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Optimising predictive maintenance in commercial buildings in Saudi Arabia

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Abstract

This systematic review examines how predictive maintenance (PdM) can improve the reliability and energy performance of commercial buildings in Saudi Arabia. PdM uses sensors, the Internet of Things (IoT), data analytics, and artificial intelligence to monitor asset condition and anticipate failures before they occur. Although these technologies are increasingly applied internationally, adoption in Saudi commercial buildings remains constrained by harsh climatic conditions, high cooling demand, implementation costs, cybersecurity concerns, and shortages of specialised skills. The review synthesises evidence on maintenance challenges, PdM applications, and the transferability of international practices to the Saudi context. The findings indicate that effective implementation requires predictive models calibrated to local temperature, dust, equipment, and energy-use conditions; durable sensing infrastructure; workforce development; and cooperation among building owners, technology providers, policymakers, and academic institutions. These measures support the energy-efficiency, digital-transformation, and sustainability objectives of Saudi Vision 2030. Overall, context-specific PdM can reduce unplanned downtime, improve asset reliability, and strengthen the long-term sustainability of Saudi commercial buildings.

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1. Introduction

Commercial buildings are integral to urban development because they accommodate businesses, services, and economic activity. Facility managers must maintain these buildings while responding to the increasing complexity of building systems. Traditional reactive and time-based maintenance can be inadequate for this purpose. Predictive maintenance (PdM) uses technologies such as the Internet of Things (IoT), condition monitoring, and artificial intelligence (AI) to support timely, data-driven interventions. In Saudi Arabia, rapid urban development and the objectives of Vision 2030 are increasing the need for reliable and energy-efficient commercial buildings. Extreme heat and dust accelerate the deterioration of building systems, particularly HVAC and chilled-water equipment, strengthening the case for locally adapted PdM solutions (Al-Tamimi, 2022; Alsarory, 2017).

Despite its potential, the most effective application of PdM in Saudi commercial buildings remains insufficiently established. Practices developed in other regions may not transfer directly to Saudi Arabia's distinctive climatic and operational conditions. This systematic review therefore examines local maintenance challenges and evaluates how international PdM practices can be adapted to the Saudi context. In doing so, it supports the national goals of technologically advanced, resource-efficient, and environmentally responsible urban development.

1.1. Aims and Objectives

The primary aim of this study is to systematically review and synthesise the existing literature on predictive maintenance (PdM) strategies in commercial buildings, focusing on their application and optimisation in Saudi Arabia.

- To identify the specific maintenance issues faced by commercial buildings in Saudi Arabia.
- To review predictive maintenance strategies in commercial buildings within Saudi Arabia.
- To identify the applicability of global PdM practices to Saudi Arabia, considering factors such as climate, building types, and energy usage patterns.

1.2. Background

Predictive maintenance has transformed the management of commercial building assets by combining sensors, IoT devices, machine-learning models, and data analytics to monitor equipment condition and anticipate failures. In contrast to reactive maintenance and fixed-interval preventive maintenance, PdM supports condition-based intervention, which can reduce unplanned downtime, improve reliability, and extend asset life. The integration of sensor data with cloud computing and analytical tools also enables scalable monitoring across complex building portfolios (Bouabdallaoui, Lafhaj, Yim, Ducoulombier, & Bennadji, 2021; Subri & Suleiman, 2024).

PdM is particularly relevant to Saudi Arabia, where rapid urban development, high cooling demand, extreme temperatures, and dust exposure place sustained pressure on HVAC, electrical, and chilled-water systems. Sensor networks can monitor temperature, airflow, vibration, energy consumption, and other indicators of asset condition in real time. When predictive models are calibrated to local operating conditions, this information can support earlier intervention, reduce avoidable energy use, and improve the durability of critical assets (Al-Tamimi, 2022; Malek Almobarek, Mendibil, Alrashdan, & Mejjaouli, 2022).

PdM can also reduce the financial and operational consequences of unexpected equipment failures. However, much of the available evidence originates outside Saudi Arabia, where climatic, regulatory, and organisational conditions differ. International studies do not always address the effects of persistent heat and dust on cooling systems or sensing equipment. Successful adoption therefore requires not only technical readiness but also organisational change, staff training, investment, and locally appropriate maintenance frameworks (Alsarory, 2017; Alshehri, 2016).

1.3. Significance of the Study

This study addresses a clear gap by focusing on PdM solutions for commercial buildings in Saudi Arabia. Its findings are relevant to facility managers, policymakers, building owners, and technology providers seeking to improve reliability, reduce energy waste, and limit unplanned downtime under severe climatic conditions. By identifying the adaptations required for local implementation, the review also contributes to the energy-efficiency, digital-transformation, and sustainability objectives of Saudi Vision 2030.

2. Materials and Methods

2.1. Research Design

This study adopted a qualitative systematic-review design to examine PdM practices relevant to commercial buildings in Saudi Arabia. Evidence was drawn from peer-reviewed studies, conference papers, theses, and technical sources that addressed building maintenance, condition monitoring, energy efficiency, or Saudi operating conditions. The review followed the PRISMA 2020 framework to structure identification, screening, eligibility assessment, and inclusion (Page et al., 2021).

After the database searches, records were screened for relevance and methodological quality. The Critical Appraisal Skills Programme (CASP) checklists were used, where applicable, to assess study design, clarity, validity, and usefulness (Critical Appraisal Skills Programme, 2018). Combining a transparent PRISMA selection process with critical appraisal strengthened the consistency and reproducibility of the review. The synthesis focused on the application of AI, IoT, machine learning, and condition monitoring to commercial-building systems and on the extent to which these approaches support Saudi Arabia's sustainability and technology objectives.

2.2. Search Strategy

The search covered Google Scholar, ScienceDirect, JSTOR, ResearchGate, and relevant institutional repositories. Search terms included combinations of "predictive maintenance," "commercial buildings," "Saudi Arabia," "HVAC systems," "urbanisation," "energy consumption," and "climate-specific maintenance strategies." The review considered journal articles, conference papers, theses, government publications, and technical reports published from 2015 onwards. Sources were screened for direct relevance to building maintenance, PdM technologies, energy efficiency, or operational conditions comparable to those in Saudi Arabia.

2.3. Study Eligibility

Studies were assessed against predefined eligibility criteria to ensure that the evidence was current, relevant to commercial buildings or facilities management, available in English, and sufficiently empirical to support the review objectives. Table 1 summarises the inclusion and exclusion criteria applied during screening.

Table 1. Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
Studies published from 2015 onwards to ensure the inclusion of the latest advancements in PdM.	Studies published before 2015, because they may not reflect recent technological and methodological developments.
Studies focusing on predictive maintenance (PdM) strategies relevant to commercial buildings or facilities management.	Literature not directly relevant to building management, such as studies focused on industrial PdM or unrelated fields.
Studies written in the English language to ensure clarity and consistent interpretation.	Non-English studies to avoid misinterpretation or translation challenges.
Primary research studies that offer original data, findings, or case studies for direct relevance to the research.	Secondary or theoretical literature without empirical evidence or actionable insights.

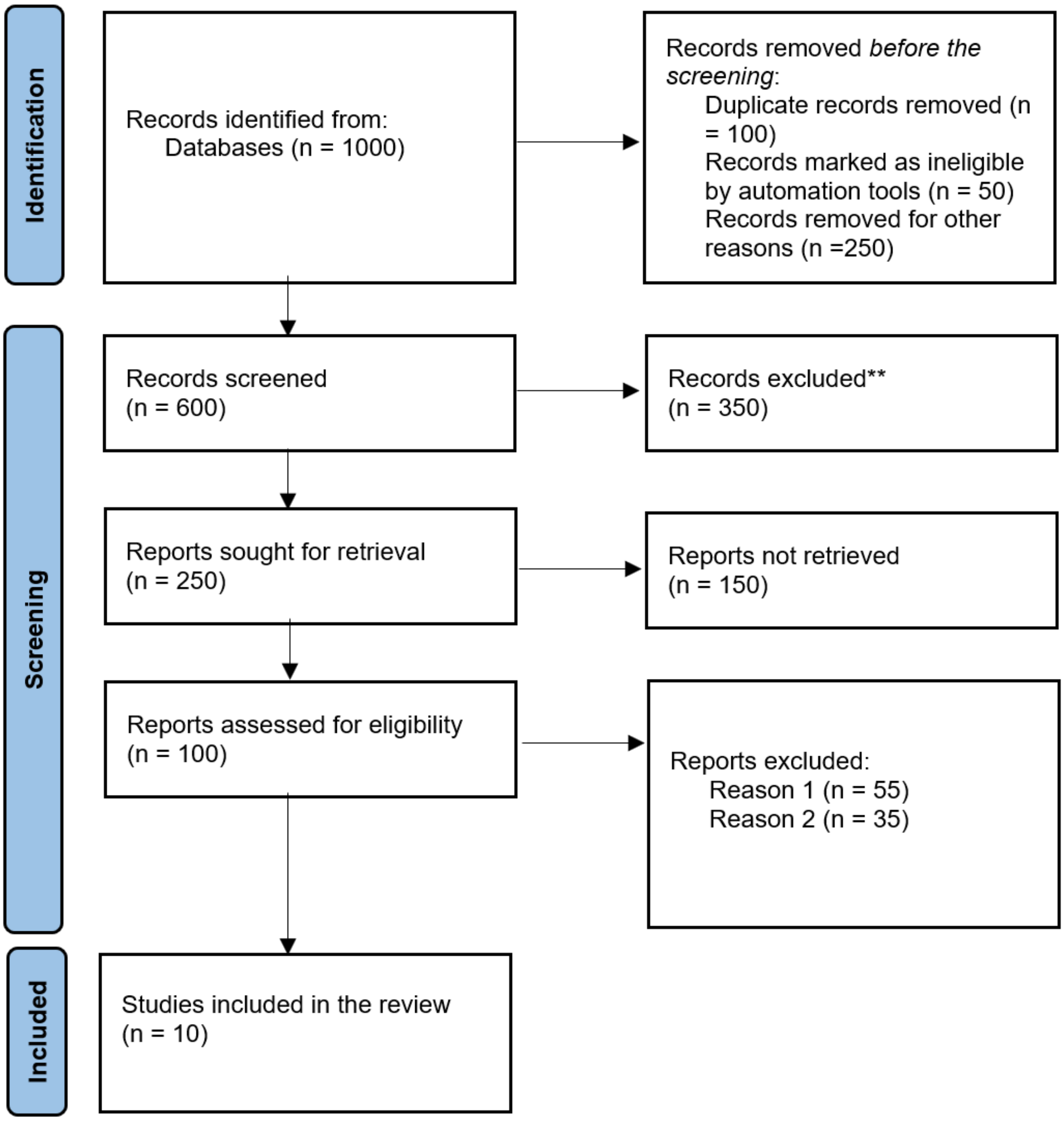

Figure 1. PRISMA flow diagram of the study-selection process.

2.4. Data Collection

Data were collected through a structured review of academic, institutional, government, and technical publications that met the eligibility criteria. Nine core studies were selected for detailed appraisal because of their relevance to commercial-building maintenance, chilled-water or HVAC systems, condition monitoring, energy efficiency, or Saudi operating conditions. Information was extracted on each study's purpose, methods, principal findings, and relevance to PdM implementation. The comparison emphasised AI, IoT, machine learning, cloud-based monitoring, and the organisational, financial, climatic, and skills-related barriers to adoption.

2.5. Data Analysis

The extracted evidence was analysed thematically to identify recurring patterns across the included studies. The analysis involved familiarisation with the sources, coding of relevant findings, grouping codes into candidate themes, reviewing and refining the themes, and interpreting them in relation to the study objectives (Braun & Clarke, 2006). Particular attention was given to environmental stressors, energy efficiency, AI and machine learning, the transferability of international practices, and implementation barriers in Saudi Arabia.

2.6. CASP Analysis of Articles

The nine core studies were critically appraised for focus, methodological appropriateness, data quality, clarity of results, potential bias, precision, validation, applicability, and consistency with other evidence. CASP questions were adapted to accommodate the different study designs represented in the review. The appraisal informed the interpretation of the findings rather than serving as a simple numerical ranking. Studies with insufficient methodological clarity or limited relevance to the Saudi context were treated cautiously in the synthesis.

3. Results and Discussion

3.1. Results (Thematic Analysis)

3.1.1. Maintenance Challenges in Commercial Buildings in Saudi Arabia

Saudi Arabia's rapid urbanisation, high temperatures, humidity in coastal areas, and frequent dust exposure create significant maintenance challenges for commercial buildings. These conditions accelerate the deterioration of HVAC, electrical, and chilled-water systems, increase energy consumption, and raise maintenance costs. Dust can obstruct filters and airflow, while prolonged heat places cooling equipment under sustained load. Inadequate envelope performance and inefficient operation further increase cooling demand and equipment stress (Al-Tamimi, 2022; Nasir & Aziz, 2018).

These conditions strengthen the need for maintenance strategies that detect deterioration before failure. PdM uses historical and real-time condition data to forecast faults and schedule interventions at an appropriate time. Evidence from chilled-water systems shows that fault patterns can be identified and prioritised through data-driven maintenance, thereby improving reliability and reducing avoidable disruption (Almobarek & Mendibil, 2023; Malek Almobarek et al., 2022).

Machine-learning models, IoT sensors, and analytical platforms can support early fault detection and identify changes in equipment performance. For commercial-building operators, these technologies offer a basis for faster intervention, improved asset life, and more efficient maintenance planning. Their effectiveness, however, depends on reliable data, appropriate model selection, and integration with a coherent maintenance-management process (Bouabdallaoui et al., 2021).

3.1.2. Role of Predictive Maintenance (PdM) in Enhancing Energy Efficiency

Saudi Arabia's extreme heat makes energy efficiency a central concern for commercial-building operation. HVAC systems account for a substantial share of building energy demand, and their consumption rises as outdoor temperatures increase. Condition monitoring and timely maintenance can identify blocked filters, refrigerant problems, control faults, and other inefficiencies before they cause excessive energy use or system failure (Bouabdallaoui et al., 2021; Subri & Suleiman, 2024).

PdM combines real-time monitoring with predictive algorithms so that maintenance can be scheduled according to actual equipment condition rather than fixed intervals. Measurements such as temperature differentials, airflow, vibration, and energy consumption can reveal developing inefficiencies and support targeted intervention. This approach can reduce unplanned downtime, improve system performance, and contribute to the energy-efficiency objectives of Saudi Vision 2030.

Evidence from chilled-water and HVAC applications indicates that machine-learning models can identify fault patterns and improve maintenance decisions (Malek Almobarek et al., 2022; Bouabdallaoui et al., 2021). By shifting resources from emergency response towards planned, condition-based intervention, PdM can reduce energy losses associated with degraded equipment and support longer asset life.

3.1.3. Machine Learning and AI in PdM for Commercial Building Systems

Machine learning and AI extend PdM by analysing large volumes of building-system data for patterns, anomalies, and emerging faults. Decision trees and other predictive models have been applied to chilled-water systems, while machine-learning frameworks have been developed for building facilities more broadly (Almobarek & Mendibil, 2023; Bouabdallaoui et al., 2021). These approaches can improve fault detection, reduce downtime, and support more efficient use of maintenance resources.

In Saudi Arabia, AI- and machine-learning-based PdM may be particularly valuable for HVAC systems operating under sustained heat and dust exposure. Models can analyse changes in temperature, airflow, energy use, and other indicators to estimate the likelihood of component failure. Facility managers can then prioritise interventions and reduce the risk of disruptive breakdowns.

AI can also support maintenance prioritisation by ranking detected faults according to their severity, operational consequences, and urgency. Repeated analysis allows predictive models to improve as additional condition and failure data become available. Nevertheless, automated outputs should complement engineering judgement and established maintenance controls rather than replace them. Reliable data governance, model validation, cybersecurity, and appropriately trained personnel remain essential.

3.1.4. Applicability of Global PdM Practices to Saudi Arabia's Unique Environment

International PdM practices provide useful technical foundations, but they must be adapted to Saudi Arabia's high temperatures, dust exposure, intensive cooling demand, and building characteristics. Retrofitting can improve envelope and system performance, while PdM can monitor upgraded or existing assets and identify emerging inefficiencies (Al-Tamimi, 2022). The value of these measures depends on local calibration and an understanding of how climatic conditions affect both building equipment and sensing devices.

Saudi PdM frameworks should therefore incorporate environmental variables such as ambient temperature, dust concentration, humidity, and seasonal cooling load. Generic maintenance intervals or models trained in milder climates may not accurately represent local failure behaviour. Continuous condition data can help operators adjust inspection and maintenance frequencies and optimise cooling-system performance under demanding conditions.

Sensor durability, communications reliability, data quality, and cybersecurity also require attention in harsh environments. Large-scale implementation across commercial portfolios demands coordinated standards, interoperable systems, and financial planning. Although PdM can generate long-term benefits, the initial cost of sensors, platforms, integration, and workforce development may be difficult for owners of older buildings. Incentives, phased implementation, and evidence-based business cases may therefore support wider adoption.

3.1.5. Overcoming Implementation Barriers for PdM in Saudi Arabia

PdM has the potential to improve the efficiency, reliability, and energy performance of Saudi commercial buildings, but several barriers must be addressed. Existing maintenance practices may be constrained by inconsistent standards, limited technical capacity, high costs, and weak integration between maintenance processes and digital systems. A structured maintenance-management framework is therefore necessary to guide technology selection, data responsibilities, intervention criteria, and continual improvement (Alshehri, 2016).

A second barrier is the initial cost of sensors, connectivity, analytical platforms, integration, and system upgrades. The financial challenge may be greater in older buildings that also require extensive refurbishment. Phased deployment, cost-sharing arrangements, incentives, and government support could improve accessibility. Skills shortages present an additional constraint because effective PdM requires personnel who can interpret condition data, operate digital platforms, validate alerts, and translate analytical results into maintenance action.

Government bodies, industry, and educational institutions can help close this skills gap through targeted training and professional development. Localised assessment tools can also help building owners evaluate asset criticality, data readiness, environmental exposure, and organisational capability before investment. Saudi-specific tools and frameworks are especially important because high heat and dust can influence failure modes and technology performance (Alsarory, 2017). Change management and user involvement should accompany technical implementation to reduce resistance and support sustained use.

3.2. Discussion

3.2.1. To Identify the Specific Maintenance Issues Faced by Commercial Buildings in Saudi Arabia

The literature identifies a combination of environmental, operational, and design-related maintenance challenges in Saudi commercial buildings.

Extreme heat and dust accelerate the degradation of HVAC, electrical, and chilled-water systems, while inefficient operation and envelope performance can increase cooling demand and equipment stress (Al-Tamimi, 2022). Facility managers must therefore address overheating, premature component wear, blocked filters, and energy losses alongside routine service requirements. Rapid urban development and increasing building use add further pressure to maintenance resources and infrastructure.

The findings indicate that conventional preventive maintenance alone may not adequately address variable deterioration under harsh conditions.

Data analytics, IoT monitoring, and locally calibrated predictive models can help identify emerging faults and schedule intervention before failure (Bouabdallaoui et al., 2021).

Maintenance programmes should therefore reflect Saudi Arabia's climatic exposure, asset criticality, building design, and actual operating patterns.

3.2.2. To Review Predictive Maintenance Strategies in Commercial Buildings within Saudi Arabia

The reviewed PdM strategies combine condition monitoring, IoT sensors, data analytics, and machine-learning algorithms to forecast equipment faults and support maintenance planning. These methods can reduce unplanned downtime, extend asset life, and improve energy performance (Malek Almobarek et al., 2022; Bouabdallaoui et al., 2021). For Saudi commercial buildings, monitoring should focus particularly on HVAC and chilled-water systems exposed to sustained cooling loads, dust, and high ambient temperatures.

Relevant indicators include temperature differentials, pressure, vibration, airflow, refrigerant condition, energy consumption, and filter performance.

Integrating these data with building or energy management systems can support coordinated maintenance across large portfolios. Cloud-based platforms may improve scalability, but adoption still depends on cybersecurity, data quality, local expertise, and a credible financial case.

3.2.3. To Identify the Applicability of Global PdM Practices to Saudi Arabia, Considering Factors Such as Climate, Building Types, and Energy Usage Patterns

Global PdM practices are applicable to Saudi Arabia only when adapted to local climate, building types, and energy-use patterns. International approaches commonly use IoT sensors, AI, and machine learning to monitor assets and forecast failure.

In Saudi Arabia, these models should incorporate heat, humidity, dust exposure, intensive cooling demand, and the characteristics of local HVAC and chilled-water systems. Building form and envelope performance also affect equipment load and should be considered when interpreting condition data (Al-Tamimi, 2022). Implementation decisions must additionally account for sensing and communications infrastructure, skilled personnel, cybersecurity, and lifecycle cost.

4. Conclusion

This review shows that PdM can help address the distinctive maintenance challenges of commercial buildings in Saudi Arabia. Extreme heat, dust, and intensive cooling demand increase the deterioration and energy consumption of HVAC and chilled-water systems. Locally adapted PdM can use IoT monitoring, data analytics, AI, and machine learning to detect emerging faults, support timely intervention, reduce downtime, and improve resource use.

Adoption nevertheless faces substantial barriers, including initial investment, fragmented maintenance processes, limited digital infrastructure, skills shortages, data-quality concerns, and cybersecurity risks. Effective implementation requires clear maintenance governance, phased investment, workforce development, reliable sensing systems, and predictive models calibrated to Saudi operating conditions. Cooperation among building owners, facility managers, technology providers, policymakers, and academic institutions can help translate international practice into sustainable local solutions aligned with Saudi Vision 2030.

4.1. Future Implications

Future research should develop and validate Saudi-specific predictive models using operational data from commercial buildings exposed to extreme heat, dust, humidity, and intensive cooling loads. Longitudinal studies should compare the costs, energy performance, reliability, and asset-life outcomes of PdM with reactive and time-based maintenance. Research is also needed on cybersecurity, sensor durability, data governance, interoperability, and the skills required to manage advanced maintenance systems.

Further work should examine how PdM can be integrated with building management systems, renewable-energy technologies, and portfolio-level energy strategies. Pilot projects involving industry, government, and academic partners could establish performance benchmarks and provide credible evidence for investment decisions. International collaboration can accelerate knowledge transfer, but resulting methods should be tested and calibrated locally before large-scale deployment.

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Appendices.

Appendix 1. Data extraction table.

Title	Aims and Objectives	Methodology	Findings
Almobarek and Mendibil (2023): "Predictive Maintenance for Chilled Water Systems"	To apply machine learning models to predict faults in chilled water systems and optimise their operational efficiency.	Applied machine-learning methods to operational fault data from chilled-water systems.	Identified recurring fault patterns and demonstrated the value of data-driven PdM for chilled-water systems.
Bouabdallaoui et al. (2021): "Framework for HVAC Predictive Maintenance"	To develop a predictive maintenance framework for HVAC systems that reduces energy waste and enhances efficiency.	Applied a machine learning-based framework to analyse real-time sensor data from HVAC systems.	Improved fault detection and energy efficiency in HVAC systems, emphasising the role of advanced analytics in PdM implementation.
Subri and Suleiman (2024): "Condition Monitoring for Sustainable Buildings"	To investigate how PdM contributes to sustainability by improving energy efficiency and system longevity.	Used a mixed-method design involving stakeholder questionnaires and building case studies in Malaysia.	Reported potential sustainability benefits, including energy savings, lower maintenance costs, and longer component life.
Al-Tamimi (2022): "Energy Retrofitting in Saudi Office Buildings"	To explore energy retrofitting strategies and their impact on energy efficiency in Saudi governmental office buildings.	Conducted a detailed analysis of retrofitting measures and their outcomes in selected office buildings.	Demonstrated significant energy savings and operational improvements, aligning with Saudi Vision 2030 energy conservation goals.
Nasir and Aziz (2018): "Building Maintenance Challenges"	To examine the performance of building maintenance operation and management in selected Malaysian commercial buildings.	Used questionnaires, interviews, and three commercial-building case studies.	Reported limited awareness and implementation of effective maintenance-management practices.
Alshehri (2016): "Quality Management in Building Maintenance"	To investigate the role of quality management systems in improving building maintenance efficiency.	Analysed maintenance frameworks and surveyed building operators on quality management practices.	Highlighted the importance of structured frameworks and quality management systems in reducing inefficiencies and operational challenges.
Alsarory (2017): "Localised Predictive Maintenance Solutions for Saudi Arabia"	To develop an assessment tool for improving operation and maintenance requests for proposals for high-	Master's thesis using a structured assessment-tool development approach in the Saudi	Proposed a locally relevant assessment tool to strengthen operation and maintenance procurement and evaluation.

	rise buildings in Saudi Arabia.	high-rise-building context.	
Shin et al. (2021): "AI-Assisted Human Inspections in Building Maintenance"	To improve multi-class recognition of structural defects using a generative adversarial network.	Developed and tested an image-based deep-learning model for classifying structural defects.	Improved defect-recognition performance, demonstrating the potential of AI-based visual inspection for building maintenance.
Malek Almobarek et al. (2022): "Survey of Maintenance Faults in Chilled Water Systems"	To identify and categorise faults in chilled water systems and assess their frequency and impact.	Conducted an industry survey involving maintenance officers and analysed fault frequency data from operational records.	Identified common chilled-water-system fault types and frequencies to support data-driven maintenance prioritisation.

Appendix 2. CASP table.

Article Title	Did the study address a focused issue? (Q1)	Did the authors use an appropriate method to answer their questions? (Q2)	Was the data collected from a clear and suitable source? (Q3)	Were the controls selected in an acceptable way? (Q4)	Did the authors use appropriate measures to address potential bias? (Q5)	Did the authors account for potential confounding factors in the design and/or analysis? (Q6)	Are the results clear to the reader? (Q7)	Are the results precise? (Q8)	Is the model validated? (Q9)	Is the model applicable to a general population? (Q10)	Do the results fit with other available evidence? (Q11)	Score
Almobarek and Mendibil (2023): Predictive Maintenance for Chilled Water Systems	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	11
Bouabdallaoui et al. (2021): Framework for HVAC Predictive Maintenance	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	11
Subri and Suleiman (2024): Condition Monitoring for Sustainable Buildings	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	11
Al-Tamimi (2022): Energy Retrofitting in Saudi Office Buildings	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	11
Nasir and Aziz (2018): Building Maintenance Challenges	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	10
Alshehri (2016): Quality Management in	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	11

Building Maintenance												
Alsarory (2017): Localised Predictive Maintenance Solutions for Saudi Arabia	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	10
Shin et al. (2021): Structural Defect Recognition Using a Generative Adversarial Network	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	11
Malek Almobarek et al. (2022): Survey of Maintenance Faults in Chilled Water Systems	Yes	Yes	Yes	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported	3