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Advancing Quality Risk Management: A Comparative Overview of Traditional and Modern Tools in Pharma

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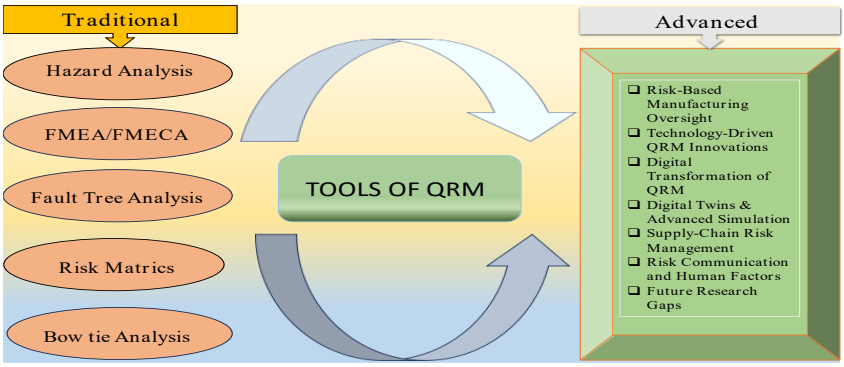
ABSTRACT

A key component of pharmaceutical manufacturing, quality risk management (QRM) guarantees patient safety, product quality, and regulatory compliance throughout the product lifecycle. ICH Q9 and its Q9(R1) version refined risk assessment formality, decision-making, and product availability concerns. The conventional tool includes hazard analysis, FMEA, HACCP, and fault-tree analysis; innovative uses of real-time release testing, statistical process control, and risk-based oversight showed added value. Real-time monitoring and adaptable, flexible decision-making to reduce errors are made possible by technologies like PAT and continuous manufacturing. Although there are still challenges with understanding and governance, the potential given by digitalization, AI, ML, and predictive analytics enhance early deviation discovery and probabilistic evaluation. Newer technologies like digital twins and blockchain offer scenario testing, supply-chain resiliency, and traceability.Although there are still challenges with understanding and governance, the potential given by digitalization, AI, ML, and predictive analytics enhance early deviation discovery and probabilistic evaluation. Newer technologies like digital twins and blockchain offer scenario testing, supply-chain resiliency, and traceability.Still the limitations in ML understanding , regulatory harmonization, scalable digital twin adoption, and cross-industry benchmarking persists. The present status, developments, and prospects of QRM across global pharmaceutical production are highlighted in this article..

Keywords: Quality Risk Management, Process Analytical Technology , Artificial intelligence, Regulatory Compliance; Pharmaceutical Manufacturing

Graphical Abstract:



INTRODUCTION

QRM provides a systematic and structured process for the identification, assessment, control, communication, and review of risks concerning the quality of pharmaceutical products and processes across the product lifecycle. It is not confined to a single stage in drug development but covers everything from the initial development stages of the drug, its manufacture, its packaging, its distribution, and extends right up to post-market surveillance. The central aim of QRM is to make certain that potential risks to product quality, patient safety, and supply chain reliability are proactively managed and minimized.[1-2] By putting risk-based thinking into decision-making, pharmaceutical manufacturers are thus in a position to manage resources more efficiently, underpin regulatory compliance, and also make themselves more resilient against disruptions. The importance of QRM is underlined by its direct link to patient safety and product availability.

Any inadequate risk management can hamper the saftey & efficacy of the pharmaceutical product that can lead to adverse health consequences, costly recalls or market scarcity. Regulatory bodies, such as the U.S. Food and Drug Administration (FDA), emphasize QRM as the core of pharmaceutical quality systems, assuring that risk control strategies are not only scientifically sound but also harmonized across the industry. Updates in recent international guidelines, particularly ICH Q9(R1), have focused attention on the role of QRM in managing technical and organizational risks, as shown in figure 1, which include those affecting product supply. These changes indicate a greater emphasis on structured decision-making and requirements for risk management practices to be proportionate to the level of risk and thus to ensure patient-centered, sustainable pharmaceutical operations.[3-5]

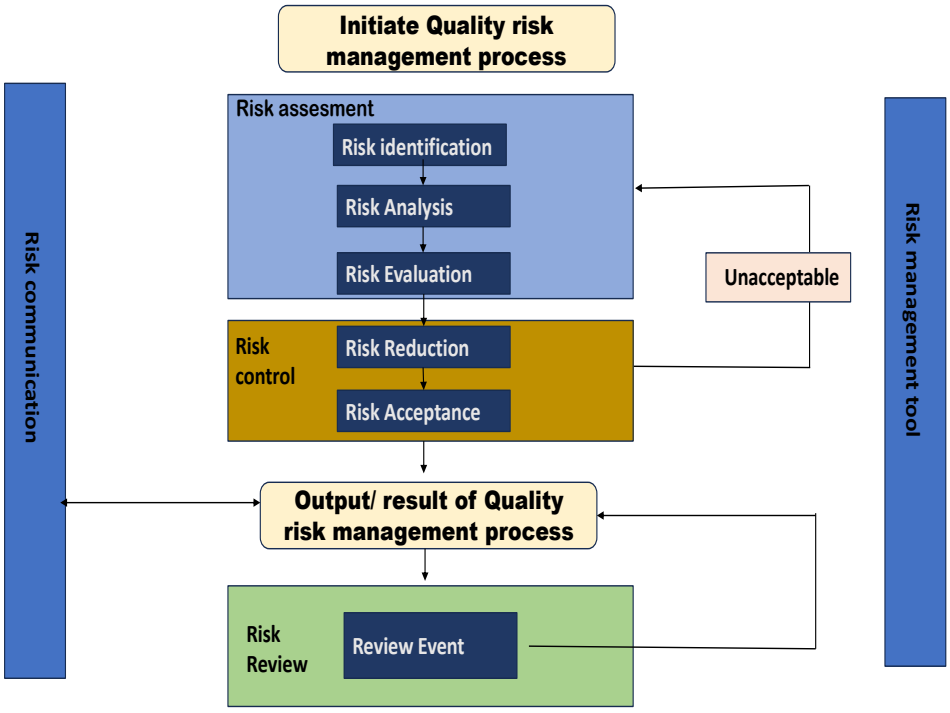


Figure 1: Quality Risk Management in Pharmaceuticals

2. Regulatory Landscape and Recent Guideline Updates

The pharmaceutical industry's QRM procedures have developed and matured thanks in large part to the global regulatory environment. ICH initially issued the ICH Q9 guideline for QRM in 2005, defining a harmonised approach to the evaluation, mitigation, and communication of quality concerns. The fundamental tenets of QRM—science-based decision-making, proper transparency in risk communication, and proportionality in the use of QRM tools—were emphasised in this foundational text. Data are summarized in Table 1.[6] Over the years, however, inconsistencies were seen to arise in practical implementation of these principles regarding the level of formality in risk assessments and in the application of risk-based thinking into decisions concerning product availability.[7] To address these gaps, the revised guideline ICH Q9 (R1), finalized in 2023, provided clarification and refinement on four areas: defining the degree of formality needed in QRM activities, addressing risks impacting product availability, reducing subjectivity in risk assessment, and strengthening decision-making practices. Data is summarized in Table 1.The revised guidelines stress the necessity of adjusting the degree of formality to the importance of the risk, keeping it straightforward for low-risk issues and more stringent for high-impact ones.[8] Importantly, the formal consideration of product availability underscores the increasing recognition that supply interruptions may jeopardize public health, necessitating proactive management within QRM frameworks. The European Medicines

Agency (EMA), the United States Pharmacopeia (USP), and the U.S. Food and Drug Administration (FDA) are examples of regional regulatory agencies that have harmonized with these global standards while giving region-specific instructions to facilitate implementation. For example, FDA includes QRM ideas into its risk-based inspection models and promotes their application in pharmaceutical development and quality systems.[9] The EMA stresses the integration of QRM into advanced manufacturing technologies like as continuous manufacturing and Process Analytical Technology (PAT), while USP utilizes risk-based techniques within its compendial standards. Core QRM Frameworks and Classical Tools are illustrated in Table 1. Collectively, these global and regional regulatory drivers have elevated QRM from a compliance exercise to a strategic framework that fosters innovation, operational efficiency, patient safety, and reliable access to medicines.[10]

3. Core QRM Frameworks and Classical Tools

The foundation of a robust QRM system relies on structured frameworks and established tools that facilitate the processes of identifying, analyzing, and mitigating risks to pharmaceutical quality. Over time, a number of traditional approaches have been widely accepted and recommended by regulatory bodies due to their demonstrated efficacy and flexibility.[11–13] The methodical identification of probable chemical, physical, or microbiological dangers that can harm a product's quality or patient safety is known as "hazard analysis." Manufacturers can also prioritize resource allocation and control strategies based on an evaluation of the potential and severity of those mistakes. FMEA and its more comprehensive version, FMECA[14–16], are proactive instruments that evaluate the potential failures of particular parts, systems, or processes and the potential repercussions of those failures. These methods use numerical RPNs to guide manufacturers through the identification of critical areas where preventive measures should be taken. The concept of HACCP, originally developed for food safety, has found wide adaptation in pharmaceuticals, particularly in sterile manufacturing. It focuses on pinpointing critical control points within a process at which risks could effectively be minimized or eradicated, so that preventive measures can be embedded at the most critical points.[17-20] Fault-tree analysis is a top-down approach to risk assessment. It provides a clear depiction of the causal pathways by mapping out potential root causes in a tree-like structure, starting from an undesirable event, like product contamination. Risk matrix is a simple decision tool that simply organizes hazards into two dimensions, probability and impact. This allows rapid prioritization, particularly when various hazards are being considered.[21-22] Bow-Tie Analysis mixes Fault Tree Analysis and event-tree analysis. It shows how to prevent and reduce a central risk and gives a complete idea of how to handle risks both before and after they happen. Basics of these tools include accepting risk, talking about it, managing it, checking it, and writing it all down. Risk acceptance sets the limits of what's desired, so risks are lowered to levels regulators and manufacturers can agree on. Talking about risk means sharing clear information about risks across teams and with regulators. Risk control means making and using plans to lower risks to levels that are required.(Table 1) Risk review ensures sure that risk assessments are current and valid throughout the product lifetime, while documentation offers traceability, consistency, and compliance with regulatory expectations. The foundation of pharmaceutical QRM is made up of these frameworks and concepts.

Table 1. Core QRM Frameworks and Classical Tools

Tool/Framework	Description	Application in Pharmaceuticals	Strengths	Limitations
Hazard Analysis	Identifies potential sources of risk (chemical, microbiological, physical)	Early-stage risk identification in manufacturing & facility design	Simple, preventive	May lack depth for complex systems
FMEA / FMECA	Analyzes failure modes, effects, and criticality; assigns Risk Priority Number (RPN)	Assessing process steps, equipment reliability, formulation risks	Quantitative, systematic, proactive	Can be resource-intensive; subjective scoring
HACCP	Focuses on Critical Control Points to prevent risks	Widely used in sterile manufacturing & cleanroom operations	Preventive, structured, regulatory acceptance	Limited for non-process risks
Fault-Tree Analysis (FTA)	Top-down approach mapping causes of failures	Root-cause analysis of contamination or equipment failure	Visual, causal pathways	Data-heavy, requires expertise
Risk Matrix	Categorizes risks by probability and severity in a grid format	Quick prioritization of multiple risks	Easy to apply, widely understood	Oversimplified, subjective scales

Bow-Tie Analysis	Combines FTA + event tree; shows prevention and mitigation measures	Visualizing both preventive & corrective controls for critical events	Holistic risk control view	Complex for very large systems

4. Risk-Based Approaches to Manufacturing Release and Oversight[23-26]

As seen today, pharmaceutical manufacturing has evolved from traditional batch testing to more dynamic and information-based oversight mechanisms in which QRM has to play a central role in ensuring product quality and regulatory compliance.

Real-Time Release Testing (RTRT)

One of the major innovations supported by QRM is Real-Time Release Testing. As opposed to waiting for post-production quality tests, RTRT builds on in-line and on-line analytical technologies to assess critical quality attributes during manufacturing. This method speeds up product release and cuts down the chances of releasing bad batches. To make it work, you need a solid QRM system that details the important factors, explains why real-time measurements matter, and proves the monitoring systems are dependable.

Statistical Process Control (SPC)

SPC is simply another method to deal with risk. It monitors a process to ensure it remains within acceptable limits. SPC helps find issues early, so they can be resolved before they cause damage, rather than after they occur. QRM assists in determining metrics to track, acceptable variances, and ways to adjust processes to keep product quality consistent. Risk-Based Batch Release Strategies use QRM during routine quality checks. These strategies change the amount of testing needed depending on product or process risk. For instance, if you already have a lot of information about a product, you may not need to test it very often. New products might need more tests. This method can help your product quality meet requirements and saves both time and expenses.

QRM is great for getting ready for inspections and submitting government reports. Regulators want to be sure your company's quality processes are based on real risks, scientifically sound, and improving all the time. QRM helps you explain your decisions, what went wrong, and how you fixed it.

When regulators inspect, they'll check if you considered risks during development, manufacturing, and quality control. For regulatory paperwork, QRM documents are important for showing how you identified, managed, and monitored major risks over time.By using QRM during product release and when tracking plans, pharma companies can follow the rules, be more productive, reduce waste, and ensure patient safety. The summarized data are presented in Table 2.

Table 2. Risk-Based Approaches to Manufacturing Release & Oversight

Approach	Description	Role of QRM	Benefits	Challenges
Real-Time Release Testing (RTRT)	Uses in-line/on-line tools to test quality attributes during manufacturing	Defines critical parameters, validates analytical models, ensures reliability	Faster release, less waste, continuous assurance	High cost, requires advanced PAT infrastructure
Statistical Process Control (SPC)	Uses control charts and statistical tools to monitor variability	Identifies acceptable limits, defines corrective actions, reduces deviations	Preventive, data-driven, ensures consistency	Requires robust data collection and expertise
Risk-Based Batch Release	Testing/release decisions based on product/process risk profile	Determines extent of testing based on risk; justifies reduced/targeted testing	Optimizes resources, flexible oversight, regulatory confidence	Needs strong historical data & justification
Inspection Readiness & Regulatory Reporting	Ensuring compliance through risk-based documentation and communication	Provides evidence of risk control, CAPAs, lifecycle monitoring	Builds regulator trust, supports innovation (e.g., continuous manufacturing)	Heavy documentation load, requires risk-aware culture

5. Process Analytical Technology (PAT) and Continuous Manufacturing[25-27]

PAT in Pharmaceutical Manufacturing

Process Analytical Technology represents a regulatory and scientific framework advocated by the FDA to drive innovation

in product development with the use of risk-based quality assurance in pharmaceutical processes. PAT uses sensors, spectroscopy, and in-line monitoring right on the production line to measure critical process parameters (CPPs) and critical quality attributes (CQAs) in real time. You can see the data in Table 3.Unlike old-school end-product testing, which takes time to get results, PAT cuts down on guesswork. It gives you a constant flow of data so you can spot problems right away and fix them. For instance, near-infrared and Raman spectroscopy are often used to keep an eye on how evenly things are mixed and the drug concentration while things are being made. This makes sure the product is consistently high quality without having to wait for quality control checks later on.

The rules support using PAT.FDA has a guide, Guidance for Industry: PAT-A Framework for Innovative Pharmaceutical Development, Manufacturing, and Quality Assurance, that goes along with ICH Q8, Q9, and Q10. Basically, it says to use your brain and think about possible problems. This idea makes managing risks super important: spot the risks, watch what's important, and create good controls to keep patients safe and make sure the product works right. All the info is in Table 3. So, PAT not only helps you follow the rules but also makes things quicker, cuts down on bad batches, and gets products out faster.

Continuous Manufacturing and QRM

Think of making medicine not in big pots, but on a steady stream – ingredients always going in. That's continuous manufacturing. It changes how we deal with problems. If things mess up with batch-making, you see it when it's done. But with the stream method you have to keep watch all the time. Small issues can blow up fast and spoil a lot if you don't catch them quick. So having tools that keep track of everything is key. You need to watch things closely and jump in the instant something's off.

When it comes to Process Analytical Technology (PAT) in Continuous Manufacturing (CM), keeping tabs on your model's performance is a must. If you're using spectroscopy, those chemometric models need a checkup. Update them as needed, and be sure to follow Quality Risk Management (QRM) to keep things reliable. The ISPE advises that you should think about product quality when you're combining PAT and CM. Double-check that the equipment works, the controls are running smoothly, and the data is accurate. Putting PAT and CM together helps catch manufacturing risks early, keeps you in line with the rules, and gets you set for digital production down the road.

Table 3. Role of PAT and Continuous Manufacturing in QRM

Aspect	PAT Contribution	Continuous Manufacturing Contribution
Risk Identification	Detects CPPs/CQAs using sensors & spectroscopy	Identifies real-time deviations in continuous flow
Risk Control	Enables immediate corrective actions	Requires continuous feedback loops for stability
Regulatory Framework	FDA PAT Guidance; ICH Q8–Q10	ISPE guidelines; FDA/EMA support CM adoption
Advantages	Reduces batch failure, faster release, real-time assurance	Consistent quality, scalability, resource efficiency
Challenges	High cost, model validation & calibration	Rapid error propagation, complex model governance

6. Digitalization, Data Analytics, and AI/ML for Predictive QRM[28-30]

Predictive Analytics in QRM

In this context, the integration of digitalization and advanced data analytics has helped QRM evolve from a reactive to a predictive framework. Predictive analytics checks out loads of info from factories, tests, and supply chains to see if there are any problems coming down the road. Like, if the temperature changes a bit or a machine's vibrations are unusual, that means it's about to break, or a product didn't meet the specifications. Catching these things early can mean less downtime, things running smoother, and safer workers.

Role of AI/ML in Risk Prediction

AI/ML is changing how we guess risks in quality. It helps us figure out risk levels and see trends that regular stats fail to capture. ML looks at old data to link causes and better guess when issues will occur. Like, models can learn to split batches into risky or safe groups. Plus, they can find unusual things in the process. AI can also guess when machines might break, which lowers unexpected stops and keeps quality consistent.

Model Validation, Explainability, and Governance

When using AI/ML in industries with lots of rules, it's super important to focus on things like making sure the AI works right, being able to explain how it does what it does, and keeping it under control. Checking the AI means it gives correct answers on data and situations . Regulars want to understand how AI makes choices, mainly when it comes to risk. So, we have to avoid AI that nobody gets. Companies should also have rules for how AI is trained, used, watched to see if it's working well, and re-checked later. If, for example, drug companies consider all of this when managing risk, they can use AI/ML, keep patients safe, and keep regulators happy.All data are summarized in table 4.

Table 4. Applications of Digitalization and AI/ML in QRM

Application	Description	QRM Contribution	Challenges
Predictive Analytics	Uses historical and real-time data to detect early warning signals	Prevents deviations before they escalate	Requires robust datasets, data integrity
ML-Based Risk Assessment	Classifies and predicts batch/process risks	Supports probabilistic risk assessment	Black-box models difficult to explain
Anomaly Detection	Identifies unusual patterns in process data	Enables real-time corrective actions	Risk of false positives/negatives
Predictive Maintenance	Forecasts equipment breakdowns using sensor data	Reduces downtime, ensures consistent quality	Needs continuous monitoring & retraining
Governance & Validation	Framework for lifecycle management of AI models	Ensures regulatory compliance and reliability	Resource intensive, evolving guidelines

7. Digital Twins and Virtual Process Models[31-34]

Pharmaceutical manufacturers are beginning to utilize digital twins to create virtual versions of their current and future manufacturing processes in real time. Digital twins mix science-based models with data analysis to copy the processes within a medication production facility. They help guess what might happen and spot possible problems. For instance, a digital twin of a bioreactor lets you test different events, like a part breaking or a process changing. This way, manufacturers can test things out beforehand. This gives them a way to lower risks and plan better supply chains, which is super important when things get complicated worldwide.For instance, assume you've got a bioreactor. A digital twin can show you what happens to your final product if the temperature or pH changes. This way, the manufacturer can partially visualize what those changes do before they even make the product. Also, in supply chains, digital models can help a manufacturer see the possible problems if, like, raw materials are short or shipments are late, and then come up with backup plans. But, getting digital twins to really work hinges on good data, everything working together, and IT and operations platforms integrating smoothly. You also run into issues like poorly organized data, not enough people who know how to set up digital twins, and worries about cybersecurity. For an overview of the data included in this report, see Table 5.

Table 5. Role of Digital Twins in QRM

Application Area	Benefit in QRM	Limitation
Process simulation	Predicts risks before physical execution	Requires high-quality data
Failure-mode analysis	Identifies weak points for proactive mitigation	Integration challenges across systems
Supply-chain modeling	Strengthens resilience and contingency planning	High implementation cost

8. Supply-Chain Risk Management and Resilience[35-38]

There are numerous vulnerabilities in the pharmaceutical supply chain, such as; sourcing risks, political instability, disruption of logistics and cold chain issues associated with the delivery of temperature-sensitive products. To handle risks well, drug

companies can use organized ways to spot and cut down on problems in how they get their supplies. Organizations should check their suppliers, audit them, and keep track of their materials to be sure they meet rules and have good quality. All of this should be part of their regular responsibilities.

Keeping vaccines and other biological products at the right temperature during shipping is a critical concern. If things get too warm or cold, these products may not be secure or be effective. So, people are using things like tracking product temperature all the time, using blockchain, planning logistics ahead to make sure everything stays good during shipping. Groups like the FDA and EMA are checking on suppliers overseas more often and want to see their plans for dealing with unexpected problems to make sure they're ready for all eventualities.

Using computer systems and AI dashboards to keep an eye on things helps businesses spot when something doesn't quite meet their quality standards fast. When companies put quality risk management ideas into their supplier and distribution deals, they can lower the chances that issues such as pandemics or natural catastrophes will interfere with their organizational processes.

9. Model Life-Cycle Management and Validation[39-42]

In pharmaceuticals, using complex data analysis like Process Analytics Technologies (PAT) and AI with Machine Learning is becoming normal. These things are now part of the entire product lifecycle, so it's extra important to have a solid Quality Risk Management (QRM) system. This helps manage the model lifecycle—from when it's made to when it's retired, including checking, putting it to work, watching it, redoing it, and stopping it. Each step needs strong rules and top-notch quality to make sure everything's accurate and reliable, and that it all fits with the rules.

Checking the model gives confidence that it will give same answers when the setting conditions are set.Regulatory Authorities require significant detailed information on the model from the period of its creation and development to the present time, including: assumptions made; dataset(s) used; performance metrics; and change-control protocols. Continuous model monitoring is needed to detect when the model has "drifted", i.e., its performance will degrade when process parameters (dynamics) or inputs change significantly. Therefore, retraining and version control strategies are of critical importance in order for the model to stay consistent with its intended performance over time.

Table 6. Lifecycle Stages of Models in QRM

Stage	Key Activity in QRM Context	Regulatory Expectation
Development	Design and training with relevant datasets	Documentation of methods and data
Validation	Confirm reliability under operating ranges	Evidence of reproducibility
Monitoring	Continuous performance tracking	Periodic reports and auditability
Retraining/Updates	Adjusting to new process data	Change control documentation
Retirement	Controlled phase-out of obsolete models	Archived validation records

10. Risk Communication, Decision-Making, and Human Factors[43-47]

Effective QRM, which cannot be confined within the domain of technical tools only, requires open risk communication and codified decision-making models. Formal criteria for judgments limit subjectivity, which enables evidence-based appraisals of risks without the prejudice of individual subjective views. Thus, it can be said that developing a consensus among cross-functional stakeholders, such as the quality assurance, manufacturing, R&D, and supply-chain teams, helps businesses in agreeing upon the prioritization of risks and strategies of mitigation. Training programs are essential in implementing the QRM principles into the business culture. The employees must understand not only the tools but also the reasoning behind the risk-based decisions. Fostering an open environment where risks can be reported without fear of retribution enhances the effectiveness of the QRM system.

11. Future Directions and Research Gaps

While there have been significant achievements in the field of QRM for pharmaceutical manufacturing, a number of issues need further consideration and will require organized and prioritized improvement if this area is to be sustainably developed and globally harmonized.

Standardized Frameworks for ML Explainability

The rising dependence on ML and AI models in QRM presents an interpretability challenge.Okay, here's a more human-sounding rewrite:Usually, regulatory groups and people in the industry want clear reasons behind model predictions, especially if those predictions affect patient safety and product quality. Having set ways to explain ML, like rules for feature importance, model clarity, and error checks, can really help build trust and get regulators on board. If we don't have these

things, it can be hard to see how decisions are made, and that could slow down how widely ML is used, like shown in Table 7.

Harmonized Regulatory Expectations

Globally, different regulatory groups have their own ways of doing things when it comes to figuring out risks, checking models, and using tech. This makes things complicated for pharmaceuticals, that work in lots of countries. But, the goal is to get everyone on the same page with rules from the International Council for Harmonisation. If that happens, audits would be easier, we wouldn't have to do the same adherence requirements over and over, and we could come up with more innovative techniques to handle quality risk management.

Wider Adoption of Digital Twins

Digital twins are good for simulating systems and assessing potential hazards, but they have limitations. They can be expensive, challenging to install, and you need to be technically proficient for their operation. So, we need to figure out how to make them cheaper and easier to use, especially for smaller companies. Showing how they pay off in the long run and coming up with some standard ways to use them will significantly assist encourage wider adoption among businesses. See Table 7 for the data.

Integration of Blockchain for Supply-Chain Traceability

Pharmaceutical supply chains still struggle with things like counterfeit medications, unclear processes, and altered data. Adding blockchain to QRM systems could create permanent records of everything that happens when making and sending drugs. This would strengthen the supply chain, help follow the rules for keeping meds cold, and stop bad drugs from getting to people. But, we need to study how well it handles growth, works with other systems, and keeps data private before we can use it fully. The data are summarized in Table 7.

Cross-Industry Standard Datasets for Model Benchmarking

A big problem slowing down AI/ML in QRM is that we don't have standard datasets to train and test models. Since every company has its own data, it's hard to compare models or figure out what works best. Creating standard, anonymous datasets across industries would really help to benchmark and make models more reliable, which would speed up innovation in QRM.Collaboration between academia, industry, and regulators is imperative and needs to be carried out, as depicted in table 7.

Table 7. Future Directions and Research Gaps in QRM

Focus Area	Future Direction	Research Gap/Challenge
ML Explainability	Develop standardized frameworks for interpretability	Lack of universal guidelines for transparency
Regulatory Harmonization	Align global QRM expectations (ICH-driven)	Fragmented regulations across regions
Digital Twins	Encourage scalable, cost-effective adoption	High cost and technical expertise requirements
Blockchain in Supply Chains	Enhance traceability and anti-counterfeiting	Scalability, privacy, and interoperability
Standard Datasets for Benchmarking	Create cross-industry shared datasets	Limited collaboration and data confidentiality

CONCLUSION:

It has positioned QRM as a key driver for patient safety, product quality, and regulatory compliance in today's pharmaceutical manufacturing. While traditional tools, such as Hazard Analysis, FMEA, HACCP, Fault-Tree Analysis, and Bow-Tie Analysis, have become the cornerstone for structured identification, evaluation, and mitigation of risk over the years, matrices of risk and structured approaches to decision-making have facilitated prioritizing possible hazards. Real-Time Release Testing, SPC, and risk-based batch release are some of the contemporary advances that have shifted the paradigm from reactive to predictive oversight of manufacturing processes and facilitate proactive control of critical quality attributes. Adoption of Process Analytical Technology and continuous manufacturing has advanced QRM further by offering real-time monitoring, immediate corrective actions, and data-driven assurance regarding the quality of the product. Recent advances in Digitalisation, AI, and ML have also been instrumental in further developing predictive capability in Risk Assessment to pre-identify potential catastrophic Client Risks that could impact patients' safety. In addition to these technologies, emerging technologies such as Blockchain, Digital Twins, etc., are enhancing available capability to better assess a full array of

associated Operation Risks through the supply chain, as well as traceability of products and production processes within the overall supply chain. While significant advances have taken place to date, there still remain multiple opportunities for researchers to further investigate ML explainability; harmonization of global regulatory expectations; widespread use and acceptance of Digital Twins; utilization of Blockchain, and build cross-industry benchmarking datasets. Addressing these areas will enable the implementation of more robust, transparent, and worldwide harmonized Quality Risk Management Systems (QRMS) and provide better assurance of patient safety while ensuring greater regulatory confidence and improving operational outcomes.

Today, Quality Risk Management has transformed from a Regulatory Compliance-driven requirement into a Key Strategic Enabler of Innovation, Efficiency, and Risk-Informed Decision-Making in pharmaceutical production; the future development of QRMS based on the incorporation of Digital Technologies and Harmonized Regulations will be key to the creation of Safe, Quality, and Sustainable Medications for all populations.

Conflict of Interest:

The author declares the no any conflict of interest.

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