278)
IV_VC_{kt}		0.923*** (0.025)	0.725*** (0.088)			0.000 (0.012)	0.000 (0.592)
Observations	7383	7383	1249	7383	7383	1249	1249
Cragg-Donald Wald F statistics	2369.251	441.066	22.773				
Sargan test p-value				1.000	1.000	1.000	1.000

Note: Columns (1)–(3) show the results of weak IV tests for IVs used in the 2SLS estimations in Table 6. The dependent variables are the endogenous variables ($HealthThreatening_{jkt-1}$, $LowHazard_{jkt-1}$, $ln\left(1+Number_{jkt-1}\right)$, FC_{kt}, and VC_{kt}), respectively. Columns (4)–(7) show the results of the overidentification test for IVs used in the 2SLS estimations in Table 6. The dependent variables are the predicted error term from 2SLS estimations in Table 6. Product (HS-2)-year and importer-year fixed effects have been included. Standard errors are in parentheses and are clustered by importer-product-year. *, **, and *** denote $p < .10$, $p < .05$, and $p < .01$, respectively.