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Core logic and effectiveness bottlenecks of pediatric clinical pharmacy interventions for rational drug use

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Abstract

Rational drug use in pediatrics remains a global challenge due to children's distinct physiological characteristics, limited clinical evidence, and insufficient pediatric-specific drug information systems. Existing research has demonstrated the value of clinical pharmacy interventions but has rarely explored their underlying logic and systemic limitations. To address this gap, this study develops a three-dimensional analytical framework, Technology Tools, Pharmacist Role, and Medical System, to examine the core logic and effectiveness bottlenecks of pediatric clinical pharmacy interventions. Using theoretical analysis and cross-national comparison, the framework maps how technological infrastructures, professional roles, and institutional mechanisms interact to shape rational drug use. Results reveal that fragmented digital systems, underdefined pharmacist responsibilities, and inadequate policy and funding support remain the main barriers to effective intervention. The framework demonstrates strong explanatory power in identifying how these dimensions must operate synergistically to achieve optimal outcomes. This study provides both theoretical and practical insights for advancing pediatric pharmacotherapy by guiding the systematic integration of digital tools, clinical pharmacist participation, and supportive healthcare policies to enhance safety, efficacy, and sustainability in pediatric medication practices.

Keywords: Pediatric clinical pharmacy, Rational drug use, Technology tools; Pharmacist role, Medical system

1. Introduction

Pediatric rational drug use is crucial for ensuring the safety, efficacy, and optimal therapeutic outcomes for children, whose physiological characteristics significantly differ from adults [1]. Children's varying metabolic rates, organ functions, and body composition make them more vulnerable to adverse drug reactions (ADRs), improper dosing, and ineffective treatments [2]. These differences necessitate careful consideration of drug choices, dosages, and therapeutic regimens in pediatric care. Rational drug use in pediatrics involves the appropriate selection, dosage, and administration of medications based on a thorough understanding of pediatric pharmacology, as well as the child's specific condition and needs.

Despite the recognition of the importance of rational drug use, significant challenges remain in its effective implementation. Pediatric patients are often treated using medications developed and tested on adults, leading to a lack of pediatric-specific formulations, dosing guidelines, and clinical evidence [3]. Furthermore, the complexities of drug interactions, pediatric comorbidities, and the rapid changes in children's physical development further complicate prescribing practices. These challenges create a critical need for clinical pharmacy interventions to guide healthcare professionals in making informed and safe medication decisions for children.

Clinical pharmacy interventions are a cornerstone of rational drug use, aiming to ensure safe and effective medication management [4]. Pharmacists are essential in reviewing prescriptions, advising on drug therapy, detecting potential ADRs, and offering guidance on medication adjustments, particularly in pediatrics. The intervention of clinical pharmacists helps minimize medication errors, optimize drug regimens, and promote better therapeutic outcomes by tailoring medication plans to individual pediatric patients [5,16].

However, despite the proven benefits of clinical pharmacy interventions, several limitations persist. In many healthcare settings, pharmacists' roles in pediatric drug use are often underutilized, with limited involvement in direct decision-making and patient care [6]. Many pharmacists, particularly in pediatric care, face challenges such as inadequate pediatric-specific training, lack of access to pediatric

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databases, and a limited presence within multi-disciplinary clinical teams. These issues limit the full potential of clinical pharmacy interventions, especially in complex pediatric cases that require specialized knowledge and expertise.

Moreover, the healthcare infrastructure in many regions is not equipped to support the effective integration of clinical pharmacy interventions, with insufficient collaboration between pharmacists, clinicians, and healthcare institutions [7,17]. These gaps result in suboptimal outcomes in pediatric drug use and highlight the need for an improved, system-wide approach.

Research on pediatric clinical pharmacy interventions has been gaining momentum globally, with numerous studies emphasizing the importance of pharmacists' roles in improving medication safety and therapeutic efficacy. Internationally, advanced healthcare systems have made significant strides in integrating clinical pharmacy practices into pediatric care. For example, many developed countries have established pediatric-specific drug databases, implemented pharmacist-led medication therapy management programs, and embedded pharmacists into clinical decision-making processes. These initiatives have proven effective in reducing medication errors, enhancing patient outcomes, and ensuring safer drug administration [8].

However, the implementation of similar practices in developing countries or regions with limited healthcare infrastructure remains a challenge. Studies show that many healthcare systems, particularly in low- and middle-income countries, face significant gaps in pediatric pharmacy practices. There is a lack of standardized pediatric pharmacotherapy guidelines, limited use of clinical pharmacy services, and a shortage of pharmacists with specialized pediatric training [9]. Furthermore, the effectiveness of clinical pharmacy interventions in these regions has not been adequately evaluated, highlighting the need for research that examines the unique challenges these systems face and how they can be addressed [10,18].

The gap between research and practice is also evident in the underutilization of technology in pediatric clinical pharmacy interventions. While clinical decision support systems, electronic health records, and drug information systems have been shown to improve drug safety in adults, their application in pediatric care is often limited or fragmented. There is a need for a systematic approach that considers how these technological tools can be better integrated into pediatric drug use management.

To address these challenges, this paper introduces a three-dimensional framework for analyzing pediatric clinical pharmacy interventions: Technology Tools, Pharmacist Role, and Medical System. This framework provides a holistic approach to understanding the core logic of rational drug use in pediatrics and identifies the bottlenecks that hinder the effectiveness of clinical pharmacy interventions.

The Technology Tools dimension focuses on the role of technological advancements, including electronic health records, clinical decision support systems, and specialized pediatric drug databases, in enhancing the rational use of drugs. These tools are essential for improving prescription accuracy, monitoring drug interactions, and providing evidence-based guidance to healthcare professionals.

The Pharmacist Role dimension emphasizes the critical function of pharmacists in clinical decision-making, patient education, medication review, and therapy management. Pharmacists' involvement ensures that drug therapy is optimized, adverse drug reactions are minimized, and individual needs are met, particularly in pediatric patients.

Finally, the Medical System dimension examines the broader healthcare environment, including policies, institutional structures, and collaborative mechanisms, which play a vital role in supporting or limiting the effectiveness of clinical pharmacy interventions. The successful integration of pharmacy interventions into pediatric care requires robust healthcare policies, interdisciplinary collaboration, and adequate resource allocation.

The objective of this study is to conduct a systematic analysis of the core logic and effectiveness bottlenecks of pediatric clinical pharmacy interventions using the "Technology Tools, Pharmacist Role, Medical System" framework. By focusing on the interactions between these three dimensions, the study aims to provide insights into how the rational use of drugs in pediatrics can be

improved. The analysis will explore the ways in which technology, the pharmacist's role, and the healthcare system can be better aligned to overcome existing barriers and enhance pediatric drug safety and efficacy. Through this lens, the study seeks to identify the logical pathways for improving pediatric drug use and address the underlying bottlenecks that hinder the full potential of clinical pharmacy interventions.

2. Analytical Framework & Approach

2.1 Theoretical basis

The three-dimensional framework, comprising Technology Tools, Pharmacist Role, and Medical System, is grounded in the intersection of healthcare system dynamics, technological advancements, and professional roles in clinical practice. This framework aims to provide a comprehensive lens for evaluating the effectiveness of pediatric clinical pharmacy interventions. The theoretical underpinnings of this framework are informed by several key theories and models in healthcare management, systems thinking, and clinical pharmacology.

At the core of this framework is the systems theory, which posits that healthcare systems are complex, interdependent entities that require integration across multiple domains, technology, professional roles, and organizational structures. Systems theory helps in understanding how different elements interact within the healthcare system and how these interactions influence clinical outcomes. The framework also draws on the socio-technical systems theory, emphasizing the need for balancing technological tools with human expertise and organizational structures to achieve optimal results. By applying these theories, the framework not only explores the technical and professional dimensions but also considers the broader healthcare environment that shapes the implementation and impact of clinical pharmacy interventions.

2.2 Technology tools

The Technology Tools dimension focuses on the critical role that technological advancements play in rational drug use, particularly in the context of pediatric care. In the era of digital health, the role of information systems, automation, and evidence-based resources in clinical decision-making is increasingly significant. The rapid expansion of health informatics has provided healthcare professionals with powerful tools to improve decision-making, optimize patient care, and reduce errors.

A central component of this dimension is informatics, which refers to the digital management of patient data, including electronic health records (EHR), medication management systems, and prescription databases [11]. These tools enable pharmacists and clinicians to access real-time, accurate information, ensuring safer and more effective medication administration. In pediatrics, where weight-based dosing and age-specific drug formulations are crucial, having access to up-to-date, child-specific drug information is vital for minimizing dosing errors and adverse drug reactions.

Furthermore, the automation aspect of technological tools, such as clinical decision support systems (CDSS), provides decision-making assistance by alerting healthcare providers about potential drug interactions, allergies, or inappropriate doses[12]. These automated tools reduce the likelihood of human error, especially in high-risk areas like pediatrics, where a slight deviation from the recommended dose can have severe consequences.

Lastly, evidence-based resources, such as pediatric drug databases, clinical guidelines, and research repositories, play a vital role in ensuring that drug use is aligned with the latest scientific evidence. The integration of these resources into clinical practice supports the ongoing development of rational drug use strategies, enhancing the pharmacist's and physician's ability to make informed decisions based on up-to-date clinical evidence.

2.3 Pharmacist role

The Pharmacist Role dimension highlights the essential contribution of pharmacists in ensuring safe and rational drug use, particularly in pediatrics [13]. As healthcare providers with specialized expertise in pharmacology, pharmacists are uniquely positioned to intervene in clinical decision-making, offer medication counseling, and monitor the effects of treatments. Clinical decision-making is a critical area where pharmacists influence pediatric drug therapy.

In pediatric care, dosing and medication regimens require precise adjustments based on the child's age, weight, and underlying conditions. Pharmacists play an essential role in reviewing prescriptions, ensuring that the chosen medication is appropriate for the patient's specific characteristics, and advising physicians on possible alternatives or adjustments.

The communication and coordination skills of pharmacists also play a crucial role in promoting rational drug use. Pharmacists must effectively communicate with physicians, nurses, and other healthcare providers to ensure that medication-related decisions are coordinated. This collaborative approach helps in minimizing medication errors and ensures that the patient's medication regimen is optimized. Effective communication also extends to patients and their caregivers, where pharmacists provide counseling on medication adherence, proper administration, and potential side effects.

Moreover, individualized management is an area where pharmacists contribute significantly to pediatric care. Each child's response to medication may differ based on genetics, comorbidities, and environmental factors. Pharmacists, by closely monitoring treatment outcomes and adjusting regimens as necessary, can help optimize drug therapy for individual pediatric patients. This tailored approach is particularly important in pediatric care, where standard dosing and treatment guidelines may not always apply.

2.4 Medical system

The Medical System dimension examines the broader healthcare environment within which clinical pharmacy interventions operate. Healthcare systems, particularly those involved in pediatric care, are influenced by various structural factors, including policy frameworks, organizational structures, and collaborative mechanisms [14]. These factors determine the resources available to pharmacists and influence how their role is integrated into clinical practice.

Policy plays a crucial role in shaping the practice of pediatric pharmacy. Government regulations, national healthcare policies, and institutional guidelines dictate how pharmacy services are delivered, the funding allocated to pediatric care, and the overall accessibility of clinical pharmacy interventions. Well-designed policies can encourage the integration of clinical pharmacy into pediatric care, while poorly defined policies can limit the potential impact of pharmacy interventions.

Organizational structures are another critical factor that affects the implementation of clinical pharmacy services. The ability of healthcare institutions to support pharmacist-led interventions, including the availability of pediatric-specific resources and the establishment of collaborative care teams, is vital. In some healthcare settings, pharmacists are embedded within multidisciplinary teams, working closely with physicians, nurses, and other healthcare professionals to provide comprehensive care. In other settings, pharmacists may have a more peripheral role, limiting their ability to contribute to clinical decisions.

Collaborative mechanisms refer to the ways in which different healthcare professionals coordinate and work together [15]. The success of pediatric clinical pharmacy interventions often depends on effective collaboration between pharmacists and other healthcare providers. This requires not only well-defined roles but also institutional support for interprofessional communication and shared decision-making. Collaborative care models, where pharmacists are integrated into clinical pathways and routinely engage with other team members, have been shown to improve patient outcomes and ensure rational drug use.

2.5 Analytical approach

This study adopts a comparative approach that examines both domestic and international experiences with pediatric clinical pharmacy interventions. By analyzing practices from different healthcare systems, such as those in developed countries like the United States and European nations, this research identifies best practices and common challenges. The international comparison will highlight the successes and limitations of pediatric pharmacy interventions, offering insights into how different healthcare environments support or hinder the role of clinical pharmacists.

Theoretical induction will be used to derive broader generalizations from the analysis of the three

dimensions within different healthcare contexts. Through a detailed examination of case studies, scholarly literature, and practical examples, this paper will develop a deeper understanding of how the interaction between technology tools, pharmacist roles, and medical systems influences pediatric drug safety and efficacy.

Finally, the paper will engage in framework mapping to visualize the relationships and interactions among the three dimensions. By mapping these dimensions to real-world examples and practices, the study aims to offer a practical, actionable framework for improving pediatric clinical pharmacy interventions across different healthcare systems.

3. Results of Framework Application

3.1 Technology tools dimension

Technological tools play a pivotal role in improving the rational use of drugs in pediatrics. The primary pathways through which technology enhances drug safety and efficacy are through accurate data management, decision support, and evidence-based resources. Health informatics, particularly electronic health records (EHRs), are instrumental in ensuring that healthcare professionals have access to patient-specific data, enabling informed decisions about drug prescriptions. The integration of clinical decision support systems (CDSS) enhances drug prescribing by providing real-time alerts for potential drug interactions, dosing errors, and age-appropriate drug formulations. Moreover, evidence-based resources, such as pediatric drug databases and clinical guidelines, ensure that medication choices align with the latest scientific research and best practices, which is crucial in pediatric care, where therapeutic standards differ significantly from adult medicine.

While technological tools have made significant strides in many areas of healthcare, their application in pediatrics remains fragmented. The widespread adoption of EHRs and CDSS is not always coupled with the development of pediatric-specific resources. As illustrated in Table 1, current databases and decision support systems often lack critical pediatric-oriented features such as weight-based dosing, age-adjusted safety information, and dedicated adverse drug reaction monitoring. This gap highlights the mismatch between existing technological infrastructures and the clinical needs of pediatric practice.

Despite the availability of advanced technological tools, the effectiveness of these resources is often limited due to a mismatch between the tools available and the specific clinical needs of pediatric care. Many existing technologies, such as adult-focused drug databases and clinical support systems, fail to address the unique challenges of pediatric pharmacotherapy, such as weight-based dosing, age-specific drug metabolism, and variable drug responses in children. Additionally, the integration of technological tools into daily clinical practice remains insufficient in many settings, resulting in underutilization or misapplication of available resources. These bottlenecks hinder the full potential of technology to improve rational drug use in pediatrics.

Table 1. Comparison of general vs. pediatric-specific drug information systems

Feature	General Drug Database / CDSS	Pediatric-Specific Database / CDSS	Clinical Implication
Dosage Information	Standard adult dosage ranges	Weight-based and age-adjusted dosing	Prevents dosing errors and overmedication
Formulation Coverage	Primarily adult formulations	Pediatric formulations (liquid, dispersible tablets)	Improves administration accuracy
Adverse Drug Reaction (ADR) Data	Generalized ADR listings	Pediatric-specific ADR reporting and frequency	Enhances drug safety monitoring
Evidence Source	Adult clinical trials	Pediatric clinical studies and real-world data	Increases evidence relevance
Decision Support Alerts	General contraindications	Age-specific contraindications and off-label warnings	Reduces inappropriate prescribing
Accessibility	Widely integrated in hospital systems	Limited to specialized institutions	Restricts widespread pediatric application

3.2 Pharmacist role dimension

Pharmacists play a critical role in ensuring rational drug use, particularly in pediatric care. Their key interventions include prescription review, medication monitoring, and patient education. Pharmacists are well-placed to provide expertise in pediatric pharmacology, ensuring that medications prescribed to children are appropriate in terms of dosage, drug selection, and safety. In addition to medication review, pharmacists monitor treatment outcomes, assess for potential adverse drug reactions (ADRs), and offer guidance to both clinicians and caregivers on appropriate drug administration. The collaborative role of pharmacists in the multidisciplinary healthcare team is crucial for ensuring that drug therapies are tailored to individual pediatric patients, especially in complex cases involving polypharmacy or chronic conditions.

Despite their critical role, pharmacists' involvement in pediatric drug therapy is often limited. In many healthcare settings, pharmacists are primarily engaged in prescription review and dispensing medications, with less emphasis on active clinical decision-making or ongoing monitoring of pediatric patients. While some hospitals or clinics have integrated pharmacists into pediatric care teams, their role is often confined to reviewing prescriptions for errors and ensuring that medications are available for dispensing, rather than being involved in direct patient care. Furthermore, the monitoring of pediatric drug therapy is often insufficient, with few systems in place to track long-term treatment outcomes or detect potential adverse effects in children. This limited role reduces the overall impact of pharmacy interventions in optimizing pediatric medication use.

The effectiveness of the pharmacist's role in pediatric drug therapy is hindered by their marginalization in many healthcare settings. In particular, pharmacists are often underrepresented in clinical decision-making processes and are not fully integrated into patient care teams. This lack of integration stems, in part, from inadequate training and specialization in pediatric pharmacotherapy. Many pharmacists are not trained to manage the complexities of pediatric drug therapy, such as managing dosing adjustments based on growth, development, and disease progression. As a result, pharmacists are often relegated to supportive roles, limiting their ability to intervene proactively in improving pediatric drug use.

3.3 Medical system dimension

The Medical System dimension is critical for ensuring that pediatric clinical pharmacy interventions are implemented effectively. Systemic support, including policies, organizational structures, and collaboration mechanisms, is essential for integrating pharmacy services into pediatric care. Effective healthcare policies and institutional structures can ensure that pharmacists have the resources, support, and authority needed to intervene in pediatric drug therapy. Collaborative mechanisms between pharmacists, physicians, and other healthcare providers are also crucial for ensuring that pediatric patients receive holistic care that optimizes drug use and minimizes risks.

Currently, many healthcare systems lack comprehensive policies and frameworks to integrate pediatric clinical pharmacy services effectively. In some regions, there are no formal guidelines for pharmacists' roles in pediatric care, and pediatric drug safety is not prioritized in healthcare policy. Additionally, collaboration between pharmacists and other healthcare providers remains limited. While some multidisciplinary care models exist, they are often underfunded or not widely adopted. The lack of interprofessional collaboration often leads to fragmented care, where pharmacists are not fully involved in clinical decision-making. Furthermore, resource allocation for pediatric pharmacy services is often insufficient, with limited access to pediatric-specific drug databases, training programs, and clinical support tools. These gaps further hinder the effective implementation of pharmacy interventions in pediatric care.

The primary bottleneck in the medical system dimension is the disconnect between policy and practice. While many healthcare systems recognize the importance of pediatric clinical pharmacy interventions, the policies designed to support these interventions often do not align with the realities of clinical practice. In some settings, policies may exist on paper but lack the practical implementation mechanisms needed to support pharmacy interventions. Additionally, healthcare institutions

may not prioritize the resources necessary for pharmacists to fully engage in pediatric drug therapy, leading to a lack of tangible support for pharmacy services at the operational level.

3.4 Core logic synthesis

The three dimensions, Technology Tools, Pharmacist Role, and Medical System, are interconnected, with each dimension influencing the effectiveness of the others. Technological tools provide the data and support needed for informed decision-making, but without the expertise of pharmacists, these tools cannot be fully utilized. Similarly, even the most well-trained pharmacists may struggle to make an impact if healthcare policies and institutional structures do not support their integration into clinical teams. Effective pediatric clinical pharmacy interventions require a holistic approach, where technology, pharmacist roles, and healthcare systems work in tandem to enhance drug safety and efficacy.

The integration of the three dimensions can be mapped into a systemic logic model for rational drug use in pediatrics. At the core of this model is the recognition that technological tools, the pharmacist's expertise, and supportive healthcare systems must work together in a coordinated way to optimize pediatric drug use. This model provides a framework for identifying the key pathways and interventions needed to address the current bottlenecks and improve the overall quality of pediatric pharmacotherapy.

Table 2. Interactions between technology tools, pharmacist role, and medical system in pediatric drug use

Dimension	Key Roles/Contributions	Key Interactions	Effectiveness Bottlenecks
Technology Tools	-Provides accurate data for decision-making -Supports decision support systems and evidence-based guidelines	-Informs pharmacists and clinicians for precise dosing -Enhances communication within teams	-Fragmented data systems -Lack of pediatric-specific databases
Pharmacist Role	-Reviews prescriptions and adjusts for pediatric needs -Educates patients and caregivers -Monitors and reports adverse drug reactions	-Works with physicians to adjust therapies based on real-time data -Uses technology to track treatment outcomes	-Marginalized role in clinical teams -Limited pediatric training
Medical System	-Defines healthcare policies and structures -Ensures institutional support for pharmacy integration -Promotes collaborative care models	-Provides frameworks for integrating technology and pharmacists into clinical practice -Ensures adequate resources for pediatric care	-Inconsistent policy support -Insufficient interdisciplinary collaboration -Lack of resource allocation for pediatric pharmacy services

Table 2 outlines the core interactions and contributions of the three dimensions, Technology Tools, Pharmacist Role, and Medical System, towards improving pediatric drug use, while identifying the key effectiveness bottlenecks that hinder full integration and impact.

4. Discussion

4.1 Theoretical significance

The "Technology Tools-Pharmacist Role-Medical System" framework introduced in this study provides a comprehensive approach to understanding pediatric clinical pharmacy interventions. By conceptualizing the interactions among these three dimensions, the framework clarifies the pathways through which technology, pharmacist involvement, and healthcare systems contribute to improving rational drug use. This model allows for a more nuanced understanding of the complex nature of pediatric drug therapy, highlighting the importance of integrating specialized tools, professional expertise, and systemic support.

In particular, the framework offers significant explanatory power for understanding how effective pediatric drug use can be achieved through coordinated action. It emphasizes that technological tools, while crucial in data management and decision support, are not sufficient on their own to ensure rational drug use without the active involvement of skilled pharmacists and an enabling medical system. The study further demonstrates that a holistic, systems-based approach is necessary for overcoming the multifaceted challenges of pediatric pharmacotherapy, which cannot be addressed by any single intervention in isolation.

This framework also provides a systematic understanding of pediatric pharmacy interventions. Traditionally, clinical pharmacy interventions in pediatrics have been fragmented, often focusing on individual aspects such as prescription review or adverse drug reaction monitoring. However, by linking technology, the pharmacist's role, and healthcare systems in a coordinated model, this framework enables a more structured approach. It moves beyond piecemeal interventions to foster a comprehensive view of how pediatric drug use can be rationalized and optimized through systemic integration.

Through this framework, it becomes apparent that the effectiveness of interventions hinges not only on technological advancements or professional expertise but also on the broader healthcare ecosystem that supports these elements. This systematic view thus facilitates a deeper understanding of the barriers and opportunities in pediatric drug management and highlights areas where interventions can be strengthened.

4.2 International comparison and insights

Internationally, developed countries such as the United States and those in Europe have made considerable progress in integrating pediatric clinical pharmacy interventions within their healthcare systems. For example, in many European countries, pediatric-specific drug databases and clinical decision support systems are widely used to ensure safe medication practices. In the U.S., a number of hospitals have embedded clinical pharmacists into pediatric clinical pathways, where they work closely with pediatricians and other healthcare providers to optimize drug regimens. This has led to significant improvements in medication safety, reduced adverse drug reactions, and better therapeutic outcomes for pediatric patients.

Moreover, these systems are often supported by strong national policies that prioritize pediatric care and ensure that pharmacists are included as key members of clinical teams. Interdisciplinary care models, which are common in the U.S. and Europe, involve collaboration among pharmacists, physicians, nurses, and other healthcare professionals to address the complexities of pediatric pharmacotherapy.

To further illustrate these cross-national differences, Table 3 compares representative practices in Europe, the United States, and China regarding pediatric clinical pharmacy interventions. It highlights structural distinctions in database development, pharmacist integration, and policy support, providing insights into how systemic and professional factors shape the effectiveness of rational drug use in pediatric settings.

Table 3. Comparative practices in pediatric clinical pharmacy interventions (Europe, United States, and China)

Aspect	Europe	United States	China
Pediatric Drug Databases	Established pediatric databases such as BNF for Children and EMA Pediatric Portal, supporting evidence-based dosing and formulations.	FDA Pediatric Labeling Database and NICHD Pediatric Trials Network ensure regulatory clarity and child-specific evidence.	Few dedicated pediatric databases; clinical systems primarily based on adult references.
Pharmacist Integration	Pharmacists embedded within multidisciplinary teams; active participation in ward rounds and treatment decisions.	Clinical pharmacists positioned within pediatric wards and intensive care units, collaborating directly with physicians.	Pharmacists mainly perform prescription review; limited clinical presence in pediatric departments.
Clinical Pathway	Pharmacists contribute to	Pharmacists co-develop	Limited involvement in

Inclusion	protocol development and ongoing therapy optimization.	pediatric treatment pathways and monitoring guidelines with physicians.	pathway design; interventions mostly reactive rather than preventive.
Training and Certification	Structured postgraduate programs and pediatric specialization under European hospital pharmacy standards.	Board of Pharmacy Specialties (BPS) certification in Pediatric Pharmacotherapy widely recognized.	Pediatric pharmacy training under development; no national certification system established.
Policy and Funding Support	National healthcare systems fund pharmacist-led pediatric services.	Reimbursement models support pharmacist interventions improving pediatric outcomes.	Policies remain fragmented; limited financial incentives for pediatric clinical pharmacy services.

Table 3 demonstrates clear cross-national differences in pediatric clinical pharmacy infrastructure, emphasizing that Europe and the U.S. have developed specialized databases, structured pharmacist roles, and policy support systems that China and other developing countries can adapt to strengthen rational pediatric drug use.

The experience of these developed countries offers valuable lessons for countries with less advanced healthcare infrastructures. Key insights include the importance of developing pediatric-specific databases that are tailored to the unique needs of children, as well as the necessity of embedding pharmacists directly into clinical pathways. In many countries, pharmacists are still underutilized in pediatric care, and their role is often limited to prescription review or medication dispensing. Embedding pharmacists within clinical teams can enhance the effectiveness of interventions by enabling real-time drug therapy management and improving communication between healthcare professionals.

Additionally, multi-disciplinary teams are essential for addressing the complex medical and pharmacological needs of pediatric patients. International models highlight that pediatric pharmacy interventions are most effective when pharmacists collaborate with other healthcare providers, leveraging their specialized knowledge to optimize drug use.

4.3 Root causes of effectiveness bottlenecks

A key bottleneck in the implementation of pediatric pharmacy interventions is the disconnect between available technologies and their practical application in clinical settings. Many advanced technological tools, such as clinical decision support systems (CDSS), are designed to enhance medication management, but their functionality is often misaligned with the specific needs of pediatric care. For example, while CDSS can provide alerts for drug interactions and dosage errors, they may not be equipped with the pediatric-specific data required for accurate dosing adjustments. This misalignment results in underutilization or incorrect application of these tools, limiting their impact on rational drug use.

Furthermore, while pediatric-specific databases and resources exist, their integration into routine clinical workflows is often insufficient. Healthcare professionals may not have easy access to these resources, or the systems may be too complex to use effectively in fast-paced clinical environments, leading to gaps in medication management.

Another key challenge is the marginalization of pharmacists in clinical decision-making, particularly in pediatrics. Although pharmacists possess specialized knowledge in pharmacology, their involvement in pediatric care is often limited to administrative tasks such as prescription review. This restricted role undermines the full potential of pharmacists to contribute to clinical decision-making and patient care.

Moreover, the lack of formal institutional support for pharmacists' roles in pediatric settings exacerbates this issue. In many healthcare systems, there is insufficient funding, training, and recognition for pharmacists in pediatric care. This lack of support prevents pharmacists from fully integrating into

multidisciplinary teams, limiting their ability to provide optimal care.

The final barrier is the underestimation of the value of pediatric pharmacy interventions within the broader healthcare system. Pediatric pharmacotherapy is often seen as secondary to other healthcare priorities, leading to inadequate resource allocation for pediatric pharmacy services. Additionally, the value of pharmacists' contributions to pediatric care is not always adequately assessed, resulting in underfunding and underappreciation of their role in improving drug safety and efficacy.

4.4 Improvement pathways

To overcome the bottlenecks in the Technology Tools dimension, the development of a comprehensive, pediatric-specific technology infrastructure is essential. This includes specialized databases, clinical decision support systems tailored to pediatric needs, and user-friendly interfaces for healthcare professionals. Additionally, integrating pediatric-specific tools into routine clinical workflows can ensure that they are effectively utilized to improve rational drug use.

In the Pharmacist Role dimension, there is a need to establish a proactive and collaborative role for pharmacists within pediatric clinical teams. Rather than being limited to prescription review, pharmacists should be integrated into multidisciplinary care teams, where they can take an active role in decision-making, patient monitoring, and therapy adjustments. This role should be defined early in the clinical process to ensure that pharmacists are actively involved in optimizing drug regimens for pediatric patients.

In the Medical System dimension, it is crucial to establish policies that support pediatric pharmacy services and recognize the value of pharmacists in improving patient outcomes. This includes providing appropriate reimbursement for pediatric pharmacy interventions and ensuring that institutional structures are in place to support the integration of pharmacists into clinical pathways. Additionally, fostering collaboration between healthcare providers through multi-disciplinary care models can help address the complexities of pediatric pharmacotherapy.

To achieve sustainable improvements in pediatric drug use, a closed-loop system must be established, where technology, pharmacists, and healthcare systems work in tandem. This system would involve continuous feedback loops in which technology informs pharmacists, pharmacists provide clinical input, and healthcare systems support the integration of these elements into clinical practice. As illustrated in Figure 1, the interaction among these three dimensions forms a dynamic cycle of improvement that continuously refines pediatric pharmacotherapy based on evidence, collaboration, and policy support. Such an integrated system is expected to be more effective in addressing the challenges of pediatric pharmacotherapy and improving patient outcomes.

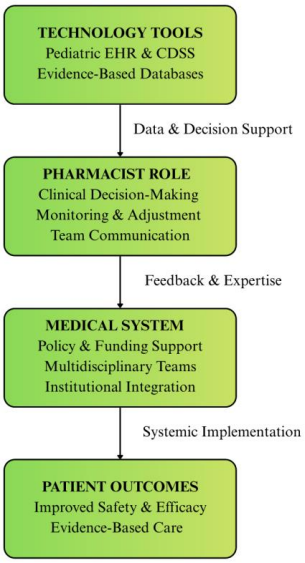

Figure 1. Integrated closed-loop model for enhancing rational pediatric drug use

4.5 Limitations and future directions

This study primarily provides an analytical framework based on existing literature and theoretical insights. One limitation is the lack of empirical validation, as this research does not include real-world clinical data to substantiate the proposed framework. Future studies should seek to validate these findings through multi-center trials and practical evaluations of pediatric pharmacy interventions.

To address the limitations of this study, future research should focus on integrating this framework

into multi-center practices to assess its practical applicability across different healthcare settings. This would allow for a more comprehensive understanding of how the framework can be implemented in diverse environments and provide empirical evidence on its effectiveness in improving pediatric drug use.

5. Conclusion

This study analyzed the core logic and effectiveness bottlenecks of pediatric clinical pharmacy interventions for rational drug use through a three-dimensional framework consisting of Technology Tools, Pharmacist Role, and Medical System. The findings reveal that each dimension contributes distinct yet interdependent functions: technological tools provide the data foundation and decision support necessary for safe medication practices; pharmacists serve as the professional bridge translating this information into individualized care; and the medical system provides the institutional, policy, and financial mechanisms required to sustain and scale effective interventions. However, significant bottlenecks persist, including fragmented digital infrastructures, underdefined pharmacist roles, and insufficient systemic policy support, which collectively constrain the full realization of rational pediatric drug use.

The analytical framework proposed in this paper offers substantial value for understanding and improving pediatric medication practices. It provides a structured means to interpret how technological, professional, and institutional elements interact within clinical settings. By mapping these interdependencies, the framework clarifies why certain interventions succeed in improving drug safety while others fail due to systemic or structural misalignment. This multidimensional lens enriches theoretical understanding of rational drug use and provides a replicable model for examining other specialized fields of clinical pharmacy, such as geriatrics or oncology.

From a clinical and policy perspective, the results carry several implications. For clinical practice, the study underscores the necessity of embedding pharmacists more deeply within pediatric care teams and enhancing their role in clinical decision-making and treatment optimization. For policymakers, the findings highlight the urgency of developing pediatric-specific data platforms, establishing clear professional pathways for pediatric pharmacists, and creating reimbursement mechanisms that reward evidence-based interventions. These measures would not only improve therapeutic outcomes but also ensure safer, more equitable healthcare for children.

Looking forward, the integration and evolution of this three-dimensional framework hold promise for advancing pediatric pharmacy interventions. Future development should focus on creating interoperable pediatric information systems, fostering cross-disciplinary collaboration, and aligning institutional policies with frontline clinical realities. By forming a closed-loop ecosystem where technology informs pharmacists, pharmacists guide clinical action, and healthcare systems reinforce best practices, pediatric drug use can become more precise, transparent, and sustainable, ultimately contributing to safer and more effective medical care for children.

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