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Reliability-Centered Maintenance Implementation in Food Packaging Production Lines: A Systematic Literature Review

Fatehi Abdullah Abdo Ahmed[1]*, Andi Pawennari[2], Irma Nur Afiah[3], Nurul Chairany[4]
Jurusan Teknik Industri, Fakultas Teknologi Industri, Universitas Muslim Indonesia, Indonesia
Gedung FTI, Kampus II UMI, Jl. Urip Sumoharjo KM. 05, Makassar, Indonesia
Email: 09120230109@student.umi.ac.id

* *Corresponding Author*

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ABSTRACT

Reliability-centered maintenance (RCM) is a structured approach to the identification of failure modes and prioritization of maintenance actions based on criticality of a particular equipment component and failure mode, therefore being suitable for meeting strict requirements for food safety and protection from contaminations in the context of food packaging production lines. Despite the efficiency of the proposed RCM-based reduction in reactive maintenance actions and associated expenses, the food industry still faces machine malfunctions, micro-stoppages, and primarily reactive maintenance approaches. This systematic review intends to aggregate, critically evaluate, and synthesize 51 peer-reviewed articles (2021-2026) devoted to the application of RCM in food packaging production with respect to effectiveness, facilitating and hindering factors, and contributions to resilience, compliance, and competitiveness. The research will use the systematic review protocol, which implies such steps as the definition of a systematic search strategy including systematic literature search in Google Scholar with four Boolean queries (800 articles initially found; 689 after duplicates elimination; 51 articles are selected for further analysis), MMAT quality appraisal, and content mapping of the selected articles in the scope of reliability engineering and food quality management. Based on the synthesis of results, the concept of an integrative framework is proposed, which links RCM, FMECA, IIoT, and HACCP to be validated empirically in the future. The framework will implement criticality classification based on RCM to determine HACCP control points in combination with IIoT-based condition monitoring, while FMECA risk indices will determine the maintenance prioritization and food-safety actions.

Keywords: Reliability-Centered Maintenance; Food Packaging Production Lines; Overall Equipment Effectiveness; FMECA; IIoT; HACCP

I. INTRODUCTION

Food packaging production lines are among the most demanding environments in manufacturing, operating at high speeds under strict hygiene requirements while functioning as the final quality gate before products reach consumers. Equipment reliability on these lines is therefore not merely an economic concern but a food-safety imperative, because unplanned failures can halt production, disrupt line balance, and compromise the integrity of in-process and packaged product. In this context, maintenance has evolved from a cost center into a strategic function whose planning directly shapes operational resilience, product safety, and supply-chain continuity in food manufacturing (Dingba, 2022).

Reliability-Centered Maintenance has emerged as one of the most influential structured approaches to maintenance planning. Founded on the systematic identification of failure modes, their consequences, and the criticality-based selection of preventive, predictive, and condition-based tasks, RCM directs maintenance resources toward the functions whose failure matters most. Recent reviews of three decades of manufacturing maintenance research confirm a sustained shift toward reliability- and risk-driven paradigms, with RCM positioned as a core methodology for aligning maintenance decisions with operational risk (Sala, Francalanza, & Arena, 2025; Shamim, 2025). Within high-demand process industries, RCM has been merged with digitalization opportunities to produce hybrid reliability-centered strategies suited to the contemporary production environment (Introna & Santolamazza, 2024).

Despite the documented capacity of RCM to reduce unplanned downtime and maintenance expenditures, food manufacturers continue to report suboptimal machinery availability caused by recurring equipment failures, micro-stoppages, and the persistence of reactive maintenance habits. Evidence from food and beverage facilities indicates that maintenance programs frequently remain fragmented, with reliability objectives disconnected from food-safety governance and from the data-driven capabilities offered by modern sensing

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and analytics technologies (Uzoigwe, 2024a, 2024b). Classical RCM frameworks also operate largely outside the regulatory logic of food manufacturing: they prioritize production loss but do not natively account for contamination risk or Hazard Analysis and Critical Control Points obligations, even though packaging and end-of-line equipment are recognized as a special challenge for hygienic design and contamination control (Pakdel, Olsen, & Bar, 2023; Pejanovic, Djekic, Kljajevic, & Smigic, 2026). This gap between reliability engineering and food-safety assurance constitutes a significant, underexplored problem in the literature.
The review is guided by the following research questions: RQ1: What is the state of the art in RCM implementation on food packaging production lines, as reported in peer-reviewed literature published between 2021 and 2026?; RQ2: What operational outcomes (availability, OEE, downtime, maintenance cost, MTBF/MTTR) are associated with RCM and its companion methodologies in food packaging contexts?; RQ3: What enablers and barriers shape the successful adoption of RCM in food manufacturing?; RQ4: How can emerging digital technologies IIoT, AI-based fault diagnosis, and digital twins reinforce RCM principles in packaging-line maintenance?; RQ5: How can RCM be integrated with food-safety frameworks such as HACCP and hygienic-design standards?

The aim of this systematic literature review is to synthesize peer-reviewed evidence on RCM implementation in food packaging production lines and to propose a conceptual framework that integrates RCM with FMECA, IIoT, and HACCP for future empirical validation. The specific objectives are: (i) to map the recent research landscape on reliability and maintenance in food packaging; (ii) to consolidate quantitative outcomes reported across case studies; (iii) to identify recurring enablers and barriers; (iv) to examine the digitalization of maintenance practice; and (v) to develop a cross-domain integration framework that extends RCM toward regulatory-aware reliability and food-safety assurance.

This review contributes to the literature in three ways: it provides an up-to-date synthesis restricted to the 2021–2026 period, distinguishing it from earlier reviews of maintenance in food production; it consolidates quantitative maintenance outcomes from packaging-line case studies into a single comparative view; and it proposes an original conceptual integration framework combining RCM, FMECA, IIoT, and HACCP, thereby responding to calls for reliability approaches that explicitly incorporate food-safety governance (Soltanali, Khojastehpour, Pais, & Farinha, 2022; Uzoigwe & Kongolo, 2024).

To sharpen the contribution's novelty, this review is explicitly differentiated from the closest prior work in the same sector: the review of RCM program effectiveness in food and beverage manufacturing facilities (Uzoigwe, 2024a). That review evaluates RCM programs across food and beverage plants generally, synthesizing effectiveness evidence and implementation challenges, but it does not restrict its lens to packaging production lines, does not consolidate packaging-specific quantitative outcomes (OEE, availability, MTBF/MTTR), and does not integrate RCM with food-safety governance instruments. The present review differs on four stated criteria: (i) it is restricted to the 2021–2026 window; (ii) it focuses on packaging and end-of-line operations, where failure consequences are amplified by line-balance disruption and contamination exposure (Pakdel et al., 2023; Pejanovic et al., 2026); (iii) it consolidates packaging-line performance outcomes into a single comparative synthesis (Aji, Rahayu, Fitra, Feriaty, & Wiyatno, 2025; Fernández Torres, Casapaico Pultay, & Loja Herrera, 2024; Maceda-Cabrejo, Velazco-Gomez, & Meza-Ortiz, 2025; Tampubolon, 2025; Trejo-Mendoza, Estrada-Barrera, & Gálvez-Mendoza, 2024); and (iv) it proposes a four-layer RCM–FMECA–IIoT–HACCP framework that operationalizes the maintenance–HACCP integration called for in recent literature (Uzoigwe & Kongolo, 2024). This extends the scope of the prior review (Uzoigwe, 2024b). A recent study published in Jurnal Rekayasa Industri also demonstrates the application of Reliability Centered Maintenance and FMEA to determine maintenance intervals and address machine downtime, reinforcing the relevance of RCM-based approaches within industrial engineering maintenance research (Yuda & Al-Faritsy, 2026). The remainder of the paper is organized as follows: Section II describes the methodology; Section III presents the results and discussion; and Section IV concludes the study with implications and a future research agenda.

II. METHODOLOGY

This study follows a systematic literature review protocol and is reported in accordance with the PRISMA 2020 statement (Page et al., 2021) consistent with recent review conventions in maintenance engineering research (Shamim, 2025). Throughout this review, the term "included studies" refers strictly to the 51 sources forming the review corpus; the PRISMA 2020 statement (Page et al., 2021) and the Mixed Methods Appraisal Tool (Hong et al., 2018) are cited additionally as methodological references for reporting and quality appraisal and are not counted among the 51. The protocol was defined prior to searching and comprises: (i) formulation of research questions; (ii) development of the search strategy; (iii) systematic querying of Google Scholar

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through four structured queries; (iv) application of inclusion and exclusion criteria; (v) quality assessment of eligible studies; (vi) data extraction and synthesis; and (vii) development of the conceptual framework.

The search strategy combined keywords from four thematic domains maintenance methodology, food packaging context, performance and risk metrics, and digitalization operationalized as four structured Boolean queries. Google Scholar was selected as the search engine because of its comprehensive interdisciplinary coverage, which is essential for a topic spanning reliability engineering, industrial maintenance, and food-quality-management literatures; systematic reviews in adjacent domains have adopted the same approach (Shamim, 2025). All four queries were executed on 29 August 2026, and the complete result sets including citation counts, DOIs, source metadata, and citation URLs were exported in tabular form for screening, ensuring a fully documented and reproducible search trail. The first 200 results of each query were exported (the Google Scholar export limit), and the combined records were deduplicated into a single screening pool of 689 unique records. The search was supplemented by backward snowballing of the reference lists of included reviews (Abdurrahman & Ferrari, 2025; Van Dinter, Tekinerdogan, & Catal, 2022).

Table 1. Structured search queries executed in Google Scholar (29 August 2026).

Query ID	Label	Search string (verbatim)	Records
Q1	RCM Packaging	("reliability centered maintenance" OR RCM OR "condition based maintenance" OR "predictive maintenance") AND ("food packaging" OR "packaging line" OR "filling line" OR "bottling line")	200
Q2	Performance/Risk	(RCM OR "reliability centered maintenance" OR FMECA OR FMEA) AND ("food packaging" OR "packaging line")	200
Q3	Industry 4.0	(RCM OR "predictive maintenance" OR "condition based maintenance") AND ("food packaging" OR "packaging line" OR "food manufacturing") AND ("Industry 4.0" OR IIoT OR "digital twin" OR "condition monitoring")	200
Q4	TPM	(TPM OR "total productive maintenance") AND ("food packaging" OR "packaging line" OR "bottling line" OR "filling line")	200

The four queries yielded 800 records in total, which after removal of 111 duplicates produced a deduplicated screening pool of 689 unique records. Considerable cross-query overlap was observed: several records appeared in more than one query result set (for example, the TPM/5S ham-packaging study (Fernández Torres et al., 2024) and the cattle-feed OEE study (Nuljan & Srithorn, 2025) appeared in both the Q2 and Q4 exports) which motivated the deduplication step before screening.

Studies were included if they: (i) were published between 2021 and 2026; (ii) addressed maintenance, reliability, or performance topics in food manufacturing, food packaging, bottling, or related process industries; (iii) reported either empirical results (case studies, experimental work, implementations) or structured reviews (systematic reviews, literature reviews); and (iv) were published in peer-reviewed journals or indexed conference proceedings. Studies were excluded if they: (i) predated 2021; (ii) concerned maintenance in non-food industries without transferable methodological relevance; (iii) were editorials, opinion pieces, or abstracts without full-text availability; or (iv) lacked verifiable bibliographic metadata.

The 689 deduplicated records were screened by title and abstract against the inclusion criteria, yielding 234 articles retained for full-text assessment (455 records excluded). Full-text review of these 234 articles identified the final corpus of 51 included studies. Title-and-abstract screening, full-text eligibility assessment, and quality appraisal were conducted by a single reviewer following the a priori protocol; to mitigate single-reviewer bias, eligibility criteria were operationalized in a documented checklist that was applied consistently across all records, and a documented checklist was applied consistently across all records. No second-reviewer verification was performed for this version of the manuscript, which is acknowledged as a limitation in Section 3.10. Data extraction captured: bibliographic details; study context (facility type, equipment); maintenance methodology; digital technologies employed; reported outcomes (availability, OEE, MTBF, MTTR, downtime, cost metrics, quality metrics); and reported enablers and barriers. A total of 51 unique primary sources were selected and organized into five thematic clusters.

Each eligible study was critically appraised using the Mixed Methods Appraisal Tool, a validated instrument designed for the mixed study types represented in this corpus (qualitative, quantitative descriptive, and mixed-methods evaluations) (Hong et al., 2018). Each study received a category rating (low, medium, or high) on the MMAT criteria; ratings informed the interpretation of findings and the strength of conclusions but

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were not used to exclude studies, preserving the breadth of the evidence base. The completed appraisal matrix is available from the corresponding author upon reasonable request.

A content-analysis approach was adopted, mapping each selected study onto reliability-engineering, industrial-maintenance, and food-quality-management dimensions. Quantitative outcomes were extracted verbatim and tabulated for comparative analysis. Qualitative findings relating to enablers, barriers, and integration pathways were coded thematically. This dual quantitative-qualitative synthesis permits both magnitude assessment of RCM outcomes and interpretation of the contextual conditions under which those outcomes materialize.

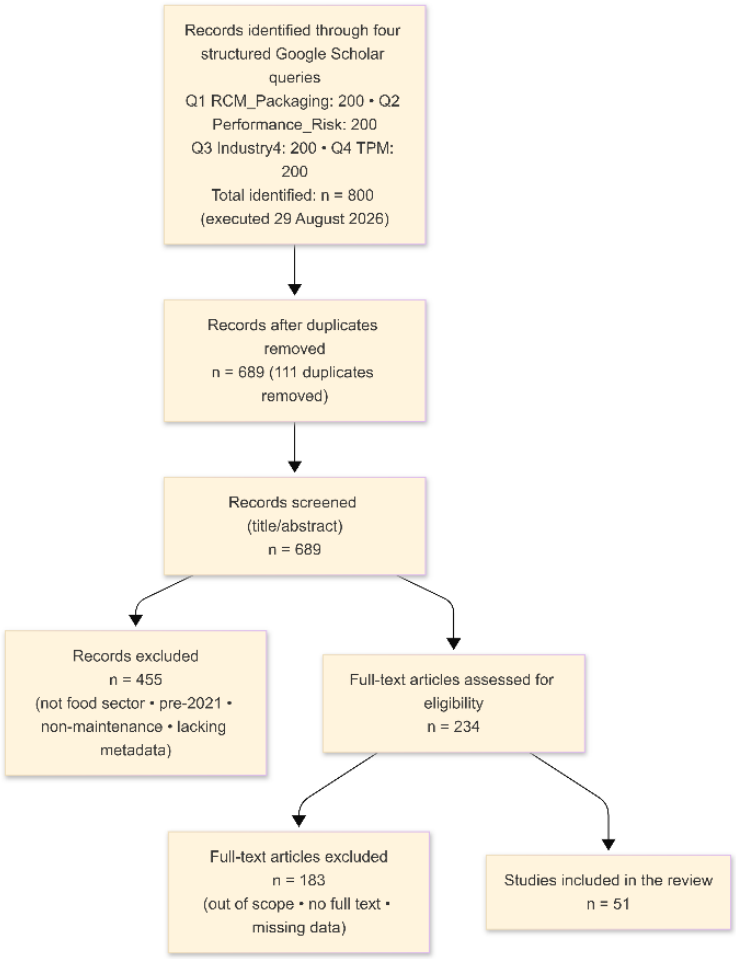


Figure 1. PRISMA 2020 flow diagram of the study selection process adapted from (Page et al., 2021).

The final stage of the methodology was theory-building: drawing on the thematic synthesis, a conceptual integration framework was constructed that combines four pillars RCM, FMECA, IIoT, and HACCP into a single governance logic for packaging-line maintenance. The framework was developed iteratively against the evidence, ensuring that each of its components (criticality classification, condition monitoring, risk scoring, and regulatory control points) is supported by the reviewed literature.

III. RESULTS AND DISCUSSION

3.1 Study Characteristics and Descriptive Findings

The 51 reviewed sources span case studies, implementation studies, and systematic reviews published between 2021 and 2026. Figure 2 shows the distribution of publications by year (2021: 7; 2022: 9; 2023: 7; 2024: 11; 2025: 15; 2026: 2; n = 51). Methodologically, the corpus divides into three groups: RCM/TPM implementation case studies reporting before–after metrics (Maceda-Cabrejo et al., 2025; Fernández Torres et al., 2024; Trejo-Mendoza et al., 2024); packaging-performance analyses using OEE decomposition (Aji et al., 2025; Srikandi & Yusianto, 2025; Tampubolon, 2025) and digitally oriented studies on condition monitoring, predictive maintenance, and digital twins (Arifeen & Petrovski, 2023; Kuhnel, Wiede, Heidemann, & Grabmaier, 2022; Maheshwari, Kamble, Belhadi, Mani, & Pundir, 2023). Reviews and framework studies constitute a smaller but influential share of the corpus (Van Dinter et al., 2022; Psarommatis, May, & Azamfirei, 2023; Sala et al., 2025).

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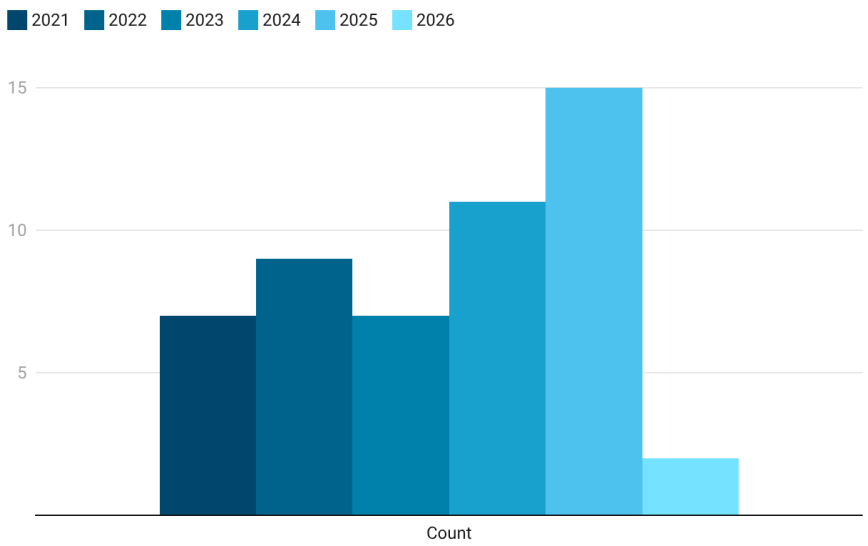


Figure 2. Publications by year included in the review (2021–2026). Data: 2021: 7; 2022: 9; 2023: 7; 2024: 11; 2025: 15; 2026: 2 (total n = 51).

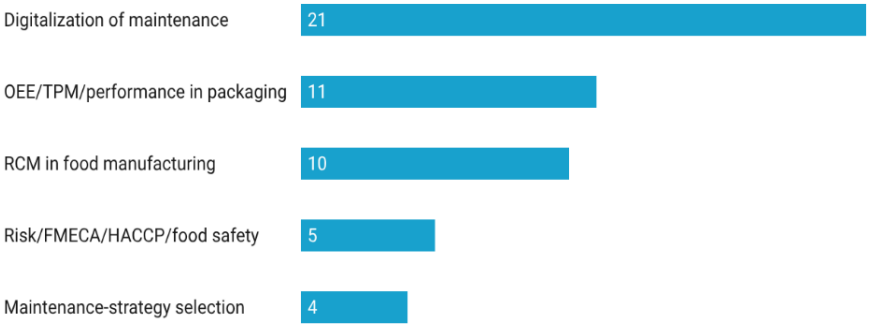


Figure 3. Thematic cluster distribution of the 51 reviewed

Figure 3 shows how the 51 reviewed sources are distributed across the five thematic clusters. Sources (n per cluster: RCM in food manufacturing, 10; OEE/TPM/performance in packaging, 11; risk/FMECA/HACCP/food safety, 5; digitalization of maintenance, 21; maintenance-strategy selection, 4) Digitalization of maintenance is the largest cluster (n = 21; 41.2%), indicating that a large share of recent literature addresses condition monitoring, predictive maintenance, and digital twins. OEE, TPM, and performance analysis in packaging (n = 11; 21.6%) and RCM in food manufacturing (n = 10; 19.6%) follow and form the empirical core of the corpus, where before–after results are reported. Risk, FMECA, HACCP, and food-safety studies (n = 5; 9.8%) and maintenance-strategy selection studies (n = 4; 7.8%) are the smallest clusters. This distribution shows that RCM in packaging is more often studied together with digital technologies than together with food-safety risk frameworks, which motivates the integrated RCM–FMECA–IIoT–HACCP framework proposed later in this review.

3.2 RCM Implementation Outcomes in Food Packaging Lines

Beyond describing the characteristics of the corpus, it is necessary to examine what the implemented interventions actually achieved in practice. The empirical studies identified in this review report their results with different indicators, such as availability, OEE, MTBF, MTTR, and maintenance cost, and were conducted in different packaging contexts, from cookie manufacturing to beverage bottling. To make these results comparable at a glance, the quantitative outcomes are consolidated in the table below. Table 2 summarizes the quantitative outcomes reported in the empirical studies within the 2021–2026 window.

Table 2. Reported Quantitative Outcomes of Reliability And Maintenance Interventions in Food Packaging Operations

Source	Context	Reported outcome
(Maceda-Cabrejo et al., 2025)	Cookie manufacturer (RCM + FMEA + criticality)	Availability 75.67% → 80%; unplanned stoppages reduced; maintenance costs reduced

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Source	Context	Reported outcome
(Benini & Santos, 2021)	Vacuum food packaging machines	Maintenance costs reduced by ≈55%
(Fernández Torres et al., 2024)	Ham packaging line (TPM + 5S)	Availability 81.02% → 88.01%; MTBF +62.44%; MTTR −5.54%
(Trejo-Mendoza et al., 2024)	Sausage-packaging area (autonomous maintenance)	OEE 71% → 82%
(Aji et al., 2025)	Packaging machines	OEE 94%; failure losses 50%, rework 22%, defects 22%
(Tampubolon, 2025)	Beverage bottling line	OEE 69.35% (A 97.9%, P 70.9%, Q 99.9%); speed losses ≈28.48%
(Srikandi & Yusianto, 2025)	Single-line packaging, two stations	OEE 85.7% and 79.32%
(Castañeda, Rodriguez, Yildiz, Aranda, & Alvarez, 2024)	Food company (TPM + SMED + RCM)	MTBF and MTTR improvements

Figure 4 visualizes the improvements in terms of availability and OEE of the three interventions with figures presented in terms of paired comparisons (Maceda-Cabrejo et al., 2025; Fernández Torres et al., 2024; Trejo-Mendoza et al., 2024). The two most common losses reported across the studies are failures and micro-stoppages with the biggest performance loss being attributed to speed reduction in the case of high-speed lines (Tampubolon, 2025), while Figure 5 displays the losses category distribution. Reliability-centered maintenance (RCM) strategy intervention results in improvements in availability in the order of 2–7 percentage points and a significant decrease in maintenance expenses (Benini & Santos, 2021; Maceda-Cabrejo et al., 2025). In the meantime, TPM and autonomous maintenance intervention strategies produce similar or even better gains due to the involvement of operators (Fernández Torres et al., 2024; Trejo-Mendoza et al., 2024). This result is also confirmed by other research in which it was concluded that RCM maintenance programs decrease downtime and increase equipment reliability in the food and beverage industry (Uzoigwe, 2024a).

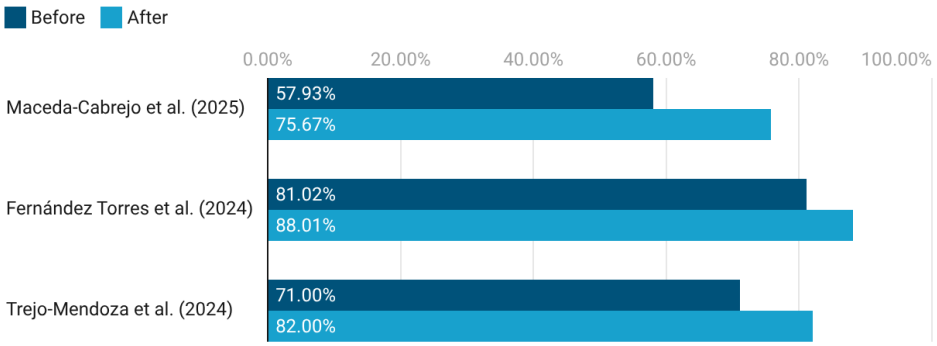


Figure 4. Before–After Comparison Of Maintenance Performance Indicators Reported In Selected Studies. Data Sources: (Maceda-Cabrejo Et Al., 2025) – OEE 57.93% → 75.67%; (Fernández Torres Et Al., 2024) – Availability 81.02% → 88.01%; (Trejo-Mendoza Et Al., 2024) – OEE 71% → 82%



Figure 5. Dominant OEE Loss Categories On Packaging Lines (Data Sources: (Aji Et Al., 2025; Tampubolon, 2025)

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Equipment failure, rework, and defect shares are drawn from a single packaging-machine study (Aji et al., 2025); the reduced-speed share is from a separate bottling-line study (Tampubolon, 2025) These are two independent case studies shown together, not one loss decomposition.

3.3 Enablers and Barriers to RCM Adoption

Analysis of the qualitative evidence leads to the identification of five key enablers. The first one is the commitment of top management and strategic alignment of the maintenance processes with production and safety objectives (Maceda-Cabrejo et al., 2025; Uzoigwe, 2024a). The second one is the existence of accurate data on failures and losses, which define the quality of FMEA and criticality assessment (Maceda-Cabrejo et al., 2025; Soltanali et al., 2022). The third one is the involvement of operators through autonomous-maintenance activities, which widen maintenance capabilities beyond the walls of the maintenance department (Sharma & Sanjit, 2022; Trejo-Mendoza et al., 2024). The fourth enabler is the development of implementation roadmaps, such as phased approach to RCM or TPM, seen in successful cases (Maceda-Cabrejo et al., 2025; Fernández Torres et al., 2024). The fifth enabler is the existence of digital capabilities, including sensing and analytics for condition-based maintenance (Kolar, Lisjak, Curman, & Pająk, 2022; Kuhnel et al., 2022). Table 3 provides more details.

Table 3. Enablers and Barriers to RCM Adoption In Food Packaging Contexts

Category	Factor	Sources
Enabler	Top-management commitment and strategic alignment	(Uzoigwe, 2024a; Maceda-Cabrejo et al., 2025)
Enabler	Reliable failure and loss data	(Soltanali et al., 2022; Maceda-Cabrejo et al., 2025)
Enabler	Operator involvement (autonomous maintenance)	(Trejo-Mendoza et al., 2024; Sharma & Sanjit, 2022)
Enabler	Structured implementation roadmap	(Maceda-Cabrejo et al., 2025; Fernández Torres et al., 2024)
Enabler	Digital infrastructure (sensing, analytics)	(Kolar et al., 2022; Kuhnel et al., 2022)
Barrier	Operator resistance; sustaining training effort	(Trejo-Mendoza et al., 2024; Uzoigwe, 2024a)
Barrier	Weak data culture undermining reliability analyses	(Uzoigwe, 2024a)
Barrier	Sensor positioning and signal interpretation on complex machinery	(Rizioli, Cristofori, Battarra, & Mucchi, 2025; Kuhnel et al., 2022)
Barrier	Multidisciplinary knowledge and data sufficiency for digital twins	(Van Dinter et al., 2022; Maheshwari et al., 2023)

3.4 The Role of Digital Technologies in RCM

The research results highlight the convergence between the decision-making logic of Reliability-Centered Maintenance (RCM) and Industry 4.0 features. Condition-monitoring frameworks of the Industrial Internet of Things (IIoT) provide the continuous equipment status data for the use of RCM condition-based activities (Kolar et al., 2022). The validation of vibration health monitoring of the equipment has been done for both the automatic packaging machines and stretch-wrapping machines, revealing that fault signatures can be detected on end-of-line equipment without interfering with the manufacturing process (Rizioli et al., 2025). Implementation of Edge-AI on the filling machines extends this approach to the detection of anomalies (Kuhnel et al., 2022), and the application of autoencoders is reported in detecting fault on smart packaging machines (Arifeen & Petrovski, 2023). The application of machine learning techniques including the support vector machines (SVM) and fuzzy inference system demonstrates the ability to diagnose the faults and estimate the critical process risk in the food production and serves as the source of risk scoring intelligence used in RCM and FMECA decision gates (Soltanali et al., 2022). Machine learning algorithms are also evaluated in predictive maintenance of the high-pressure food processing systems (Srisuwan & Innet, 2024).

Digital twins provide the simulation capability. The literature review identifies the role of virtual models in forecasting failure (Van Dinter et al., 2022; Zhong, Xia, Zhu, & Duan, 2023). The function of machine learning within digital twin framework has been formulated (Chen, Fu, Zheng, Tao, & Liu, 2023). Applications in the food industry reveal the improvement in availability, throughput, and utilization (Maheshwari et al., 2023). Frameworks such as RCM 4.0 show the feasibility of RCM implementation with the use of smart sensors and analytics (Gomaa, 2025), and hybrid RCM approaches merging with digitalization possibilities describe the transition path in practice (Introna & Santolamazza, 2024). Thus, the literature reveals the technical

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readiness of all layers of implementation of a digitally enabled RCM framework within packaging environment.

3.5 Food-Safety and Regulatory Dimensions

Although smaller in volume, the food-safety strand is decisive for the contribution of this review. Recent evidence shows that HACCP plans can and should incorporate maintenance-related control points, so that contamination prevention becomes an explicit maintenance objective (Uzoigwe & Kongolo, 2024). Hygienic-design assessments single out packaging and end-of-line equipment as high-risk zones where both design and maintenance must control contamination pathways (Pejanovic et al., 2026), and reviews of contaminant pathways through open food processing equipment corroborate the link between equipment condition and product safety (Pakdel et al., 2023). Risk-and-reliability frameworks for food processing demonstrate that maintenance intervals can be derived from process risk rather than calendar time (Soltanali et al., 2022), and intelligent fault-diagnosis systems show that criticality can be quantified continuously in food-plant processes (Soltanali et al., 2022). Together, these results establish the evidentiary basis for integrating RCM's criticality logic with HACCP's control-point logic.

3.6 Interpretation of Key Findings

Three findings merit emphasis. First, RCM and its companion methodologies deliver measurable gains in packaging operations availability improvements of 2–7 percentage points, OEE gains of roughly 10 percentage points under TPM/autonomous maintenance, MTBF increases exceeding 60%, and maintenance-cost reductions of roughly half in one RCM application (Benini & Santos, 2021; Maceda-Cabrejo et al., 2025; Fernández Torres et al., 2024; Trejo-Mendoza et al., 2024). However, these ranges are non-pooled point estimates drawn from heterogeneous single-facility studies with different baselines, equipment, measurement conventions, and reporting periods; no meta-analysis was performed, and the ranges should not be interpreted as pooled or directly comparable effect sizes. Second, equipment failures and micro-stoppages are the largest and most persistent losses on packing lines and are precisely the loss categories that condition-based and reliability-centered tasks are designed to control (Aji et al., 2025; Tampubolon, 2025). Third, the field is moving toward digitalized reliability management, with IIoT, AI, and digital-twin capabilities now mature enough to operationalize RCM's condition-based logic (Gomaa, 2025; Kuhnel et al., 2022; Maheshwari et al., 2023), yet no published framework currently binds these capabilities to food-safety governance (Uzoigwe & Kongolo, 2024).

3.7 The Proposed Conceptual Integration Framework (RCM–FMECA–IIoT–HACCP)

In continuation of the above synthesis, this study formulates a conceptual framework for integration of RCM, FMECA, IIoT and HACCP as a basis for future empirical study. The framework is formulated on a unified governance logic that is spread over four interconnected layers:
RCM layer (strategy backbone). RCM provides the decision logic for the selection of system, analysis of its functions and failures modes as well as criticality based prioritization of preventive, predictive and condition based maintenance tasks. The function-focused nature of its decision logic will ensure maintenance allocation only to packaging line functions whose failure would present the biggest threat to its continued operation and safety (Maceda-Cabrejo et al., 2025; Sala et al., 2025).

FMECA layer (risk quantification). FMECA provides the severity, occurrence and detectability indices for failure modes ranking. In this framework, these indices will be re-interpreted as dual purpose risk indices: they will govern prioritization of maintenance within the RCM and the food safety decision making within HACCP, in accordance with the risk and reliability-based maintenance logic, which is based on deriving maintenance tasks from process risks (Soltanali et al., 2022).

IIoT layer (condition intelligence). IIoT sensing infrastructures will monitor the vibrations, temperatures and operational parameters to provide the real-time information about equipment conditions. This information will trigger the RCM condition-based maintenance tasks as well as provide the status of the equipment at HACCP defined control points, related to contamination risk. Some validated applications on the machinery for packaging, filling and stretch wrapping confirm the feasibility of this layer (Kolar et al., 2022; Kuhnel et al., 2022; Rizioli et al., 2025).

HACCP layer (regulatory assurance). HACCP will contribute the food safety control logic, defining critical control points and the limits whose crossing makes the product unsafe. In this framework, maintenance-related control points will be included in HACCP plan (Uzoigwe & Kongolo, 2024), while the equipment status information provided by the IIoT layer will serve as monitoring evidence for them.

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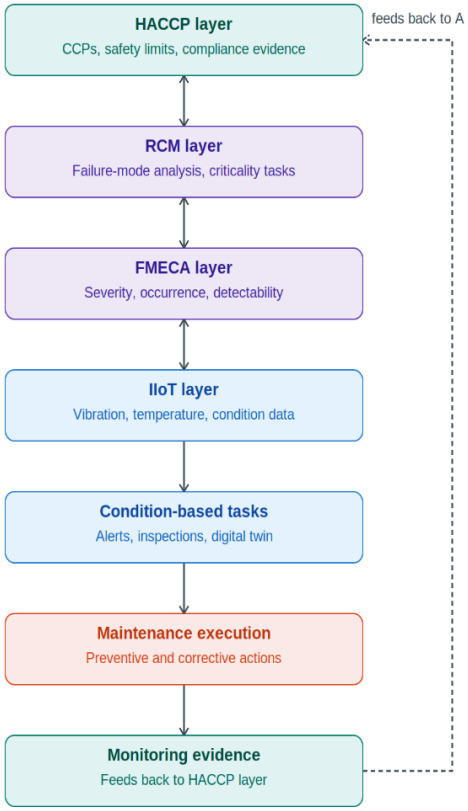


Figure 6. The proposed conceptual integration framework (RCM–FMECA–IIoT–HACCP).

To illustrate the operational logic, one may consider the stretch-wrap machine placed at the end of the packaging line (Rizioli et al., 2025). In terms of RCM layer, the functional analysis will include such functions as maintaining the film tension and ensuring the seal integrity; in terms of the failure modes analysis, the failure modes that are to be identified include the motor decay, film feed slippage, and heater decay. The FMECA layer evaluates the severity, occurrence, and detection of each failure mode, where the failure modes related to sealing are classified as high severity due to contamination risks caused by the malfunction of sealing (Pejanovic et al., 2026). IIoT layer will include accelerometers whose vibration signatures are already validated for the stretch wrapping and packaging machines (Rizioli et al., 2025); thus, the condition-based inspection will occur before any failure. In the case of filling lines, the logic is implemented by means of edge-artificial intelligence (edge-AI) for real-time anomaly detection (Kuhnel et al., 2022). In the case of HACCP, the sealing station is considered as CCP, while the vibration and temperature data become the monitoring evidence proving the fact that the CCP is operating in the prescribed limits (Uzoigwe & Kongolo, 2024). The executed tasks result in records that are included into RCM logic via the implementation of the smart-maintenance platform, which is exemplified by RCM 4.0 (Gomaa, 2025) and hybrid RCM–digitalization solutions (Introna & Santolamazza, 2024). What-if simulations based on digital twins are provided for the proactive failure prevention (Chen et al., 2023; Zhong et al., 2023). Finally, human factors are taken into account by providing the option of operator-driven autonomous maintenance (Sharma & Sanjit, 2022; Trejo-Mendoza et al., 2024).

3.8 Theoretical Implications

The framework contributes to maintenance scholarship by demonstrating that RCM's classical reliability logic can be extended, without loss of rigor, into food-safety governance addressing a gap repeatedly noted in reviews of maintenance in food production (Uzoigwe, 2024a; Uzoigwe & Kongolo, 2024). It also bridges two research streams that have evolved largely in parallel: reliability/criticality engineering and food-safety quality management (Pejanovic et al., 2026; Soltanali et al., 2022). For the digitalization literature, the framework provides a use case that grounds IIoT, AI, and digital-twin capabilities in a decision architecture, responding to the observation that digital maintenance capabilities frequently lack integration with organizational decision processes (Introna & Santolamazza, 2024; Psarommatis et al., 2023).

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3.9 Practical Implications

The framework gives guidance on the path forward for practitioners: packaging lines from food companies can start with relative criticality analysis of packaging lines via RCM, follow up with risk scores obtained through FMECA, adopt IIoT sensing where criticality analysis has shown critical points, and match the generated data with the HACCP data from control points. This process accounts for the organizational development stage, as digitization can be carried out incrementally since the framework layers can be deployed incrementally (Introna & Santolamazza, 2024). Further, the evidence suggests that investments in data culture and operator training are requirements not merely additions, for realizing the benefits identified in the case studies (Trejo-Mendoza et al., 2024; Uzoigwe, 2024a). As far as capital project level is concerned, combining maintenance strategy with equipment decision-making helps protect reliability and food supply chain in general (Dingba, 2022).

3.10 Limitations of the Review

Several limitations exist in this review. First, confining the review articles to those written between 2021 and 2026 limits the review to contemporary issues, leaving behind the history that formed the foundation of current practices. Second, there is a limited empirical base, and the quantitative results obtained come from case studies from one facility without using controlled experiments. Third, a meta-analysis of the studies was not possible because of the different outcome measures used in each study (Maceda-Cabrejo et al., 2025; Fernández Torres et al., 2024). Fourth, some sources could only be accessed from their indexed metadata and abstracts, limiting the depth of coding in qualitative analysis. Fifth, this review has mainly been carried out by one reviewer, and therefore, inter-rater reliability score could not be calculated, which is a limitation in systematic reviews conducted by a single person (Page et al., 2021). These limitations have been acknowledged in the future research agenda.

IV. CONCLUSION

This review summarizes the findings based on 51 peer-reviewed scientific papers on the topic of Reliability-Centered Maintenance in food packaging production lines between 2021 and 2026. From the literature between 2021 and 2026, it is clear that application of RCM and methodologies related to it leads to successful results – increased availability, overall equipment effectiveness (OEE), decreased downtime and maintenance cost. The findings show that the losses on the packaging line are caused by machine breakdowns and micro-stoppages, problems, which can be solved using RCM methodology. Moreover, from this literature review, it becomes evident that progress in digitalization made condition-based and predictive maintenance sufficiently advanced to be used in packaging processes. Also, food safety concepts, HACCP, are increasingly becoming incorporated into maintenance planning, and this process becomes a strategic target of maintenance actions. Based on these findings, an integration theoretical framework for RCM, FMECA, IIoT and HACCP is suggested.

Four directions for future research on this topic can be identified from the literature review. First, longitudinal empirical verification of integrated RCM–FMECA–IIoT–HACCP approaches in food packaging factories, which will go beyond case studies, to multi-factory and multiyear designs taking into account context considerations is necessary. Second, there is a need to develop maturity models for introducing of digital reliability solutions in packaging environment to allow manufacturers to plan their investments in sensors, analysis, and digital twin. Third, comparative research is needed to evaluate the advantages and disadvantages of RCM versus TPM, SMED, and predictive maintenance on identically equipped packaging lines. Fourth, research is needed on organizational facilitators of success of RCM implementation, such as data culture, operator training and commitment of top management.

Limitation of this study is in the conceptual nature of suggested RCM–FMECA–IIoT–HACCP framework based on generalized scenarios synthesized from the literature and not on the case of any particular production. Therefore, the framework needs to be empirically tested using case studies in certain manufacturing industry.

DECLARATION

ARTIFICIAL INTELLIGENCE USE STATEMENT (AI STATEMENT)

The authors declare that no artificial intelligence (AI) was used in the preparation, writing, or data analysis for this article.

AUTHOR CONTRIBUTION STATEMENT

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Author 1: Conceptualization, methodology, literature search and screening, quality assessment, data extraction and analysis, development of the conceptual framework, visualization, and writing of the original draft.
Author 2: Supervision, validation, and review and editing of the manuscript.
Author 3: Methodology, validation, and review and editing of the manuscript.
Author 4: Supervision, project administration, and final editing of the manuscript. All authors have read and approved the final published version of the manuscript.

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CONFLICT OF INTEREST STATEMENT
The authors declare that there is no conflict of interest, either financial or non-financial, related to the conduct of the research or publication of this article.

STATEMENT OF RESEARCH AND PUBLICATION ETHICS (ETHICAL CONSIDERATION / PUBLICATION ETHIC)
This study is a systematic literature review of published sources and did not involve human participants, personal data, or animals. Therefore, ethical clearance and informed consent were not required.

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