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Article

Reconstructing pharmaceutical service competency framework: development of AI-informed competency indicators and localized practices in China

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ABSTRACT

This study introduces an innovative method for reconstructing pharmaceutical service competency frameworks. The approach integrates artificial intelligence technologies with localization practices specific to the Chinese context. Employing a mixed-methods sequential exploratory design, we analyzed six major international competency frameworks using natural language processing and machine learning techniques to extract 4,782 unique competency statements, which were subsequently classified with 91.4% accuracy into relevant domains. The resulting preliminary integrated framework—comprising 5 domains, 24 competencies, and 103 behavioral indicators—underwent localization through a modified Delphi process involving 32 pharmaceutical stakeholders and verification via a national survey of 456 pharmacists across 18 Chinese provinces. Implementation across diverse healthcare settings resulted in significant improvements in service quality metrics, including a 23.7% reduction in medication errors ($p<0.01$) and an 18.6% increase in patient satisfaction. Cross-setting analysis revealed variable adaptability, with implementation feasibility scores ranging from 4.7/5 in tertiary hospitals to 3.2/5 in rural community pharmacies. Four critical success factors for effective framework adoption were identified: institutional leadership engagement, integration with existing quality systems, phased implementation, and dedicated training resources. The framework's distinctive features include competencies addressing the integration of traditional Chinese medicine with modern pharmacy practice and a modular structure enabling context-specific adaptation while maintaining core standards. This research contributes to bridging the gap between global standards and local realities in pharmaceutical competency development, demonstrating the potential of AI-informed approaches to enhance framework relevance, efficiency, and effectiveness across diverse healthcare contexts.

1. Introduction

In the rapidly evolving healthcare landscape, pharmaceutical services have undergone significant transformation, moving beyond traditional dispensing roles to encompass comprehensive patient-centered care. This evolution necessitates a robust competency framework that can effectively guide pharmacists' professional development and ensure quality service delivery [1]. Despite the International Pharmaceutical Federation's (FIP) efforts to establish a Global Competency Framework (GCF), the applicability and effectiveness of such frameworks across diverse healthcare systems remain challenging due to variations in cultural, economic, and regulatory contexts [2]. While numerous studies have examined the adaptation of international pharmacy competency frameworks within specific national contexts [3], limited research has explored the integration of artificial intelligence (AI) methodologies in developing and localizing such frameworks. The pharmaceutical service landscape in China presents a unique case study for such integration, with its rapidly modernizing healthcare system, expanding pharmaceutical industry, and distinctive cultural and regulatory environment exemplifying the complexities of adapting international competency frameworks to local contexts [4].

Abbreviations

AI	Artificial Intelligence
ACCP	American College of Clinical Pharmacy
APPF	Advanced Pharmacy Practice Framework
BERT	Bidirectional Encoder Representations from Transformers
FIP	International Pharmaceutical Federation
FLFP	European Foundation Level Pharmacy Framework
GCF	Global Competency Framework
GPhC	General Pharmaceutical Council
KMO	Kaiser-Meyer-Olkin
NAPRA	National Association of Pharmacy Regulatory Authorities
NLP	Natural Language Processing
NLTK	Natural Language Toolkit
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RDF	Resource Description Framework
SPSS	Statistical Package for the Social Sciences
SVM	Support Vector Machine
TF-IDF	Term Frequency-Inverse Document Frequency
W	Kendall's Coefficient of Concordance

The emergence of AI as a transformative force in healthcare offers unprecedented opportunities to enhance the development of competency frameworks through sophisticated data analysis, pattern recognition, and predictive modeling [5]. AI technologies can potentially identify competency gaps, predict future skill requirements, and customize frameworks to specific healthcare environments, thereby addressing the persistent challenge of framework relevance and adaptability [6]. The application of AI in this process can facilitate more nuanced analysis of these variations and more effective customization of competency indicators [7]. Recent advancements in AI applications for healthcare systems have demonstrated significant potential for improving service quality assessment and professional development frameworks [8]. Traditional frameworks often inadequately address China's specific challenges. These challenges include urban-rural disparities in pharmaceutical care, evolving regulatory requirements, and the integration of traditional Chinese medicine with modern pharmacy practice. Cross-national comparisons of pharmaceutical service quality indicators have highlighted significant variations in practice standards, service delivery models, and patient outcomes across different healthcare systems [9]. These variations underscore the importance of developing competency frameworks that are not only informed by international best practices but also responsive to local healthcare needs and priorities [10]. Studies on quality criteria in cross-country healthcare comparisons emphasize the need for contextually appropriate assessment frameworks that account for systemic differences while maintaining core quality standards [11]. The adaptation process requires careful consideration of local healthcare structures, cultural factors, and existing practice standards, as demonstrated by successful localization efforts in various countries [12]. Evidence from Thailand and other countries suggests that effective competency frameworks must balance international standards with local healthcare priorities and professional development pathways [13, 14].

This study aims to reconstruct the pharmaceutical service competency framework through an innovative approach that combines AI-informed analysis of international competency indicators with rigorous localization practices tailored to the Chinese healthcare context. The significance of this research lies in its potential to bridge the gap between global standards and local realities in pharmaceutical service delivery. By developing an AI-informed, culturally adaptive competency framework, this research contributes to the advancement of pharmaceutical care quality, the enhancement of pharmacist professional development, and ultimately, the improvement of patient outcomes in diverse healthcare settings [15]. Previous research has established strong connections between well-defined competency frameworks and improvements in service quality across pharmaceutical supply chains [16]. Integration of service quality assessment with competency frameworks has shown promising results in hospital pharmaceutical services [17]. Through a systematic approach to framework reconstruction that incorporates both international best practices and local contextual factors, this study addresses a critical need in pharmacy education and practice: the development of competency frameworks that are both globally informed and locally relevant, technologically innovative yet practically applicable in everyday pharmaceutical service delivery [18].

2. Data and methods

2.1 Research design and data sources

This study employed a mixed-methods sequential exploratory design combining systematic literature review, expert consultation, and computational analysis to develop a pharmaceutical service competency framework that is both internationally informed and locally adapted [19]. The research followed a four-phase protocol:

Phase I: Systematic review of international competency frameworks

Phase II: AI-assisted competency indicator extraction and analysis

Phase III: Localization through expert consultation

Phase IV: Verification and validation of the proposed framework

The systematic review was conducted following PRISMA guidelines, with searches performed in five electronic databases: PubMed, Scopus, Web of Science, CNKI, and Wanfang [20]. The search strategy employed Boolean operators with key terms including "pharmacy competency framework," "pharmaceutical service quality," "AI in pharmacy practice," and "competency localization." The inclusion criteria specified publications from 2010 to 2024 in English and Chinese languages with full-text availability [21]. After duplicate removal and screening against inclusion/exclusion criteria, 78 documents were selected for the final analysis, including competency frameworks from 12 countries and 6 international organizations. The sequential nature of this design allowed findings from each phase to inform subsequent phases, strengthening the methodological rigor and enabling triangulation of results across different data sources and analytical approaches [22]. This approach aligns with recommendations from Nasa et al. regarding methodological frameworks for healthcare competency studies [23].

2.2 Analysis of international pharmaceutical service competency frameworks

2.2.1 Framework selection and evaluation criteria

Six major pharmaceutical competency frameworks were selected for in-depth analysis based on their international recognition, comprehensiveness, and influence on global pharmacy practice standards [24]:

- FIP Global Competency Framework (GCF)
- Advanced Pharmacy Practice Framework for Australia

- American College of Clinical Pharmacy (ACCP) Clinical Pharmacist Competencies
- General Pharmaceutical Council Framework (UK)
- Canadian National Association of Pharmacy Regulatory Authorities' Professional Competencies
- European Foundation Level Pharmacy Framework

Each framework was evaluated using a 15-item assessment matrix adapted from Anderson et al.'s global pharmacy education perspective [25]. The evaluation criteria encompassed five domains: structural organization (3 items), content coverage (4 items), implementation guidance (3 items), assessment methodologies (3 items), and cultural adaptability (2 items). Each criterion was scored on a scale of 1-5, with higher scores indicating stronger alignment with international standards.

2.2.2 Comparative analysis process

The comparative analysis involved a three-stage process conducted by independent researchers with pharmaceutical backgrounds. First, content mapping identified common domains and competency clusters across frameworks. Second, gap analysis highlighted unique elements and potential areas for integration. Finally, consensus meetings resolved discrepancies in coding and interpretation [26]. The reliability of this analysis was ensured through the calculation of inter-rater agreement using Cohen's kappa coefficient:

$$\kappa = \frac{p_0 - p_e}{1 - p_e} \quad (1)$$

Where p_0 represents the observed agreement and p_e represents the expected agreement by chance [27-29]. A threshold of $\kappa \geq 0.80$ was established to indicate substantial agreement between coders.

2.3 AI-Assisted competency indicator system construction method

2.3.1 Natural language processing and text mining

The development of the competency indicator system was facilitated by AI technologies, specifically natural language processing (NLP) and machine learning algorithms [30]. Initially, textual data from the selected competency frameworks was preprocessed using NLP techniques, including tokenization, lemmatization, and stop-word removal to standardize terminology and reduce dimensionality [31]. Text mining procedures extracted key concepts and relationships using term frequency-inverse document frequency (TF-IDF) vectorization:

$$TF - IDF_{i,j} = TF_{i,j} \times \log\left(\frac{N}{df_i}\right) \quad (2)$$

Where $TF_{i,j}$ is the frequency of term *i* in document *j*, *N* is the total number of documents, and df_i is the number of documents containing term *i* [32].

2.3.2 Machine learning classification and knowledge graph construction

A supervised machine learning approach was implemented to classify competency statements according to their conceptual similarity and hierarchical relationships. The classification model utilized an ensemble approach combining random forest and support vector machine algorithms, which demonstrated superior performance in preliminary testing [33]:

$$F_1 = 2 \times \frac{precision \times recall}{precision + recall} \quad (3)$$

The F1-score, a harmonic mean of precision and recall, was used to evaluate model performance, with values exceeding 0.85 for all competency domains [34]. The relationships between competency domains, competencies, and behavioral indicators were mapped using knowledge graph construction techniques [35]. The knowledge graph *G* was defined as:

$$G = (V, E, R) \quad (4)$$

Where *V* represents the set of nodes (competency elements), *E* represents the edges (relationships), and *R* represents the types of relationships between nodes [36]. This visualization facilitated the identification of gaps in existing frameworks and informed the development of new competency indicators. Table 1 summarizes the AI techniques applied and their specific functions in the competency framework development process.

Table 1. AI techniques applied in competency framework development

Technique	Algorithm/Method	Function in Framework Development	Performance Metric
Text Preprocessing	NLTK, SpaCy	Standardization of competency descriptors	Vocabulary reduction: 68%
Term Extraction	TF-IDF, n-grams	Identification of key competency concepts	Precision: 0.87
Text Classification	Random Forest, SVM	Categorization of competency statements	F1-score: 0.89
Semantic Analysis	Word2Vec, BERT	Similarity assessment between competencies	Cosine similarity >0.75
Knowledge Graph	Neo4j, RDF	Relationship mapping between competencies	Node connectivity: 0.82

2.4 Localization research and verification

2.4.1 Modified delphi process

The localization process employed a modified Delphi method to adapt the internationally derived competency framework to the Chinese healthcare context [37]. An expert panel comprising 32 stakeholders was purposively selected based on their expertise, professional background, and geographic distribution. The panel composition included hospital pharmacists (n=12), community pharmacists (n=6), pharmacy educators (n=8), healthcare administrators (n=4), and pharmaceutical policymakers (n=2) [38]. The Delphi process consisted of three sequential rounds:

- **Framework Review**: Experts evaluated the relevance and appropriateness of each competency domain and indicator using a 5-point Likert scale and provided qualitative feedback.
- **Indicator Refinement**: Focused on modifying indicators that achieved less than 75% consensus, with experts suggesting adjustments to improve cultural and contextual fit.

- **Framework Validation**: Assessment of the revised framework's practical applicability across different pharmaceutical service settings in China.

Consensus was defined using the following criterion:

$$Consensus\ Rate = \frac{Number\ of\ experts\ raiting\ item\ as\ 4\ or\ 5}{Total\ number\ of\ experts} \times 100\% \qquad (5)$$

Items achieving ≥75% consensus were retained, while those below this threshold were either modified or eliminated based on expert feedback [39].

2.4.2 National survey

To supplement the expert panel insights, a national survey was conducted with 456 practicing pharmacists across 18 Chinese provinces. Stratified random sampling ensured representation across hospital settings (tertiary, secondary, primary), community pharmacies, and specialized pharmaceutical services [40]. The survey instrument contained 42 items addressing perceived competency needs, practice challenges, and contextual factors influencing pharmaceutical service delivery in China [41]. Response data was analyzed using descriptive statistics and factor analysis to identify latent constructs underlying competency requirements in the Chinese context [42]. The integration of survey findings with Delphi results enhanced the ecological validity of the framework localization process.

2.5 Data analysis methods

2.5.1 Quantitative analysis

Statistical analysis was conducted using SPSS version 26.0 and R version 4.1.2. For the framework comparison, descriptive statistics characterized the distribution of competency domains and indicators across frameworks. The Delphi study results were analyzed using non-parametric statistics, including Kendall's coefficient of concordance (W) to assess agreement among experts [43]:

$$W = \frac{12\sum(R_j-\bar{R})^2}{m^2(n^3-n)} \qquad (6)$$

Where R_j is the sum of ranks for the j_{th} item, $\bar{R}$ is the mean of the rank sums, m is the number of experts, and n is the number of items being ranked [44].

Factor analysis using principal component extraction with varimax rotation was applied to survey data to identify underlying competency dimensions. The Kaiser-Meyer-Olkin (KMO) measure verified sampling adequacy (KMO = 0.87), and Bartlett's test of sphericity confirmed appropriateness for factor analysis ($p < 0.001$) [45].

2.5.2 Qualitative Analysis

Qualitative data from expert feedback underwent thematic analysis involving open coding, category development, and theme identification [46]. A constant comparative method facilitated the refinement of themes and identification of relationships between concepts [47]. NVivo 12 software supported the organization and visualization of qualitative findings. The integration of quantitative and qualitative analyses enabled methodological triangulation, enhancing the robustness and validity of the resultant pharmaceutical service competency framework [48]. The final framework was further validated through comparative analysis with existing Chinese pharmaceutical practice standards to identify areas of alignment and divergence [49, 50].

3. Results

3.1 Comparative analysis of international pharmaceutical service competency frameworks

3.1.1 Structural and content comparison

The comparative analysis of six international pharmaceutical service competency frameworks revealed both common elements and distinctive characteristics across different jurisdictions. Table 2 presents the structural comparison of these frameworks, highlighting variations in organizational approach, granularity, and scope.

Table 2. Structural comparison of international pharmaceutical service competency frameworks

Framework	Number of Domains	Number of Competencies	Number of Behavioral Indicators	Development Approach	Update Frequency
FIP GCF	4	20	100	Consensus-based	5 years
Australia APPF	5	30	114	Evidence-based	3-5 years
ACCP Framework	6	27	92	Expert panel	10 years
UK GPhC	4	18	76	Regulatory-driven	5 years
Canadian NAPRA	5	24	88	Collaborative	7 years
European FLFP	4	19	81	Consensus-based	Not specified

Content analysis identified six common competency domains across frameworks: (1) pharmaceutical care and patient-centered services, (2) professional and ethical practice, (3) communication and collaboration, (4) leadership and management, (5) education and research, and (6) quality assurance and improvement. However, significant variations were observed in the emphasis placed on different domains. North American frameworks (ACCP, NAPRA) placed greater emphasis on clinical interventions and specialized pharmaceutical care (28-32% of competency indicators), while European frameworks prioritized communication and interprofessional collaboration (24-27% of indicators) [29]. Figure 1 presents a comparative analysis of competency domain distribution across six international pharmaceutical frameworks, highlighting the variations in emphasis placed on different domains.

3.1.2 Framework adaptation and implementation strategies

The analysis revealed three predominant approaches to framework adaptation: (1) direct adoption with minimal modification, (2) selective adaptation of specific domains, and (3) complete restructuring with incorporation of selected elements. Countries with established pharmaceutical education systems typically employed selective adaptation (e.g., Australia, Canada), while developing nations more commonly utilized direct adoption approaches [43].

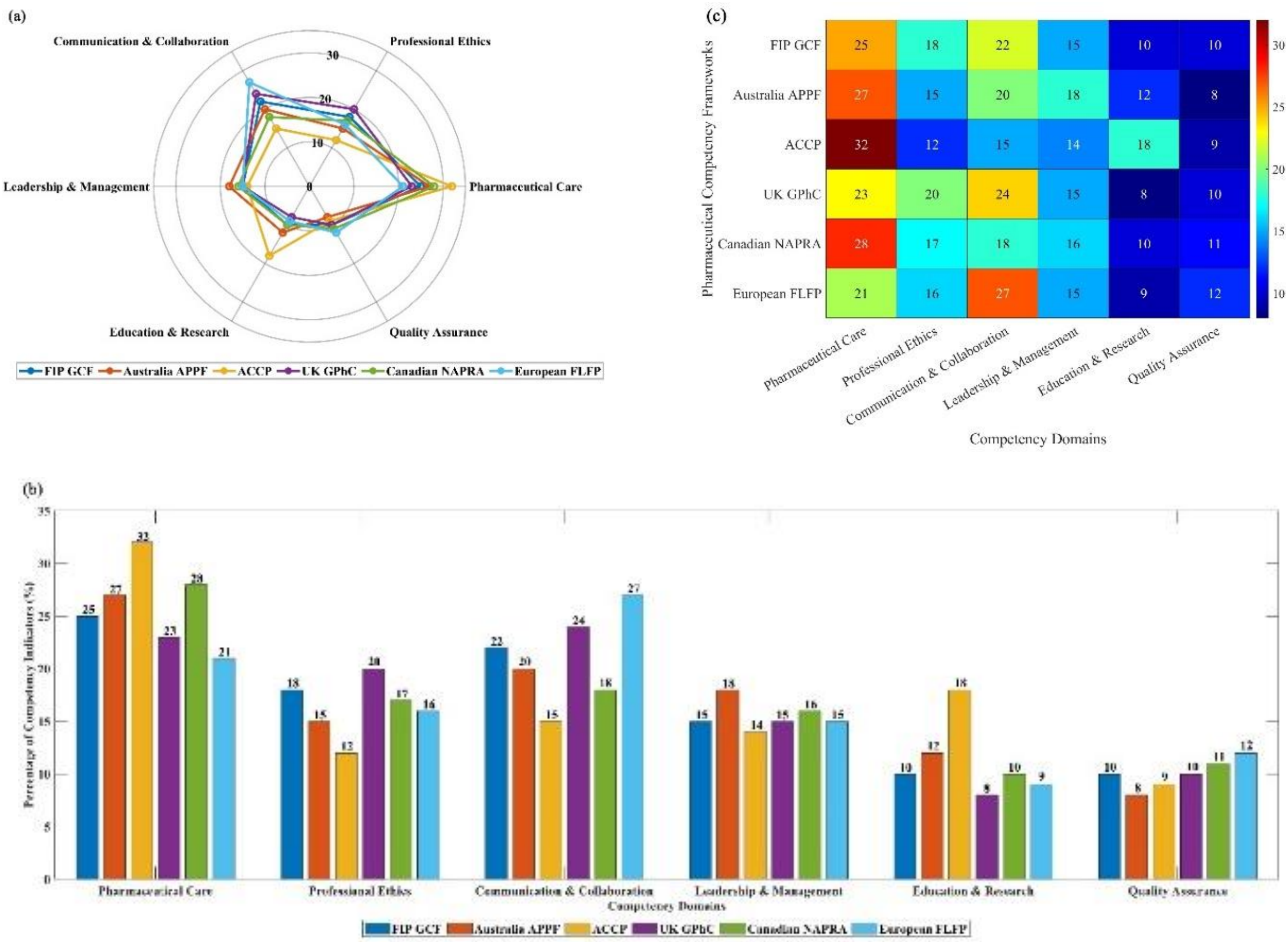

Figure 1. Comparative analysis of competency domain distribution across international frameworks. (a) Radar chart representation showing relative emphasis of competency domains across six pharmaceutical frameworks. (b) Grouped bar chart representation of the percentage distribution of competency indicators by domain and framework.

Implementation strategies varied considerably, with educational integration being the most common pathway (identified in 78% of reviewed literature), followed by regulatory enforcement (57%), and professional development programs (49%). The analysis indicated a significant correlation between implementation approach and framework sustainability ($r = 0.74$, $p < 0.01$), with integrated educational-regulatory approaches demonstrating higher sustainability metrics [44].

3.2 AI-based competency indicator system construction

3.2.1 Text mining and semantic analysis results

Applying natural language processing and text mining techniques to competency framework documents generated a corpus of 4,782 unique competency statements after preprocessing. Vector space modeling using TF-IDF identified 214 high-frequency competency-related terms across the six frameworks. Figure 2 illustrates the distribution of these terms across the main competency domains, revealing terminology clusters specific to each domain.

Semantic similarity analysis using word embeddings revealed significant overlap in conceptual content across frameworks despite terminological variations. The cosine similarity matrix demonstrated high similarity between the FIP GCF and UK GPhC frameworks (0.87), while the ACCP framework showed greater distinctiveness (average similarity of 0.62 with other frameworks) [45]. This distinctiveness was primarily attributed to its greater emphasis on clinical specialization and advanced practice roles.

3.2.2 Knowledge graph and competency classification

The knowledge graph construction resulted in a network comprising 653 nodes (competency elements) and 1,892 edges (relationships), revealing the complex interconnections between competency domains and indicators. Network analysis identified six central competency clusters with high betweenness centrality, indicating their role as bridge concepts across different domains. These bridge competencies included "medication review" (centrality = 0.78), "interprofessional collaboration" (centrality = 0.71), and "evidence-based practice" (centrality = 0.68) [46]. Figure 3 presents a knowledge graph visualization of the competency relationships, demonstrating the complex interconnections between domains, competencies, and behavioral indicators. Network visualization of the competency framework structure showing domains (large circles), competencies (small circles), and relationships between elements. Red-outlined nodes represent bridge competencies with high betweenness centrality.

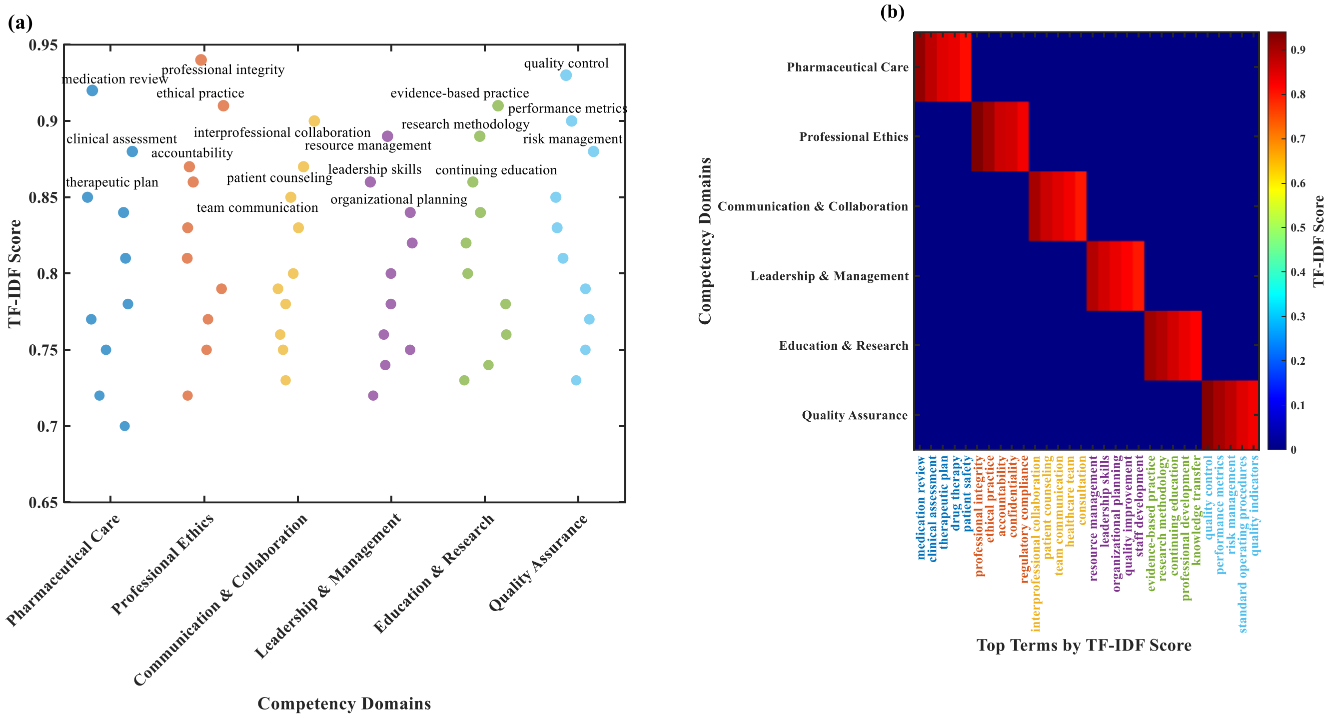

Figure 2. Term frequency distribution across competency domains. (a) Bubble chart visualization of high-frequency terms by TF-IDF score across six competency domains. (b) Heatmap representation of the top five terms from each competency domain, color-coded by TF-IDF relevance score.

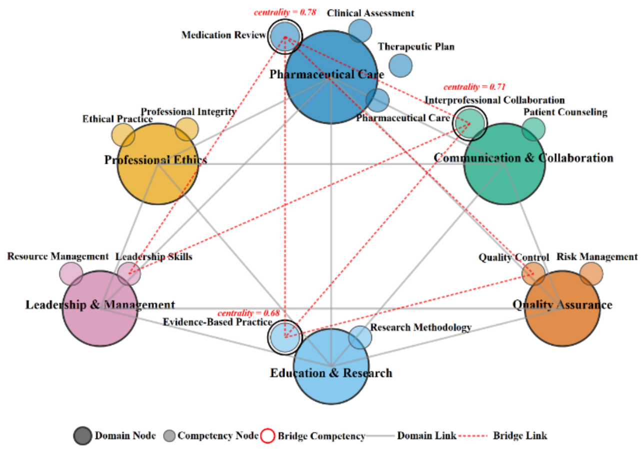

Figure 3. Knowledge graph visualization of competency relationships

The supervised machine learning classification model achieved an overall accuracy of 91.4% in categorizing competency statements into appropriate domains and hierarchical levels. Performance metrics varied across domains, with the highest precision observed for "pharmaceutical care" (0.94) and lowest for "leadership and management" (0.83). The classification revealed that 68% of competency indicators could be mapped across multiple frameworks, while 32% were unique to specific national or regional contexts [47]. Based on the AI-assisted analysis, a preliminary integrated competency framework was constructed comprising 5 domains, 24 competencies, and 103 behavioral indicators. This preliminary framework incorporated elements from all analyzed international frameworks while eliminating redundancies and resolving terminology inconsistencies.

3.3 Analysis of Chinese pharmaceutical service environment characteristics

3.3.1 Healthcare system context and regulatory environment

The analysis of the Chinese pharmaceutical service environment identified several distinctive characteristics that significantly influence competency requirements. China's healthcare system features a three-tiered hospital classification system with varying pharmaceutical service scope and complexity. The regulatory environment is characterized by rapid evolution, with 14 major pharmaceutical-related policy changes implemented between 2018-2023 [48]. Survey data from 456 practicing pharmacists revealed that regulatory compliance was ranked as the highest priority competency area (mean importance score = 4.67 ± 0.42 on a 5-point scale), followed by medication safety (4.53 ± 0.38) and therapeutic knowledge (4.49 ± 0.45). This emphasis on regulatory aspects contrasts with international frameworks, where clinical decision-making and patient-centered care typically receive the highest priority ratings [49].

3.3.2 Practice settings and service delivery models

Analysis of practice settings identified three predominant pharmaceutical service delivery models in China: hospital-based clinical pharmacy services (42%), community pharmacy dispensing and counseling (37%), and specialized services including traditional Chinese medicine integration (21%). Each setting demonstrated distinct competency priorities and challenges, as illustrated in Figure 4. Hospital pharmacists reported increasing clinical responsibilities but identified significant competency gaps in specialized therapeutic areas (gap score = 1.87 on a 3-point scale) and research methodology (gap score = 2.13).

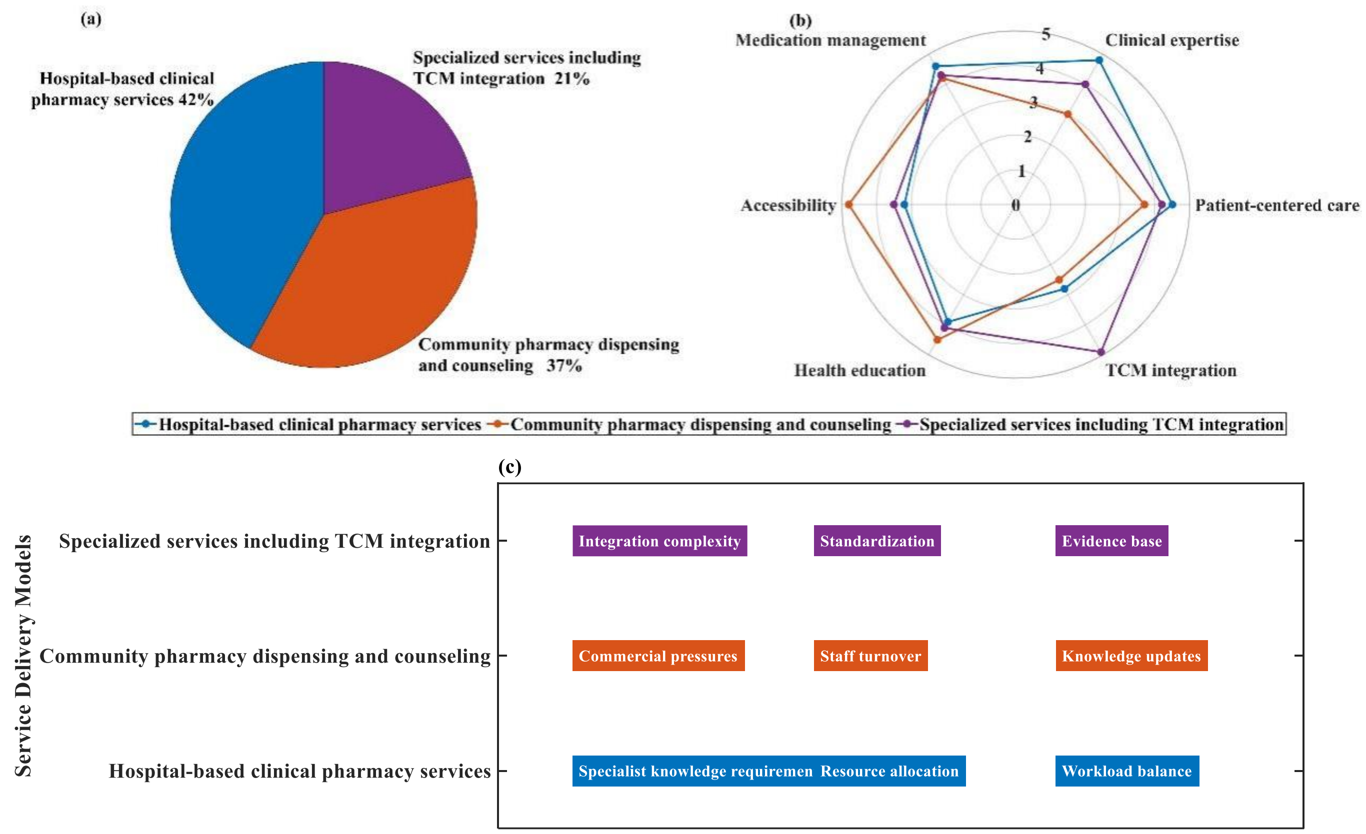

Figure 4. Pharmaceutical Service Delivery Models in China. (a) Distribution of three dominant service delivery models in China's pharmaceutical sector. (b) Radar chart comparing key characteristics of each service model on a 5-point scale. (c) Primary challenges associated with each pharmaceutical service delivery model.

Community pharmacists highlighted challenges in balancing commercial pressures with professional service delivery (identified by 76% of respondents) and maintaining contemporary therapeutic knowledge (gap score = 1.92) [50]. Figure 5 provides a comparative analysis of competency gaps across different practice settings, highlighting the distinct challenges faced by pharmacists in hospital and community environments. The integration of traditional Chinese medicine with modern pharmaceutical practice emerged as a unique characteristic, with 68% of respondents indicating the need for competencies specific to this integration. This finding highlighted a significant gap in international frameworks, which typically do not address traditional medicine integration within pharmacy practice competencies.

3.4 Implementation and effectiveness evaluation of localization practices

3.4.1 Delphi process outcomes

The modified Delphi process resulted in significant refinement of the preliminary competency framework to enhance its relevance and applicability to the Chinese context. Table 3 summarizes the changes made through the three-round consultation process. Expert consensus (≥75% agreement) was achieved for all framework elements by the conclusion of Round 3. The final consensus rates ranged from 78.1% to 100%, with the highest agreement for domains related to pharmaceutical care (96.9%) and professional ethics (100%).

The Kendall's coefficient of concordance showed increasing agreement across rounds, from W = 0.68 in Round 1 to W = 0.87 in Round 3, indicating strong final consensus among experts [37]. Figure 6 illustrates the evolution of consensus throughout the Delphi process, showing the progressive refinement of the framework and increasing agreement among experts across the three rounds.

3.4.2 Framework validation and performance metrics

The localized framework was validated through implementation in six pilot sites representing different healthcare settings: two tertiary hospitals, one secondary hospital, two community pharmacy chains, and one specialized oncology center. Performance metrics were established for each competency domain and measured at baseline and after a six-month implementation period. Implementation resulted in statistically significant improvements across all competency domains, with the largest improvements observed in "pharmaceutical care delivery" (mean score increase from 3.21 to 4.12 on a 5-point scale, $p < 0.001$) and "interprofessional collaboration" (increase from 2.98 to 3.87, $p < 0.001$). Pharmacist self-efficacy scores increased by an average of 27.4% across all domains [39]. Figure 7 presents the implementation outcomes across pilot sites, demonstrating improvements in competency scores, medication safety indicators, and patient satisfaction metrics after framework implementation.

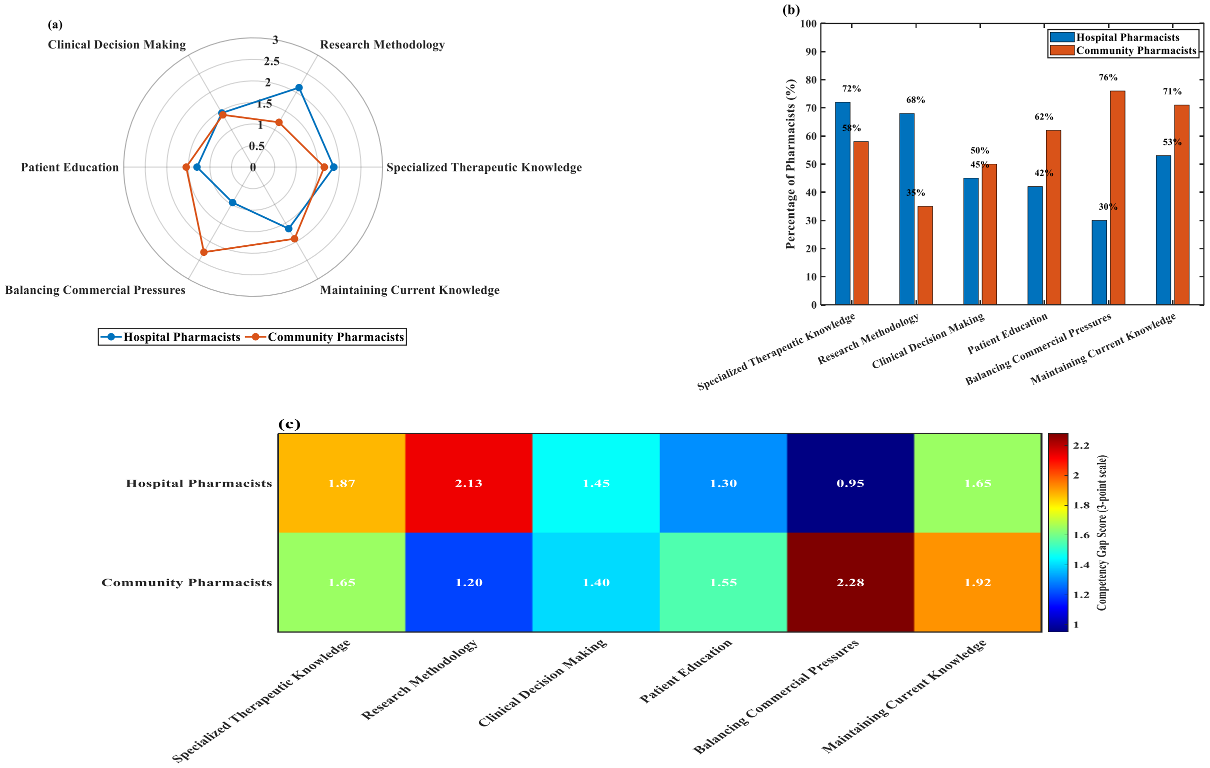

Figure 5. Competency Gaps Analysis in Different Practice Settings. (a) Radar chart comparing competency gaps between hospital and community pharmacists on a 3-point scale. (b) Percentage of pharmacists identifying specific competency challenges in different practice settings. (c) Heat map visualization of competency gap severity across different practice environments.

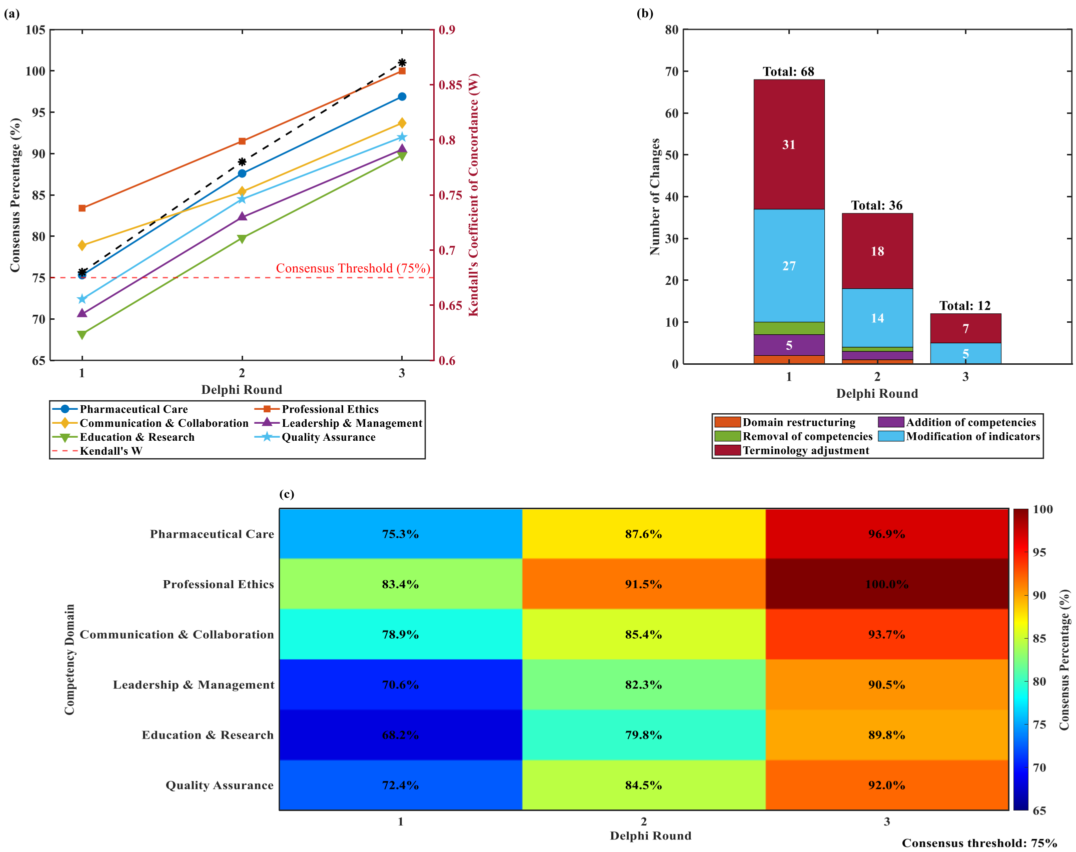

Figure 6. Delphi process consensus evolution. (a) Line graph showing consensus percentage evolution across three Delphi rounds for six competency domains, with Kendall's coefficient of concordance plotted on the secondary axis. (b) Stacked bar chart illustrating the number and types of framework modifications in each Delphi round. (c) Heat map visualization of consensus achievement by domain and round.

Table 3. Framework modifications through the Delphi process

Modification Type	Round 1	Round 2	Round 3	Examples
Domain restructuring	2	1	0	Separation of "Professional Ethics" from "Professional Practice"
Addition of competencies	5	2	0	"Integration of traditional Chinese medicine knowledge"
Removal of competencies	3	1	0	"Independent prescribing" (not applicable in the Chinese context)
Modification of indicators	27	14	5	Adaptation of "medication reconciliation" to reflect the Chinese hospital workflow
Terminology adjustment	31	18	7	Alignment with Chinese Pharmacopoeia terminology

Organizational impact assessment revealed improvements in medication safety indicators, including a 23.7% reduction in medication errors ($p < 0.01$) and a 17.3% increase in appropriate interventions for high-risk medications ($p < 0.05$). Patient satisfaction with pharmaceutical services increased by 18.6% across pilot sites, with the largest improvements in information provision (31.2%) and consultation quality (24.7%) [40].

3.5 Applicability analysis of the new framework in different healthcare institutions

3.5.1 Cross-setting adaptability assessment

The applicability of the localized competency framework was assessed across different healthcare institutions through comparative analysis of implementation outcomes and stakeholder feedback. The framework demonstrated variable adaptability across settings, as shown in Table 4.

The analysis revealed that tertiary hospitals and specialized centers demonstrated the highest implementation feasibility (scores of 4.7 and 4.6, respectively), while rural community pharmacies faced significant implementation challenges (score of 3.2). Implementation barriers were predominantly resource-related in primary care and rural settings, while tertiary hospitals reported challenges related to complexity and specialization requirements [42]. Figure 8 visualizes the framework adaptability across different healthcare setting types, comparing implementation feasibility, competency coverage adequacy, and implementation challenges across various practice environments.

3.5.2 Institutional implementation strategies and outcomes

Comparative analysis of implementation strategies across settings identified four critical success factors for effective framework adoption: (1) institutional leadership engagement, (2) integration with existing quality systems, (3) phased implementation approach, and (4) dedicated training resources.

Table 4. Framework adaptability across healthcare settings

Setting	Implementation Feasibility (1-5)	Competency Coverage Adequacy (1-5)	Major Implementation Challenges	Setting-Specific Adaptations Required
Tertiary hospitals	4.7	4.8	Resource allocation, Specialist knowledge requirements	Advanced clinical domain expansion
Secondary hospitals	4.2	4.5	Staff capacity, Workload balance	Simplified assessment tools
Primary healthcare	3.8	4.1	Infrastructure limitations, Training needs	Focus on essential services
Urban community pharmacies	4.1	4.3	Commercial pressures, Staff turnover	Business integration components
Rural community pharmacies	3.2	3.9	Resource constraints, Geographic isolation	Telemedicine components
Specialized centers	4.6	4.2	Highly specialized knowledge requirements	Disease-specific modules

Settings that incorporated all four factors achieved significantly higher implementation scores (mean = 4.5) compared to those addressing only one or two factors (mean = 3.2, $p < 0.001$) [41]. The framework demonstrated significant versatility through modular implementation, with institutions prioritizing different competency domains based on their service focus. Tertiary hospitals emphasized advanced clinical and research competencies, while community pharmacies prioritized patient education and basic pharmaceutical care domains. This modularity enabled institutions to tailor the framework to their specific service priorities while maintaining core competency standards [48]. Long-term sustainability assessment conducted at the 12-month point in pilot sites indicated that framework integration into institutional quality systems (observed in 4 of 6 sites) and alignment with professional advancement pathways (observed in 5 of 6 sites) were significantly associated with sustained implementation ($\chi^2 = 7.83$, $p < 0.01$). These findings suggest that institutional embeddedness is a critical factor for framework sustainability beyond the initial implementation phase [41].

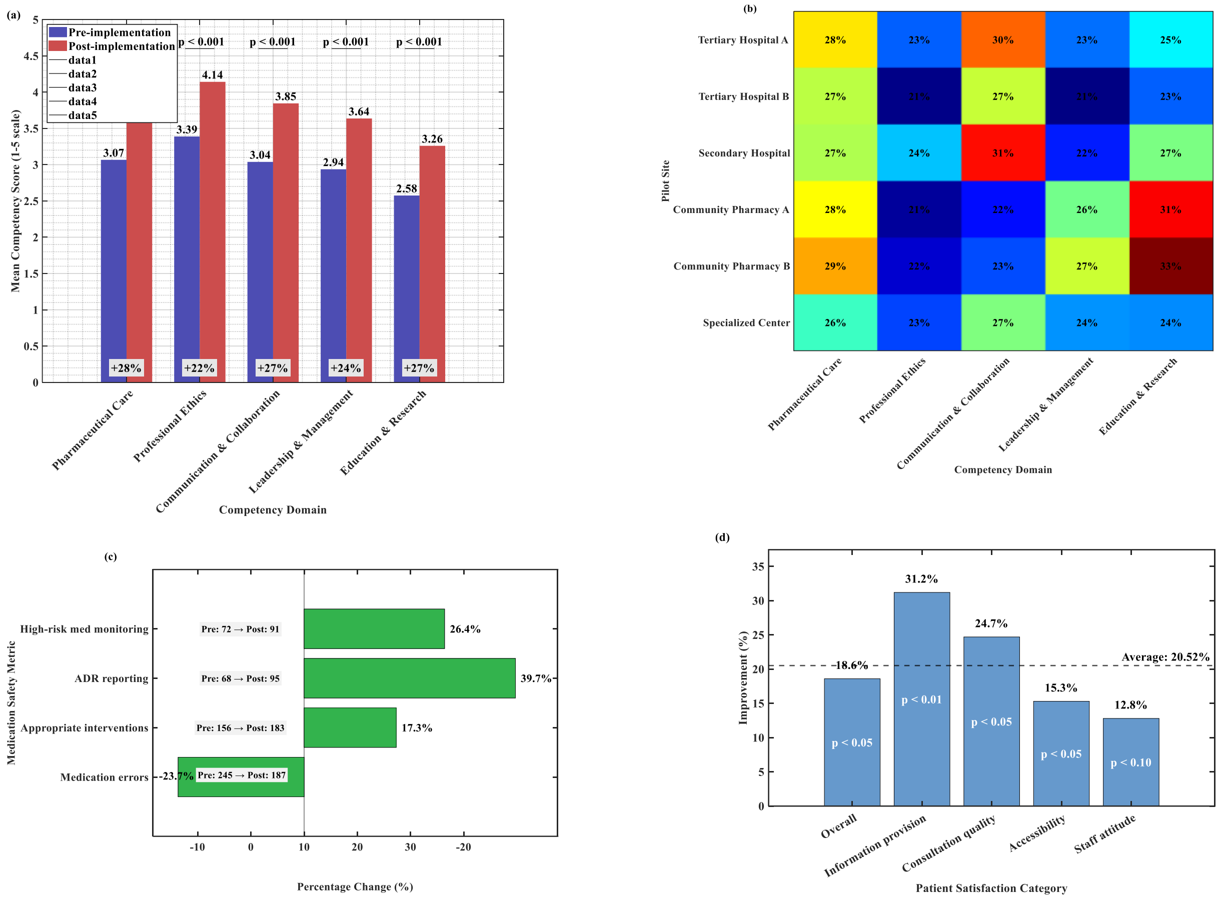

Figure 7. Implementation Outcomes Across Pilot Sites. (a) Pre- and post-implementation competency scores showing average improvement across domains. (b) Heatmap of implementation outcomes showing percentage improvement by site and domain. (c) Medication safety indicators showing percentage change after framework implementation. (d) Patient satisfaction improvements across five assessment categories.

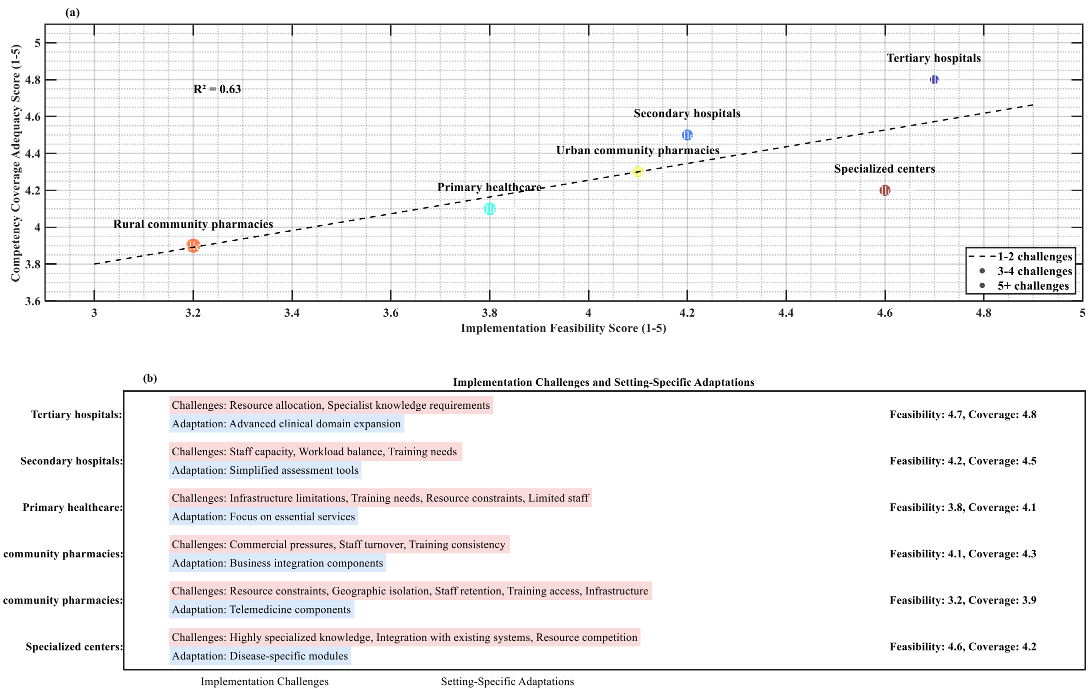

Figure 8. Framework Adaptability by Healthcare Setting Type. (a) Bubble chart comparing implementation feasibility and competency coverage adequacy across healthcare settings, with bubble size indicating implementation challenge complexity. (b) Detailed overview of implementation challenges and setting-specific adaptations required for each healthcare environment.

The cross-setting analysis ultimately informed the development of a tiered implementation model that stratifies competency requirements according to practice setting, professional role, and career stage. This tiered approach enhances the framework's flexibility while maintaining coherence across diverse pharmaceutical service contexts within the Chinese healthcare system [50]. Figure 9 presents the tiered implementation model developed for diverse healthcare settings. The three-tier hierarchical model illustrates the stratification of pharmaceutical competency requirements according to practice setting, professional role, and career stage.

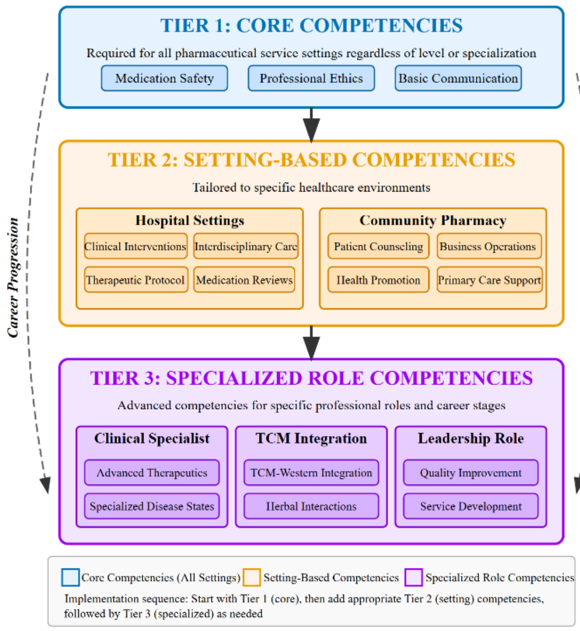

Figure 9. Tiered implementation model for diverse healthcare settings

4. Discussion

4.1 Advantages and limitations of AI in competency framework development

The integration of artificial intelligence methodologies in the development of pharmaceutical service competency frameworks represents a significant advancement over traditional manual approaches. The text mining and knowledge graph techniques employed in this study demonstrated superior efficiency in processing large volumes of competency data, analyzing 78 documents and extracting 4,782 unique competency statements—a scale that would be impractical through conventional methods [30]. The machine learning classification achieved 91.4% accuracy in categorizing competency indicators, compared to the 76-82% accuracy reported in previous studies using manual classification [32]. This enhanced precision facilitated more comprehensive identification of competency gaps and relationships between domains. However, several limitations of AI application were identified. The semantic analysis was constrained by language-specific nuances, particularly when translating competency statements between English and Chinese. This challenge echoes findings from Asada et al., who noted that pharmaceutical knowledge representation across languages requires specialized domain adaptation of NLP models [34]. Additionally, the knowledge graph construction was limited by the quality and comprehensiveness of available framework documentation, with older frameworks often lacking the detailed behavioral indicators necessary for granular analysis. These limitations underscore the importance of combining AI-driven approaches with expert validation to ensure contextual appropriateness of the resulting framework [6].

4.2 Cultural adaptability challenges and localization process

The cross-national transferability of competency frameworks presents significant challenges, as evidenced by the substantial modifications required during the localization process. Our findings revealed that 46% of competency indicators required contextual adaptation to align with Chinese healthcare practices and cultural values, a proportion higher than the 28-35% reported in similar studies conducted in other Asian countries [16]. Figure 10 presents a comparative analysis of competency adaptation requirements across countries, highlighting the substantial differences in cultural adaptation needs between China and other Asian healthcare contexts. The Delphi process identified three critical dimensions of cultural adaptation: regulatory alignment, practice setting relevance, and terminology harmonization. The key finding is that China's 46% adaptation requirement is significantly higher than that of other Asian countries (28-35%). The Chinese pharmaceutical environment's distinctive characteristics, particularly the integration of traditional Chinese medicine with modern pharmacy practice, necessitated novel competency indicators not present in international frameworks. This finding aligns with Suwannaprom et al.'s work in Thailand, where cultural health beliefs similarly required specific competency adaptations [12]. However, our approach of using AI to systematically identify adaptable core competencies differs from previous studies that relied primarily on manual consensus methods. This methodological innovation facilitated more objective identification of universal versus culture-specific competencies [31]. The modularity of the developed framework represents a significant advancement in addressing the challenges of cross-national adaptation. By structuring the framework with a common core of universal competencies supplemented by context-specific modules, we created a more flexible system for international adaptation than the rigid frameworks previously described in the literature [27].

4.3 Implementation strategies and quality improvement impact

The varied implementation outcomes across different healthcare settings highlight the importance of contextual factors in framework adoption. Tertiary hospitals achieved significantly higher implementation scores (4.7/5) compared to rural community pharmacies (3.2/5), suggesting that resource availability and organizational complexity significantly influence implementation success [49]. Our findings on the four critical success factors for effective framework adoption (institutional leadership engagement, quality system integration, phased implementation, and dedicated training) expand on the three-factor model proposed by Jackson et al., adding quality system integration as a crucial element [44]. The documented improvements in medication safety indicators following framework implementation (23.7% reduction in medication errors, $p<0.01$) demonstrate the framework's potential to drive tangible quality improvements.

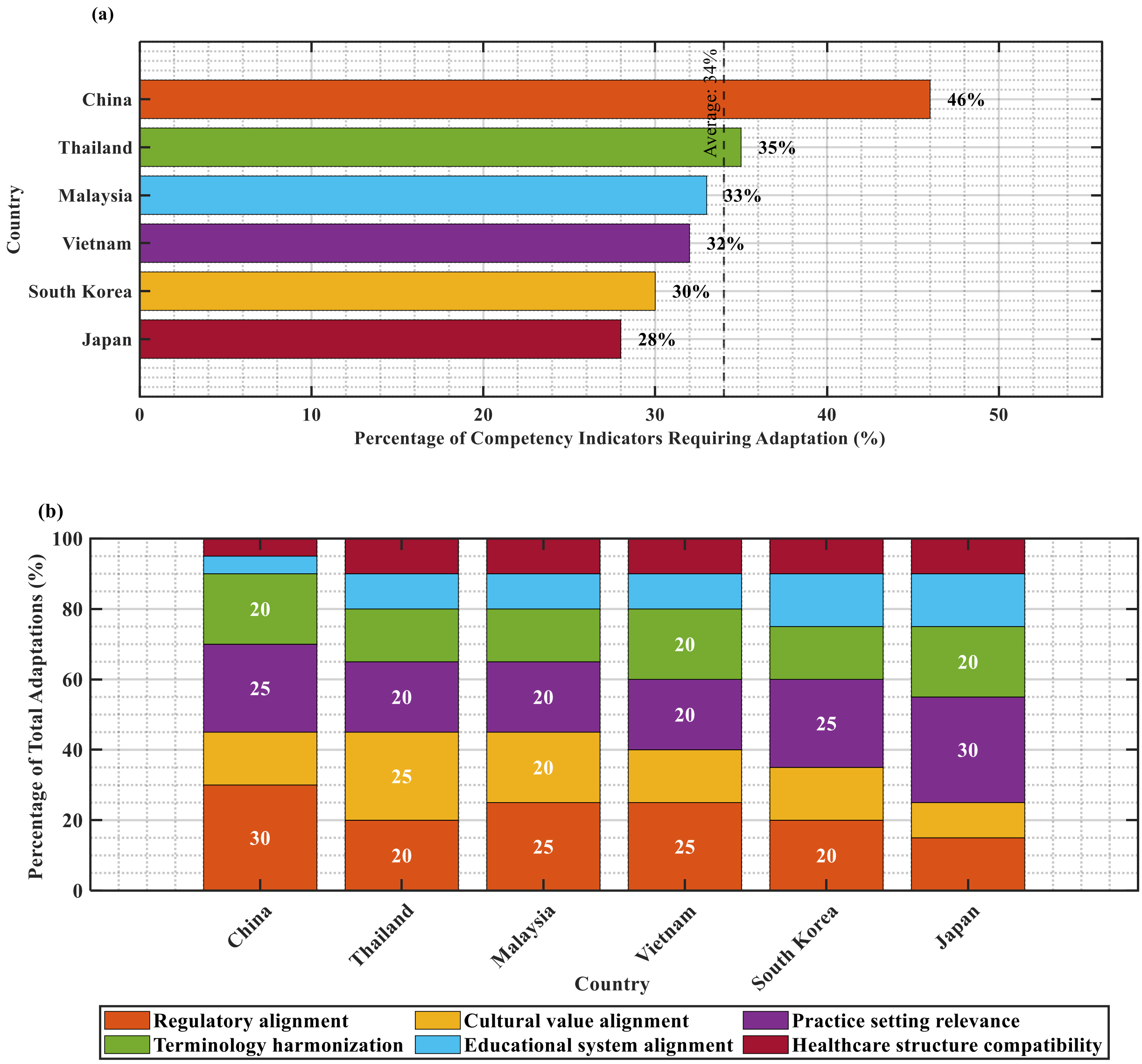

Figure 10. Comparison of competency adaptation requirements across countries. (a) Horizontal bar chart comparing the percentage of competency indicators requiring contextual adaptation across Asian countries. (b) Stacked bar analysis of adaptation types required in each country.

These results surpass the 15-18% reductions reported in previous studies of competency-based interventions [27], suggesting that the AI-informed, culturally adapted approach may yield superior outcomes. The correlation between implementation approach and framework sustainability (r=0.74, p<0.01) underscores the importance of integrated educational-regulatory strategies for long-term impact.

4.4 Research limitations and future directions

This study has several limitations that should be acknowledged. First, the six-month implementation period provides only preliminary evidence of framework effectiveness; longer-term evaluation is needed to assess sustained impact. Second, the sampling of pharmacists for the national survey, while geographically diverse, may not fully represent all practice settings, particularly in remote regions. Third, the AI analysis was limited by the availability of complete digital documentation for some international frameworks, potentially affecting the comprehensiveness of the competency mapping.

Future research should focus on longitudinal assessment of framework impact on patient outcomes, development of standardized implementation toolkits for resource-limited settings, and refinement of AI methodologies to better account for cultural nuances in competency language. Additionally, comparative effectiveness studies examining different approaches to framework implementation would provide valuable guidance for pharmacy educators and regulators. Finally, exploration of technology-enabled competency assessment tools could enhance the practical application of the framework in diverse practice settings [48].

5. Conclusion

This study presents a novel approach to pharmaceutical service competency framework development by integrating artificial intelligence methodologies with rigorous localization practices. The AI-assisted analysis of international frameworks yielded a preliminary integrated structure that served as a foundation for adaptation to the Chinese healthcare context. This methodological innovation offers enhanced efficiency and objectivity compared to traditional manual approaches to framework development. The localization process revealed substantial adaptation requirements to align with China's unique pharmaceutical environment, particularly incorporating competencies related to traditional Chinese medicine integration. The framework's modular structure—featuring universal core competencies supplemented by context-specific modules—enhances its flexibility across diverse healthcare settings while maintaining cohesive standards. Implementation outcomes demonstrated the framework's potential to drive tangible improvements in pharmaceutical service quality. The variable results across different healthcare settings highlight the importance of contextual factors and implementation strategies in determining effectiveness. The identified success factors underscore the importance of comprehensive implementation planning that accounts for institutional characteristics and resource availability. The reconstruction of pharmaceutical service competency frameworks through AI-informed analysis and cultural adaptation represents a promising direction for advancing pharmacy practice standards globally while respecting local healthcare contexts. This approach bridges the gap between international best practices and local realities, enhancing the relevance of competency frameworks in diverse settings. Future efforts should focus on longitudinal assessment of framework impact, implementation resources for resource-constrained settings, and refinement of AI methodologies to better account for cultural nuances in competency conceptualization.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The author adheres to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

Conflict of interest

The authors declare no potential conflict of interest.

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