frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 19 March 2026
DOI 10.3389/fsufs.2026.1759489

Knowledge graph-based analysis of registered pesticide coverage for medicinal crops: a case study of 10 representative Chinese herbal medicines

Liping Bian[1,2], Xianjin Liu[2], Minjiao Wang[1], Na Sun[3], Haiyan Lu[2], Xiao Fan Liu[1]* and Wei Xu[4]*

[1]School of International Pharmaceutical Business, China Pharmaceutical University, Nanjing, China, [2]Institute of Food Quality Safety and Nutrition, Jiangsu Academy of Agricultural Sciences, Nanjing, China, [3]Nanjing Zhimai Information Technology Co., Ltd., Nanjing, China, [4]Department of Media and Communication, City University of Hong Kong, Kowloon, Hong Kong SAR, China

Background: The Chinese medicinal material (CMM) industry faces a persistent dilemma of lacking legally registered pesticides. This study aims to provide data-driven support to resolve this issue and systematically evaluate the effectiveness of policy interventions that expand pesticide application scopes.

Methods: Based on pesticide registration data and multi-source information, we constructed 125 ‘CMM-pest/disease’ pairs for 10 representative CMMs. We innovatively developed a ‘Crop-Pest/Disease-Pesticide Registration Certificate’ knowledge graph and applied two metrics—Registration Certificate Resource Distribution Intensity (RDI) and Pest and Disease Control Coverage Rate (PDCR)—to quantitatively analyze pesticide resource allocation.

Results: After the scope expansion policy, the overall PDCR for the 10 CMMs increased from 49% (original registration) to 78% (extended-use included), enabling legal pesticide access for 36 previously ‘uncontrollable’ pairs. However, the graph-based analysis revealed critical systemic imbalances: over 60% of pests/diseases affecting low-value-added CMMs (e.g., *Astragali radix*, *Arctii radix*) still lack registered pesticides. Furthermore, while domestic pesticides dominate the market (94%), they exhibit lower resource allocation efficiency and are disproportionately concentrated on high-value-added CMMs compared to their imported counterparts.

Conclusion: By transitioning to a multi-dimensional, graph-based analytical framework, this study demonstrates that while scope expansion policies significantly improve pesticide accessibility, market mechanisms inherently fail low-value-added crops. These findings provide compelling evidence for policymakers to implement targeted, crop-specific registration subsidies rather than relying solely on generic scope expansions, thereby ensuring the sustainable and standardized development of the CMM industry.

KEYWORDS

Chinese medicine materials, pest and disease control, pesticide registration, policy evaluation, resource allocation

OPEN ACCESS

EDITED BY
John Franklin Leslie,
Kansas State University, United States

REVIEWED BY
A. Amarender Reddy,
National Institute of Agricultural Extension Management (MANAGE), India
Abdullah Al Mamun,
Indian Institute of Technology Kharagpur, India

*CORRESPONDENCE
Xu Wei
✉ xuwei@cpu.edu.cn
Liu Xiao-fan
✉ xf.liu@cityu.edu.hk

RECEIVED 03 December 2025
REVISED 26 February 2026
ACCEPTED 02 March 2026
PUBLISHED 19 March 2026

CITATION
Bian L, Liu X, Wang M, Sun N, Lu H, Liu XF and Xu W (2026) Knowledge graph-based analysis of registered pesticide coverage for medicinal crops: a case study of 10 representative Chinese herbal medicines. *Front. Sustain. Food Syst.* 10:1759489. doi: 10.3389/fsufs.2026.1759489

1 Introduction

As a core component of Traditional Chinese Medicine (TCM), the quality and safety of Chinese medicinal materials (CMMs) are pivotal to the sustainable development and internationalization of the TCM industry (Launois et al., 2022). However, pest and disease infestations during cultivation threaten CMM yield and quality, increasing the risk of excessive pesticide residues (Wu and Lin, 2020). Under China's Food Safety Law and Regulations on Pesticide Administration, growers may only use legally registered pesticides for pest/disease control (State Council, 2023; Standing Committee of the National People's Congress, 2024). Regarded as "specialty minor crops," CMMs have long faced a "lack of legal pesticides" due to small market scales and high registration costs. Compounded by insufficient plant protection expertise among some growers, this leads to pesticide misuse/overuse, exacerbating the "difficulty in legal pesticide application" and hindering the modernization and standardization of the CMM industry (Ding et al., 2024).

To address this challenge, efforts have been made globally. Countries/regions including the United States (U.S. Environmental Protection Agency, 2015), Canada (Health Canada, 2021), the European Union (European Minor Uses Coordination Facility, 2023), and Brazil (Ministry of Agriculture, Livestock and Food Supply (MAPA), 2022) have advanced minor-crop pesticide trials and registration, ensuring legal pesticide access via dedicated funds, technical support, and streamlined registration channels. Domestically, China's Ministry of Agriculture and Rural Affairs (MARA) has issued documents such as the *List of Specialty Minor Crops Short of Pesticides* since 2019, expanding pesticide application scopes to improve registration coverage (Ministry of Agriculture and Rural Affairs General Office, 2019). Researchers have also utilized pesticide registration databases to organize registration information (Li et al., 2022), compare pest and disease spectra (Dai et al., 2019), recommend applicable pesticides for minor crops (Wang et al., 2025), or even establish preliminary data-driven prescription recommendation models (Chinese Society of Agricultural Machinery, 2023).

Despite progress, three gaps persist in CMM pest/disease control research: (1) Insufficient targeting—most studies focus on large-scale cash crops (e.g., fruits, vegetables) rather than addressing the unique pest/disease control needs of CMMs as minor crops; (2) single-dimensional evaluation—coverage is measured solely by the number of registration certificates, ignoring the many-to-many relationships among "crops-pests/diseases-pesticides," which fails to accurately identify control gaps; (3) Low knowledge translation efficiency—lack of visualized data structures and graph-based knowledge systems limits the utility of research findings for policy-making and technical promotion.

To address these gaps, this study aimed to establish a scientific, accurate evaluation system for CMM pest/disease control resources. Using public data from the China Pesticide Information Network (as of August 2025), we analyzed 10 representative minor CMMs with industrial significance (e.g., *Ginseng radix et rhizoma*, *Dioscoreae rhizoma*, *Angelicae sinensis radix*, *Arctii radix*). We innovatively constructed a three-tier "Crop-Pest/Disease-Registration Certificate" knowledge graph, proposed the RDI metric to quantify resource allocation efficiency, and scientifically assessed the effectiveness of pesticide scope expansion policies. This study integrates standardized data cleaning, knowledge graph construction, and quantitative metric evaluation, forming a data-driven, graph-enhanced analytical framework for CMM pest/disease control.

This study offers three key strengths:

(1) Firstly, it constructs a three-layer knowledge graph of "TCM materials-pests and diseases-pesticide registration certificates" to visually present the associations among them.

(2) The *RDI* metric, combined with *PDCR*, to quantify pesticide resource allocation efficiency.

(3) Evidence-based evaluation of the effectiveness of "pesticide scope expansion" policies using the above tools.

2 Materials and methods

2.1 Research objects and data sources

We focused on 10 widely cultivated, representative CMMs: *Isatidis radix*, *Angelicae sinensis radix*, *Dioscoreae rhizoma*, *Lycii fructus*, *Ginseng radix et rhizoma*, *Notoginseng radix et rhizoma*, *Astragali radix*, *Lilii bulbus*, *Chrysanthemi flos*, and *Arctii radix*. These CMMs are valued for their rich pharmacological components, used to treat common diseases (e.g., respiratory, immune, digestive disorders, and chronic conditions), and play important roles in the TCM industry (Pharmacopoeia Commission of the People's Republic of China, 2020). They cover dominant CMM families (Leguminosae, Solanaceae, Apiaceae, Brassicaceae, Liliaceae, Araliaceae, Dioscoreaceae), have large planting scales and significant economic benefits, and span major production regions (Northeast, Northwest, Central-South, East China), reflecting diverse climatic adaptability and pest/disease spectra—making them typical for pest/disease control research (China Association of Traditional Chinese Medicine, 2024).

Pesticide registration data (96,868 records, from database inception to August 20, 2025) were retrieved from the official "China Pesticide Information Network" (China Pesticide Information Network, 2025), managed by MARA as the authoritative platform for public pesticide registration inquiries. Each record includes key information: pesticide name, registration certificate number, category, formulation, active ingredients, approval date, manufacturer, target pests/diseases, product performance, application guidelines, and precautions.

To construct a comprehensive pest/disease list for the 10 CMMs, we cross-validated three data sources: (1) Authoritative monographs [e.g., *Pest and Disease Control Technology for Chinese Medicinal Crops* (Chen et al., n.d.)], *Color Atlas of Green Pest/Disease Control for Common Chinese Medicinal Materials* (Zhuo et al., 2023). (2) Targeted studies published in the past 5 years in core agricultural journals (e.g., *Journal of Plant Protection*, *China Journal of Chinese Materia Medica*) (Dai et al., 2019; Lin et al., 2024). (3) Local technical documents (e.g., *Technical Code for Green Control of Pests/Weeds in Common CMM Cultivation*) issued by agricultural extension centers in major production areas (Shandong Association of Agricultural Science Societies, 2023). This list includes both registered and unregistered (but harmful) pests/diseases, fully reflecting the "registration status-control demand" matching relationship.

2.2 Data preprocessing

To eliminate interference from duplicate/irrelevant data, we cleaned, deduplicated, and filtered records, retaining only fields related to crop type, pest/disease type, pesticide active ingredients, and registration certificate type (domestic/imported). Expired certificates (validity ending before August 20, 2025) were excluded, resulting in 50,723 valid records.

Pest and disease grouping was conducted based on biological characteristics and control logic to ensure accurate PDCR calculation. The grouping criteria include: (1) Biological classification: pests and diseases sharing the same taxonomic category (e.g., red spider and spider mites are both arachnids requiring similar acaricides); (2) Control logic: different pest/disease names requiring identical control agents (e.g., root rot diseases across different CMMs—such as *Isatidis radix* root rot and *Angelicae sinensis radix* root rot—are grouped together due to similar pathogenic fungi and fungicide requirements). This standardization expanded the pest and disease categories from 25 to 41 types (18 fungal diseases, 5 bacterial diseases, 3 nematode diseases, 15 insect pests), forming 125 'CMM-pest/disease' pairs, thereby improving the precision of PDCR calculations and ensuring more accurate assessment of registration coverage.

Pest/disease names were standardized to ensure consistency: Synonyms (e.g., "red spider" = "spider mite") (Nong Baike, n.d.) and hierarchical terms (e.g., "slug" [general] vs. "wild slug" [specific]; "cutworm" vs. "black cutworm") (China Science Communication, n.d.) were unified using a "pest/disease name mapping table," avoiding analytical biases from nomenclature confusion (State Council, 2023).

2.3 Knowledge graph construction

This study constructs a knowledge graph containing three relationships: "crop-pest and disease-pesticide registration certificate." The nodes include 10 types of Traditional Chinese Medicine (TCM) material crops and standardized pests and diseases. Edges are established between nodes. If a certain TCM material crop is likely to suffer from a specific pest or disease, an edge is established between the TCM material crop and the pest or disease, defined as "occurrence," and the weight of the edge represents the occurrence frequency and level. If a certain pesticide can be used to control a specific pest or disease on a certain crop, an edge is established between the crop's pest/disease and the pesticide registration certificate, defined as "control," and the weight of the edge represents the number of corresponding registration certificates.

If a pesticide registration certificate clearly indicates that it is applicable to the pest or disease of the crop, the attribute of this control edge is marked as "original registration." If the pesticide is extended to be used on the TCM material crop in accordance with the *List of Pesticide Registration Efficacy Test Groups for Special Minor Crops (2019 Edition)* (Ministry of Agriculture and Rural Affairs General Office, 2019) (hereinafter referred to as the Group List), the attribute of the edge is labeled as "extended use."

2.4 Utilization rate of registration certificate resources

To comprehensively evaluate the rationality of pesticide registration resource allocation and control efficiency for different crops, this study introduces the Registration Certificate Resource Distribution Intensity (RDI) index to simultaneously reflect the matching degree between "resource input" and "pest and disease coverage".

The calculation formula is as follows:

$$\mathrm{RDI_i} = \frac{\mathrm{R_i} / \sum \mathrm{R}}{\mathrm{PDCR_i}} \quad (1)$$

$$\mathrm{PDCR_i} = \frac{\mathrm{P_i}}{\mathrm{T_i}} \quad (2)$$

Equations 1 and 2 define the Pest and Disease Control Coverage Rate (PDCR) and the Registration Certificate Resource Distribution Intensity (RDI), respectively, which are the core metrics used in this study. The RDI metric is expressed as a percentage (%), quantifying the ratio of a CMM's share of total registration certificates to its Pest and Disease Control Coverage Rate (PDCR). For instance, *Isatidis radix* has an overall RDI of 63%, indicating resource concentration relative to its coverage rate. To interpret RDI values: when RDI > 100%, the CMM's share of registration resources exceeds its PDCR, suggesting resource concentration (though not necessarily absolute surplus); when RDI < 100%, resource input is relatively insufficient but coverage efficiency remains high; an RDI closer to 100% indicates better alignment between resource allocation and control needs.

In the formula, $\mathrm{RDI_i}$ represents the registration certificate resource distribution intensity of the i-th crop; $\mathrm{R_i}$ is the number of valid registration certificates for the i-th crop; $\sum \mathrm{R}$ is the total number of valid registration certificates for the 10 crops. This index evaluates the resource allocation efficiency by quantifying the proportion of the number of registration certificates corresponding to the unit coverage rate. When $\mathrm{RDI_i} > 1$, it indicates that the registration certificate resources for the crop are relatively surplus, and there is a phenomenon of repeated registration or resource concentration; when $\mathrm{RDI_i} < 1$, it means that the input of registration resources is insufficient but the coverage efficiency is relatively high; the closer $\mathrm{RDI_i}$ is to 1, the better the matching between resource allocation and control needs.

$\mathrm{PDCR_i}$ (Pest and Disease Control Coverage Rate) represents the pest and disease control coverage rate of the i-th crop; $\mathrm{P_i}$ is the number of pest and disease species of the i-th crop that have been covered by valid registration certificates; $\mathrm{T_i}$ is the total number of all known pest and disease species of the i-th crop. The closer $\mathrm{PDCR_i}$ is to 1, the more comprehensive the control coverage is, and the lower the risk of having no pesticides available for control.

3 Results

3.1 Data overview

Of the 50,723 valid records, 457 were original registrations directly linking the 10 CMMs to 25 pest/disease categories. After applying the "scope expansion" policy, 4,825 new valid "pesticide-pest/disease" pairs were added [note: some pests/diseases affect multiple CMMs; pests/diseases with similar biological traits/control logic were grouped despite different names]. In total, 5,282 valid "pesticide-pest/disease" pairs were available, including 4,979 domestic and 303 imported pesticides.

Key trends from the data reveal significant disparities in pesticide resource allocation: high-value-added CMMs (*Ginseng radix et rhizoma*, *Lycii fructus*, *Notoginseng radix et rhizoma*) secured 65% of original registrations, while low-value-added CMMs (*Astragali radix*, *Arctii radix*) faced substantial control gaps with over 60% of their pests/diseases lacking registered pesticides even after policy implementation. Additionally, domestic pesticides dominate in quantity (94% of total registrations) but demonstrate lower resource allocation efficiency compared to imported alternatives, as detailed in subsequent sections.

Cross-validation expanded the pest/disease list from 25 to 41 categories (18 fungal diseases, 5 bacterial diseases, 3 nematode diseases, 15 insect pests), forming 125 "CMM-pest/disease" pairs. Details on pest/disease counts, certificate distribution, and coverage are shown in Table 1; specific "uncontrollable" pairs are listed in Table 2.

3.2 Effectiveness of pesticide scope expansion policies

Before the implementation of the policy for expanding the applicable scope of pesticides based on the "Group List," among the 125 "TCM material-pest and disease" pairs of the 10 TCM materials, only 61 pairs (49%) had legally registered pesticides available (Table 1). Among them, *Lycii fructus* had the highest original PDCR (86%), with original registration resources relatively concentrated; *Arctii radix* had an original PDCR of 0, and there were no legally available pesticides for all 9 species (categories) of pests and diseases; the original PDCR of *Isatidis radix* and *Angelicae sinensis radix* were 17 and 14% respectively, and more than 80% of their pests and diseases faced the dilemma of "no pesticides available for control" (Tables 1, 2).

After the implementation of the policy, the overall PDCR of the 10 TCM materials increased to 78%, and the number of "TCM material-pest and disease" pairs with no available pesticides decreased from 64 to 28 (Figures 1B1,B2). From the crop perspective, *Lycii fructus* became the only crop with full coverage of pests and diseases, and its extended registration certificates supplemented the "Aphids-*Lycii fructus*" pair that was not covered by the original registration; the PDCR of *Arctii radix* increased from 0 to 33%, and three species of pests and diseases (Nematode, Soil-dwelling Pests, Anthracnose) obtained legal pesticides through the expansion policy; the PDCR of *Isatidis radix*, *Angelicae sinensis radix*, and *Lilii bulbus* had the most significant increases, rising by 58, 57, and 50%, respectively. The number of corresponding extended registration certificates reached 2,475, 115, and 551 respectively, which effectively alleviated the pesticide shortage for core pests and diseases such as "*Isatidis radix*-Powdery Mildew," "*Angelicae sinensis radix*-Soil-dwelling Pests," and "*Lilii bulbus*-Blight" (Table 1, Figure 1A).

For example, as shown in Figures 1A,B, the policy intervention profoundly changed the availability of resources. Before the policy (Figure 1B1), *Isatidis radix* faced a severe shortage with only 2 original registered pesticides; however, after the scope expansion policy (Figure 1B2), it gained 2,475 extended-use certificates, successfully covering previously unmanageable diseases like Powdery Mildew.

The policy impact shows clear differentiation by crop economic value. While *Lycii fructus* achieved 100% coverage (including aphid control previously unavailable), and *Isatidis radix*, *Angelicae sinensis radix*, and *Lilii bulbus* gained 2,475, 115, and 551 extended registration certificates, respectively, (raising their PDCR by 58, 57, and 50%), crops with lower market value received limited benefits. Specifically, *Astragali radix* (PDCR 50%) and *Arctii radix* (PDCR 33%) still have 62 and 67% of their pests/diseases without legal pesticide options, highlighting persistent registration gaps in the minor crop pesticide system.

In terms of the increase in registration certificates, among the 4,825 new registration certificates added under the expansion policy, *Isatidis radix* accounted for the highest proportion (51%, 2,475/4,825), followed by *Dioscoreae rhizoma* (15%, 734/4,825) and *Lilii bulbus* (11%, 551/4,825). The number of extended registration certificates for these three crops accounted for 78% of the total extended quantity. However, *Astragali radix* and *Arctii radix* had a relatively small number of extended registration certificates (79 and 317 respectively), with their PDCR (Pest and Disease Control Coverage Rate) being 50 and 33%, respectively.

3.3 "Traditional Chinese medicine material-pest and disease-pesticide registration certificate" knowledge graph

3.3.1 Overall graph structure

In the three-layer "Traditional Chinese Medicine (TCM) Material-Pest and Disease-Pesticide Registration Certificate" knowledge graph

TABLE 1 Statistics on pests/diseases and pesticide registration certificates of 10 Traditional Chinese Medicine (TCM) material crops.

CMM name	Pest/disease species	Original certificates	Original coverage (species)	Extended certificates	Imported certificates	Total coverage (species)
Isatidis radix	12	28	2	2,475	86	9
Angelicae sinensis radix	7	2	1	115	9	5
Dioscoreae rhizoma	15	62	9	734	54	13
Lycii fructus	7	176	6	116	18	7
Ginseng radix et rhizoma	13	59	10	126	22	11
Notoginseng radix et rhizoma	16	31	12	166	35	15
Astragali radix	8	11	3	79	5	3
Lilii bulbus	18	14	6	551	34	15
Chrysanthemi flos	20	74	12	146	26	16
Arctii radix	9	0	0	317	14	3
Total	125	457	61	4,825	303	97

TABLE 2 List of pests and diseases of 10 species of target Chinese medicinal materials.

CMM name	Pests/diseases	Pesticides unavailable
Isatidis radix	Powdery mildew, root rot, leaf miner, wild slug, hainan microsnail, sclerotinia disease, downy mildew, black rot, white rust, cabbage butterfly, aphids, diamondback moth	Leaf miner, sclerotinia disease, black rot
Angelicae sinensis radix	Root Rot, soil-dwelling pests, sclerotinia disease, nematode, powdery mildew, gray mold, brown spot	Sclerotinia disease, brown spot
Dioscoreae rhizoma	Nematode, anthracnose, noctuid moth, leaf spot, black spot, root rot, seedling blight, whitefly, mites, thrips, wilt disease, wilting disease, bacterial wilt, soil-dwelling pests, blight	Wilt disease, wilting disease
Lycii fructus	Powdery mildew, aphids, mites, thrips, anthracnose, root rot, soil-dwelling pests	N/A
Ginseng radix et rhizoma	Black spot, rust rot, root rot, seedling blight, blight, gray mold, damping-off, anthracnose, powdery mildew, soil-dwelling pests, sclerotinia disease, nematode, red skin disease	Sclerotinia disease, red skin disease
Notoginseng radix et rhizoma	Root rot, black spot, blight, nematode, powdery mildew, gray mold, thrips, seedling blight, anthracnose, downy mildew, leaf spot, soil-dwelling pests, scale insects, wild slug, hainan microsnail, rust rot	Scale insects
Astragali radix	Nematode, powdery mildew, aphids, soil-dwelling pests, root rot, seedling blight, brown spot, pod borer	Aphids, root rot, seedling blight, brown spot, pod borer
Lilii bulbus	Blight, root rot, aphids, soil-dwelling pests, seedling blight, anthracnose, gray mold, leaf spot, nematode, wilt disease, wilting disease, bacterial wilt, black rot, angular leaf spot, scab, ulcer disease, fruit rot, sclerotinia disease	Wilt disease, wilting disease, sclerotinia disease
Chrysanthemi flos	Downy mildew, aphids, powdery mildew, gray mold, angular leaf spot, noctuid moth, rust, thrips, whitefly, soft rot, white rust, mites, soil-dwelling pests, leaf miner, black spot, root rot, southern blight, nematode, brown spot, viral disease	Gray mold, leaf miner, brown spot, viral disease
Arctii radix	Nematode, wilt disease, wilting disease, root rot, soil-dwelling pests, leaf miner, anthracnose, powdery mildew, black spot	Wilt disease, wilting disease, root rot, leaf miner, powdery mildew, black spot

constructed in this study (Figure 2), blue nodes represent 10 types of TCM materials, red nodes represent pests and diseases covered by pesticides, and yellow nodes represent pests and diseases with no available pesticides. The thickness of the edges between nodes is proportional to the weight of the number of pesticide registration certificates. For pests and diseases with no available pesticides, an edge weight of 0.1 is set to clearly define the "TCM material-pest and disease" association.

From the perspective of the overall structure of the graph, *Isatidis radix*, *Lilii bulbus*, and *Dioscoreae rhizoma* have the highest connection density of red nodes (pests and diseases covered by pesticides), which reflects that these three crops have the most sufficient pest and disease control resources. In contrast, *Arctii radix* and *Astragali radix* have the highest proportion of yellow nodes (pests and diseases with no available pesticides) (Figure 2).

For example, readers can directly identify 'control islands' by locating yellow nodes in Figure 2. The *Arctii radix* node is surrounded by multiple yellow nodes (such as Root Rot and Leaf Miner) with minimal connecting edges, visually confirming that low-value CMMs still suffer from severe pesticide shortages.

3.3.2 Differences between domestic and imported pesticide graphs

Figure 3 shows the differences in the pest and disease control spectra between domestic and imported pesticide registration certificates. As can be seen from the figure, a large proportion of domestic pesticides are concentrated on the control of Root Rot in crops such as *Isatidis radix*, *Angelicae sinensis radix*, and *Ginseng radix et rhizoma*, as well as the control of Anthracnose in *Dioscoreae rhizoma* and *Lycii fructus*. In contrast, imported pesticides have relatively balanced coverage of most pests and diseases, except for the relatively concentrated coverage of Diamondback Moth and Cabbage Butterfly.

To a certain extent, these two types of pesticides achieve complementary coverage. For example, domestic pesticides provide good coverage for the control of Soil-dwelling Pests on various crops, while imported pesticides supplement the control of insect pests such as Diamondback Moth and Cabbage Butterfly on *Lilii bulbus* and *Isatidis radix*.

For example, Figure 3 clearly illustrates the complementary relationship between the two sources. The domestic graph (left) shows thick edges converging on specific diseases like Root Rot across multiple CMMs, whereas the imported graph (right) demonstrates a more balanced distribution, filling the control gaps for insect pests like the Diamondback Moth.

From the perspective of the Pest and Disease Control Coverage Rate (PDCR), the pest and disease coverage rate of imported pesticides is significantly lower than that of domestic pesticides. At the single-crop level, *Lycii fructus* has the highest domestic PDCR (100%), with all 7 types of pests and diseases covered by domestic pesticides; *Arctii radix* has the lowest domestic PDCR (0%), with no domestic pesticides available for use; the domestic PDCR of *Angelicae sinensis radix*, *Ginseng radix et rhizoma*, and *Notoginseng radix et rhizoma* all exceed 80%, while their imported PDCR are all lower than 40%, which reflects that domestic pesticides are the core control resources for these crops.

These coverage patterns directly correlate with the findings in Section 4.1 regarding low-value-added CMM pesticide shortages. The data in Table 1 demonstrates that *Angelicae sinensis radix*, *Ginseng radix et rhizoma*, and *Notoginseng radix et rhizoma*, despite having domestic PDCR exceeding 80%, show imported PDCR below 40%,

10.3389/fsufs.2026.1759489

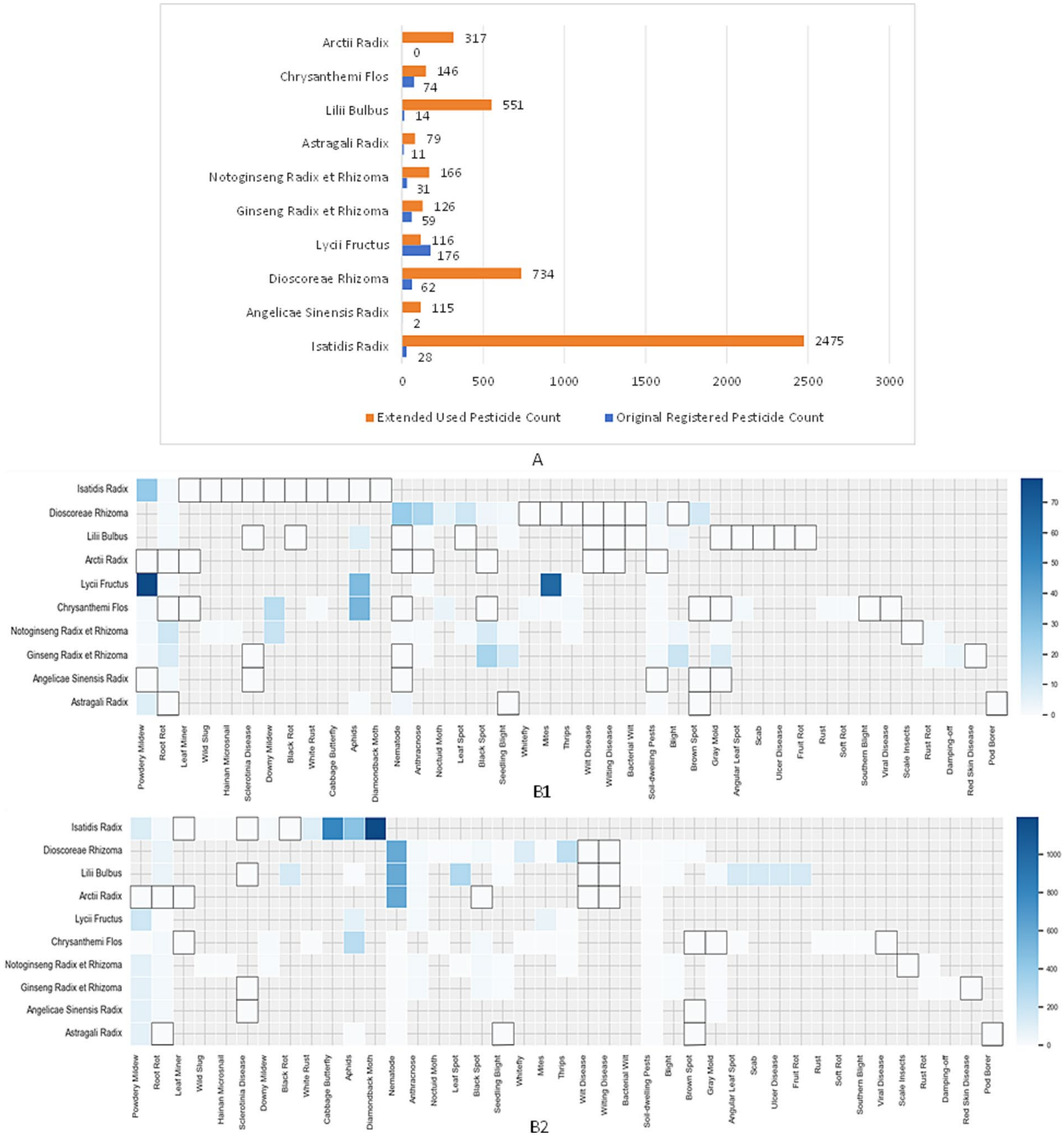

FIGURE 1
Pest and disease control status of 10 target Chinese medicinal materials. This figure presents the pesticide registration coverage for 10 Chinese medicinal materials (CMMs) before and after policy implementation. Panel **(A)** displays bar charts showing the distribution of Extended Used Pesticide Count (orange) and Original Registered Pesticide Count (blue) for each CMM. PDCR, pest and disease control coverage rate; values indicate the percentage of pest/disease pairs with at least one registered pesticide. Panel **(B)** presents heatmaps (**B1**: original registration; **B2**: extended use) where each cell represents the number of available pesticides for a specific CMM-pest/disease combination. Color intensity ranges from dark blue (high pesticide count) to white (low count). Light gray cells indicate the CMM is not affected by that pest/disease. Black-outlined cells highlight pest/disease pairs with zero registered pesticides, representing critical control gaps.

indicating domestic pesticides serve as the primary control resources for these crops. Conversely, for crops like *Arctii radix* with zero domestic PDCR, even imported pesticides provide only supplementary coverage (33%), underscoring the systemic registration deficit for certain minor CMMs.

From the perspective of the comprehensive indicator Registration Certificate Resource Distribution Intensity (RDI), the resource allocation efficiency of pesticide registration certificates for all 10 Traditional Chinese Medicine (TCM) materials is less than 1. Among them, the RDI of domestic pesticides shows obvious differences: *Isatidis radix* has the highest domestic RDI, reaching 65%, and it is the only crop with a domestic RDI exceeding 50%, while the domestic RDI of 5 TCM materials including *Angelicae sinensis radix*, *Ginseng radix et rhizoma*, *Notoginseng radix et rhizoma*, *Astragali radix*, and *Chrysanthemi flos* are all lower than 5%; for imported pesticides, except for *Isatidis radix*, the imported RDI of the other 9 TCM materials are all higher than their respective domestic RDI; from the perspective of the overall RDI of the 10 TCM materials, the average value is 14%, among which *Isatidis radix*

 10.3389/fsufs.2026.1759489

has the highest overall RDI at 63%, and *Angelicae sinensis radix* has the lowest overall RDI at only 3%.

For example, Figure 4 intuitively plots this efficiency gap: *Isatidis radix* exhibits both high PDCR and high RDI, indicating concentrated resource input, whereas *Angelicae sinensis radix* achieves a high PDCR despite a very low RDI (3%), showcasing highly efficient resource utilization.

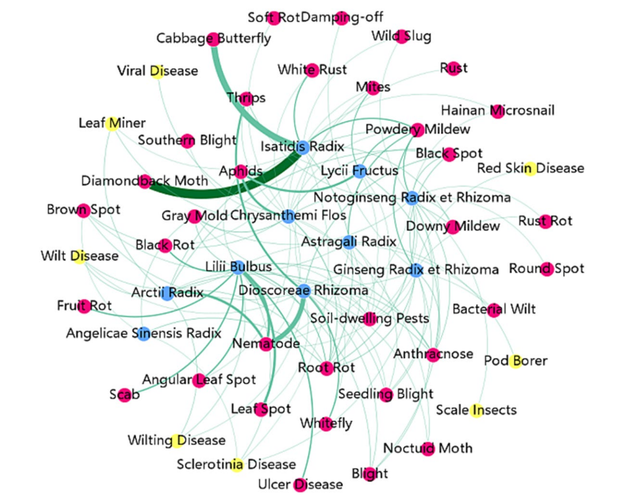

FIGURE 2
Knowledge graph of the relationship between registration certificates and pests/diseases for 10 Traditional Chinese Medicine (TCM) materials. Knowledge graph illustrating the tripartite relationship among 10 Chinese medicinal materials (CMMs), their pests/diseases, and registered pesticides. Node types: Blue circular nodes represent CMMs; red diamond nodes indicate pests/diseases with registered pesticide coverage; yellow diamond nodes denote pests/diseases lacking pesticide coverage. Edge thickness is proportional to the number of registration certificates available for each CMM-pest/disease pair. Dense red node clusters with thick edges indicate robust pesticide coverage; isolated yellow nodes reveal critical resource deficiencies.

4 Discussion

This study focuses on 10 widely cultivated Traditional Chinese Medicine (TCM) materials, including *Isatidis radix*, *Angelicae sinensis radix*, and *Dioscoreae rhizoma*, which are representative in multiple aspects such as therapeutic fields, family and genus coverage, planting scale, production area span, and economic value. Using 50,723 valid pesticide registration data entries from the "China Pesticide Information Network," the study systematically collated and statistically analyzed three levels of authoritative sources—authoritative monographs, core agricultural journals, and local documents—to construct a list of 41 species (categories) of pests and diseases for the 10 TCM materials, forming 125 "TCM material-pest and disease" pairs.

On this basis, the study used knowledge graph visualization tools to identify the "island phenomenon" in the control of "TCM material-pest and disease" pairs (e.g., no pesticides matched any pests or diseases in the original registration of *Arctii radix*). Additionally, it innovatively applied the Registration Certificate Resource Distribution Intensity (RDI) index to systematically measure the pesticide resource allocation efficiency of the 10 TCM materials, providing a quantitative basis for the subsequent optimization of registration resources and adjustment of relevant policies.

4.1 Macro-summary and trend insights of data results

This challenge is not unique to China's CMM sector Reddy et al. (2024) examined pesticide regulation for minor crops in Indian

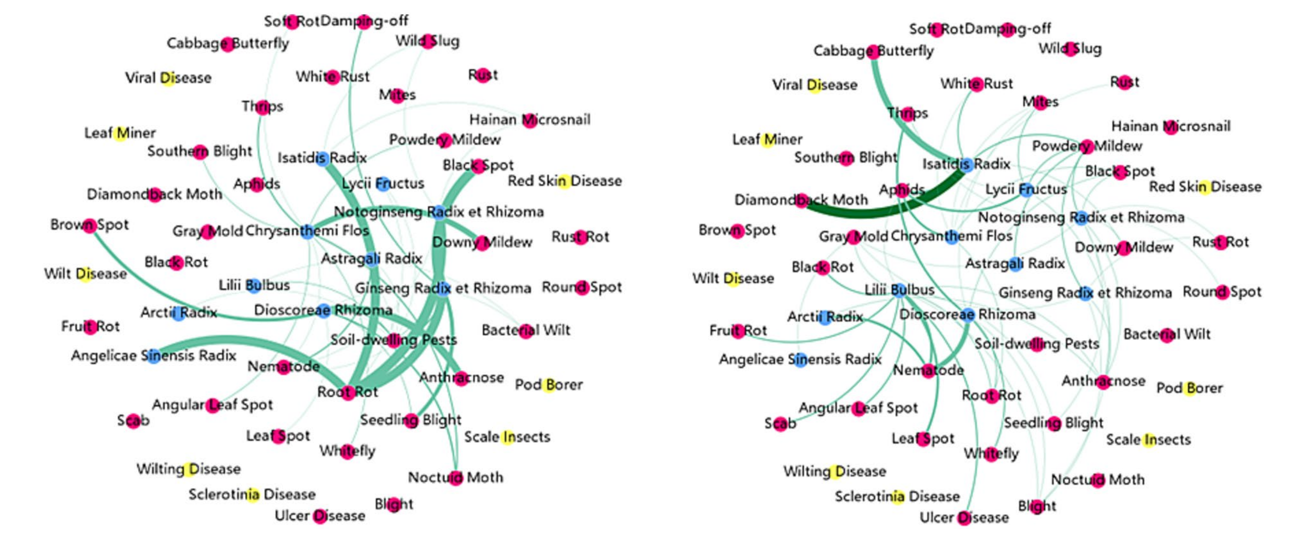

FIGURE 3
Left: Knowledge graph of domestic pesticide registration certificates and pests/diseases; right: knowledge graph of imported pesticide registration certificates and pests/diseases. Comparative visualization of domestic (left panel) versus imported (right panel) pesticide registration coverage across 10 CMMs. Node coding: Blue circular nodes, CMMs; red diamond nodes, covered pests/diseases; yellow diamond nodes, uncovered pests/diseases. Edge thickness reflects registration certificate count. Domestic networks show clustering around specific disease types, while imported networks exhibit more uniform distribution with concentration on insect pests. The complementary coverage pattern demonstrates differential registration strategies between domestic and imported pesticides.

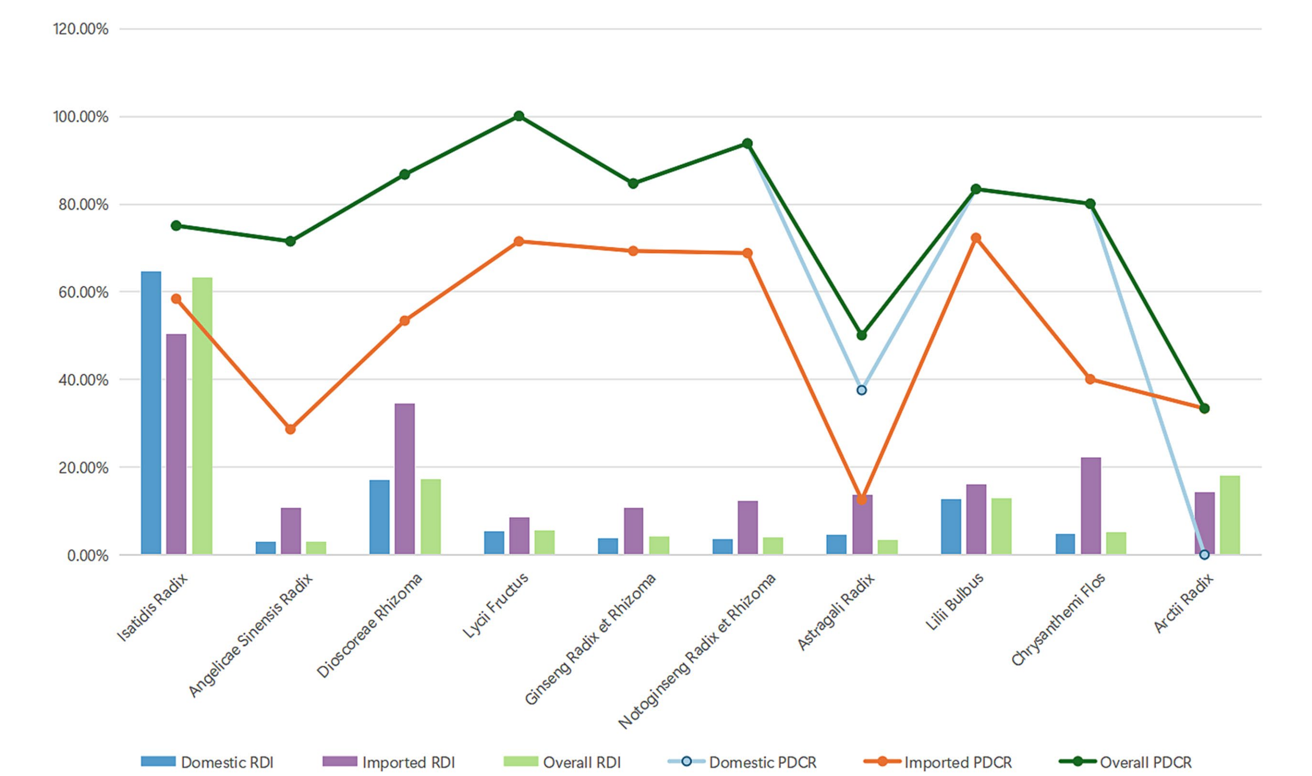

FIGURE 4
Resource utilization of domestic and imported registration certificates for Traditional Chinese Medicine (TCM) materials. Scatter plot comparing resource allocation efficiency (RDI) against coverage breadth (PDCR) for 10 CMMs. Axes: X-axis, PDCR (% of pest/disease pairs with registered pesticides); Y-axis, RDI (registration certificate resource distribution intensity, %). Points above diagonal indicate resource concentration; points below suggest efficient utilization. *Isatidis radix* exemplifies high resource concentration (PDCR 75%, RDI 65%), while *Angelicae sinensis radix* demonstrates high efficiency (PDCR 71%, RDI 3%).

agriculture, highlighting similar tensions between market-driven registration incentives and public plant protection needs for specialty crops with limited commercial scale. Their study emphasized that effective minor crop pesticide policies require targeted government intervention including registration subsidies, technical support, and streamlined approval pathways—recommendations that align with our findings on the need for enhanced policy support for low-value-added CMMs in China's medicinal material industry.

From the current status of pesticide registration for pest and disease control of the 10 TCM materials, the implementation of policies expanding the applicable scope of pesticides (such as the Group List) has significantly alleviated the dilemma of "difficulty in accessing pesticides." Before the policy implementation, only 49% of the 125 "TCM material-pest and disease" pairs had legally available pesticides; after the implementation, the overall coverage rate increased to 78%, and 36 pairs that previously had no available pesticides (e.g., "*Isatidis radix*-Black Rot," "*Angelicae sinensis radix*-Soil-dwelling Pests") obtained support from registered pesticides, demonstrating a clear effect of policy intervention. Among them, the improvement of *Arctii radix* was particularly prominent: in the original registration stage, none of its 9 species (categories) of pests and diseases had legally available pesticides, while after the policy implementation, its PDCR increased to 33%, and 3 species of pests and diseases (Nematode, Soil-dwelling Pests, Anthracnose) achieved registration coverage. However, it should be noted that the coverage of expansion policies for crops with low economic added value still needs to be strengthened (Reddy et al., 2024). Specifically, five out of eight pests and diseases of *Astragali radix* (accounting for 62%) and six out of nine pests and diseases of *Arctii radix* (accounting for 67%) still have no available pesticides. This reflects that the long-term dilemma of "pesticide shortage" for special minor crops has not been fully resolved, and further policy inclination is required.

From the perspective of the variety distribution of registration resources, the characteristic of imbalance is significant. Crops with high economic value, such as *Ginseng radix et rhizoma*, *Lycii fructus*, *Notoginseng radix et rhizoma*, and *Lilii bulbus*, occupy more original registration resources (e.g., *Lycii fructus* has 176 original registration certificates, accounting for 38% of the total original registration quantity). In contrast, *Arctii radix* has 0 original registration certificates, and *Angelicae sinensis radix* has only 2, showing obviously insufficient coverage. Essentially, this difference reflects the potential tension between market mechanisms and public plant protection needs: enterprises are more inclined to invest in registration costs for high-value-added crops, while the public plant protection needs of low-value-added crops cannot be met spontaneously through the market. This also reveals that in the future policy implementation, it is necessary to specifically strengthen registration subsidies and technical support for crops with low economic added value to balance the distribution of resources.

4.2 Strategic analysis of domestic and imported pesticides

Further analysis of the Registration Certificate Resource Distribution Intensity (RDI) index and registration data reveals that after the implementation of the expansion policy, domestic pesticides occupy an absolutely dominant position in the total number of registrations, but their resource utilization efficiency is significantly lower than that of imported pesticides. This efficiency difference stems from the fundamental distinction in their registration strategies: domestic pesticides exhibit a highly concentrated targeting characteristic. For example, 44% of domestic registration certificates for *Ginseng radix et rhizoma* and *Notoginseng radix et rhizoma* are concentrated on the control of Powdery Mildew; while imported pesticides have a limited total quantity (303 items), they feature a prominent multi-target characteristic per certificate.

In addition, imported pesticides play a key supplementary role in crops with low coverage. For instance, imported pesticides provide more registration options for the control of insect pests such as Diamondback Moth and Cabbage Butterfly on *Isatidis radix*. This complementary relationship indicates that under the existing registration framework, the two types of pesticides assume different functions: basic coverage and precise supplementation. The high value-added attribute of Traditional Chinese Medicine (TCM) materials may reduce price sensitivity, which also provides potential space for optimizing the broad-spectrum performance of domestic pesticides.

4.3 The correlation between pesticide registration data and actual application

Although registration data provides a basis for legal pesticide use, there remains a significant disconnect between such data and actual pest control needs. For crops with no registered pesticides (e.g., *Arctii radix*), farmers are forced to illegally use pesticides registered for vegetables (such as chlorpyrifos and lambda-cyhalothrin), which drastically increases the risk of pesticide residue exceeding standards (Northwest A&F University, n.d.). Meanwhile, the existing registration system struggles to dynamically respond to the evolution of pests and diseases. For example, pests and diseases that have broken out in recent years—such as *Astragali radix* Brown Spot (Lücaodi Garden Network, n.d.) and *Dioscoreae rhizoma* Wilt Disease (Ma et al., 2019)—have not been included in the registration catalog. This lag stems from two factors: first, high registration costs and long-term maintenance expenses have dampened the innovation motivation of domestic enterprises; second, the pest and disease monitoring system is inadequate, and data from grassroots agricultural technology stations fail to effectively connect with the registration review system. It is suggested to establish a two-way traceability mechanism, enabling the secure transmission of field pesticide application data to registration authorities through digital technology. Additionally, special dynamic monitoring should be implemented for high-risk crops to shorten the market launch cycle of new pesticides.

4.4 Application value and practical possibilities of the knowledge graph

The knowledge graph of TCM material pesticide registration constructed in this study realizes the spatial presentation of 125 "TCM material-pest and disease" combination relationships through the Gephi platform, achieving three key breakthroughs: First, it visually exposes weak coverage links (such as the isolated state of the *Arctii radix* node), providing precise targets for policy intervention; second, it quantifies biases in resource allocation (e.g., registration certificates for *Dioscoreae rhizoma* Nematode account for 54% of the total registration certificates for this crop, while those for *Chrysanthemi flos* Powdery Mildew only account for 0.55%); third, it reveals the complementarity between domestic and imported pesticides (e.g., domestic pesticides cover 88% of Soil-dwelling Pests, and imported pesticides dominate the control of 100% of *Chrysanthemi flos* Rust).

This knowledge graph can be directly applied to agricultural decision support systems: by identifying field pest and disease images, it can automatically match the list of registered pesticides; combined with historical meteorological data, it can generate regional outbreak risk heatmaps. In subsequent research, by constructing an extended model incorporating the registration cost of individual pesticides, a risk–benefit assessment mechanism can be further established to calculate the quality and safety risk thresholds of low economic value-added crops. Based on this, registration subsidy policies for characteristic crops can be designed to resolve the structural contradiction between high registration costs and low economic returns.

4.5 Generalizability and future refinements

The knowledge graph and RDI-PDCR evaluation framework proposed in this study extend beyond the 10 specific CMMs analyzed. This methodology can be generalized to evaluate plant protection resource allocation for other specialty minor crops globally, such as tropical fruits or regional niche vegetables, which similarly suffer from the "minor crop, major pest" dilemma. Furthermore, the graph-based analytical logic could be adapted for veterinary medicine to monitor and assess the off-label use of drugs across different minor animal species.

Future refinements of this model will incorporate the economic costs of pesticide registration. By integrating dynamic data such as enterprise registration fees and crop market values, an advanced risk–benefit assessment model could be developed. This would allow policymakers to quantitatively determine the exact financial subsidy threshold required to incentivize domestic enterprises to register pesticides for low-value-added crops.

5 Conclusion

This study advances the field of agricultural policy evaluation by transitioning from traditional, single-dimensional pesticide counting to a multi-dimensional, knowledge graph-based analytical framework. By introducing the Registration Certificate Resource Distribution Intensity (RDI) metric alongside the PDCR, we quantitatively mapped the complex "crop-pest-pesticide" tripartite relationships for 10 representative CMMs.

While our findings confirm that recent policy expansions successfully increased overall legal pesticide coverage from 49 to 78%, the novel graph-based approach revealed critical, non-obvious systemic flaws: the market mechanism inherently fails low-value-added crops (e.g., *Arctii radix*), and there is a stark efficiency disparity between domestic (highly concentrated) and imported (broad-spectrum) pesticide registration strategies. These insights provide data-driven evidence for policymakers to move beyond generic scope expansions and implement targeted, crop-specific registration subsidies to truly resolve the pesticide shortage in the CMM industry.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

This study did not involve human subjects or animal experiments, and thus required no ethical approval.

Author contributions

LB: Conceptualization, Formal analysis, Writing – review & editing, Writing – original draft. XL: Formal analysis, Writing – original draft. MW: Writing – original draft, Data curation. NS: Data curation, Writing – original draft. HL: Writing – original draft, Conceptualization. XFL: Writing – review & editing, Conceptualization. WX: Writing – review & editing, Conceptualization.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This work was supported by the National Key Research and Development Program (2022YFD2100604).

Conflict of interest

NS was employed by Nanjing Zhimai Information Technology Co., Ltd.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Chen, K., Tan, Y., Li, M., and Li, X. (n.d.). Pest and Disease Control Technology for Chinese Medicinal Crops. Available online at: https://www.shukui.net/book/3551253.html (Accessed March 11, 2026).

China Association of Traditional Chinese Medicine (2024). *China Traditional Chinese Medicine Industry Development Report 2024: Medicinal Materials and Decoction Pieces*. Beijing: Social Sciences Academic Press.

China Pesticide Information Network (2025) in Pesticide Registration Database, Beijing: Ministry of Agriculture and Rural Affairs.

China Science Communication (n.d.) *Agrotis ipsilon* (Black Cutworm) Available online at: https://www.kepuchina.cn/article/articleinfo?business_type=100&ar_id=345581 (Accessed March 11, 2026).

Chinese Society of Agricultural Machinery. (2023). A CDSSM-based prescription recommendation method for crop diseases. J. CSAM. Available online at: http://www.j-csam.org/jcsam/article/abstract/20230331 (Accessed March 11, 2026).

Dai, D., Shen, Y., Shen, Y., Wu, J., Liu, Y., and Zhang, C. (2019). Research progress on chemical control for main disease and insect pests of characteristic Chinese herbal medicines in Zhejiang Province. *Chin. J. Pestic. Sci.* 21, 759–771. doi: 10.16801/j.issn.1008-7303.2019.0097

Ding, D., Jiang, F., Cao, L., and Kang, L. (2024) Innovate and create novel mycoinsecticide system to promote green development of agriculture Bull. Chin. Acad. Sci. 40 1089–1102. Available online at: https://bulletinofcas.researchcommons.org/journal/vol40/iss6/20/ (Accessed March 11, 2026).

European Minor Uses Coordination Facility (2023). European Union Policy Framework on Minor-Use Plant Protection Products Brussels EMUCF. Available online at: https://www.minoruses.eu/ (Accessed March 11, 2026).

Health Canada (2021). *Minor Use Pesticide Program: Memorandum of Understanding between Agriculture and Agri-Food Canada and Health Canada*. Ottawa: Health Canada.

Launois, R., Cabout, E., Benamouzig, D., Velpry, L., Briot, K., Alliot, F., et al. (2022). Barriers and expectations for patients in post-osteoporotic fracture care in France: the EFFEL study. *Value Health* 25, 571–581. doi: 10.1016/j.jval.2021.10.005

Li, F., Dong, F., Yang, J., Luo, Y., Gao, K., Piao, X., et al. (2022). Current status and prospects of pesticide use risk management for characteristic minor crops in China. *Mod. Agrochem.* 21, 1–7.

Lin, K., Nan, J., Hu, Y., Mou, W., and Fan, H. (2024). Research progress on green prevention and control technologies for diseases and pests in medicinal plants. *Plant Health Med.* 3, 1–10.

Lücaodi Garden Network (n.d.) Which Pesticides Can Be Used to Control Burdock Root?. Available online at: https://www.lvcaod.com/news/huamuxuetang/8250153.html (Accessed March 11, 2026).

Ma, Y., Guan, Y., Wang, Q., Li, M., Pan, X., and Zhang, Y. (2019). Research progress on main diseases of *Astragalus membranaceus* and their control measures. *Special Wild Econ Anim Plant Res* 41, 101–107.

Ministry of Agriculture and Rural Affairs General Office (2019) in *Notice on Issuing the List of Minor-Use Characteristic Crops With Shortage of Plant Protection Products... Nong Ban Nong [2019] No. 10*, ed. MARA (Beijing: Ministry of Agriculture and Rural Affairs.).

Ministry of Agriculture, Livestock and Food Supply (MAPA) (2022) in *Ordinance No. 691/2022: Guidelines for Pesticide Registration on Minor-Use and Specialty Crops (CSFI)*, ed. MAPA (Brasília: Ministry of Agriculture, Livestock and Food Supply (MAPA)).

Nong Baike (n.d.) What Is the Difference Between Spider Mites and Red Spider Mites?. Available online at: https://www.ke82.com/wenda/1731554103607319.html (Accessed March 11, 2026).

Northwest A&F University (n.d.) How to solve the "World-wide problem" of Regulating Pesticide use on minor crops?. Available online at: https://greenpesticide.nwsuaf.edu.cn/yjdt/a92d6028eade42b68e51fc8693ff6ac8.htm (Accessed March 11, 2026).

Pharmacopoeia Commission of the People's Republic of China (2020). *Pharmacopoeia of the People's Republic of China 2020 Ed*. Beijing: China Medical Science and Technology Press.

Reddy, A. A., Reddy, M., and Mathur, V. (2024). Pesticide use, regulation, and policies in Indian agriculture. *Sustainability* 16:7839. doi: 10.3390/su16177839

Shandong Association of Agricultural Science Societies (2023) in *T/SAASS 117–2023 Technical Code of Practice for Green Management of Diseases, Pests and Weeds in*

Common Chinese Medicinal Crops, ed. SAASS (Jinan: Shandong Association of Agricultural Science Societies (SAASS)).

Standing Committee of the National People's Congress (2024). *Food Safety Law of the People's Republic of China (rev. 2021-04-29)*. Beijing: Standing Committee of the National People's Congress.

State Council (2023). *Regulations on Pesticide Administration (rev. 2022-03-29)*. Beijing: Department of Policy and Law, Ministry of Agriculture and Rural Affairs.

U.S. Environmental Protection Agency (2015). Pesticide Control Act of 1963. Available online at: https://www.epa.gov/pesticides (Accessed March 11, 2026).

Wang, S., Wang, X., and Liu, Y. (2025). Degradation behavior and safety evaluation of pyraclostrobin on three characteristic minor crops. *Chinese Agricultural Science Bulletin* 41, 151–157. doi: 10.11924/j.issn.1000-6850.casb2024-0085

Wu, H., and Lin, W. (2020). A commentary and development perspective on the consecutive monoculture problems of medicinal plants. *Chin. J. Eco-Agric.* 28, 775–793. doi: 10.13930/j.cnki.cjea.190760

Zhuo, F., Liu, W., and Zhao, Z. (2023). *Color Atlas of Green Pest and Disease Control for Common Chinese Medicinal Crops*. Beijing: China Agriculture Press.