

Implementing PACS in hospital radiology services: implications for efficiency, digital integration, and continuity of care

Suherman Hadi Saputro¹, Nurwahyu Tajuddin^{1✉}, Muh Nur Syihab¹, Muh. Saifur Rohmad¹, Purwanto¹, Fajar Meilinda Omega Sutandi¹

Department of Radiologic
Imaging Technology, Politeknik
Sandi Karsa, South Sulawesi,
Indonesia

✉Corresponding author:
nurwahyutajuddin1999@gmail.com

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ABSTRACT

Introduction: igital transformation is increasingly essential for improving hospital efficiency and care integration. Picture Archiving and Communication Systems (PACS) can streamline radiology workflows; however, evidence regarding their implications for service efficiency, operational costs, and continuity of care in hospital settings remains limited. This study evaluated the implementation of PACS and its implications for radiology service efficiency, digital integration, and continuity of patient care.

Methods: A descriptive qualitative study was conducted in the Radiology Department of Dr. La Palaloi Regional Hospital, Maros, Indonesia, during 2024–2025. Informants were purposively selected from radiologists, radiographers, radiology management and administrative staff, information technology personnel, referring physicians, and patients. Data were collected through direct observation, semi-structured in-depth interviews, and document review. Data were analyzed using reduction, descriptive display, and conclusion drawing, with source and method triangulation and member checking.

Results: PACS transformed film-based workflows into digitally integrated services. Chest radiography waiting time decreased from approximately three hours to 30–40 minutes. Transition to filmless services reduced dependence on radiographic film, previously costing approximately IDR 1 billion during 2021–2023. PACS integration with the hospital information system enabled real-time image access, improved clinical information exchange, and supported continuity of care. Reported patient satisfaction was approximately 82%.

Conclusion: PACS implementation can support hospital digital transformation by improving radiology workflow efficiency, reducing dependence on physical resources, strengthening clinical integration, and facilitating continuity of care.

Keywords: picture archiving and communication systems; radiology information systems; digital health; health services; efficiency; continuity of patient care.



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Highlight:

- PACS transformed conventional film-based radiology into an integrated digital workflow.
- Chest radiography waiting time decreased from approximately three hours to 30–40 minutes.
- Filmless implementation reduced reliance on radiographic film and physical administrative resources.
- PACS–hospital information system integration enabled real-time access to images and clinical information.
- Digital image archiving supported service efficiency, clinical integration, and continuity of patient care.

INTRODUCTION

Digital transformation has become a central component of contemporary health-system development, reshaping how clinical information is generated, stored, exchanged, and used for decision-making. Hospitals are increasingly expected to provide services that are timely, efficient, coordinated, and responsive while simultaneously managing rising operational demands and the growing volume of health information[1]. Within this transformation, radiology occupies a particularly important position because diagnostic imaging generates large volumes of data that must move rapidly between imaging modalities, radiologists, referring physicians, and other clinical units[2]. Delays or fragmentation in this information flow may affect not only radiology department performance but also subsequent clinical decision-making and the continuity of patient care[3]. Consequently, digital radiology infrastructure should be considered not merely a technological investment but also an organizational and service-delivery intervention with potential implications for healthcare efficiency and integration[4].

Picture Archiving and Communication Systems (PACS) represent a major component of this digital transition. PACS enables radiological images to be electronically acquired, stored, retrieved, distributed, and viewed across authorized clinical environments. In conventional film-based radiology, service delivery depends on several physical processes, including film printing, manual transportation, storage, and retrieval[5]. These processes may generate additional waiting time, administrative workload, material costs, and risks of lost or damaged records[6]. PACS restructures this workflow by allowing images to be transferred electronically from imaging modalities to centralized storage and diagnostic workstations. When integrated with hospital information systems, PACS can also connect imaging data with relevant clinical information and make diagnostic results more readily available to clinicians[7].

The potential benefits of PACS, however, extend beyond the replacement of radiographic film. Previous studies cited in the current study indicate that PACS can improve image distribution and radiology turnaround time, while filmless workflows may reduce dependence on films, processing materials, paper, and physical storage[8]. Other reported benefits include easier image retrieval, improved internal user experience, and more efficient radiology workflows. Collectively, these findings suggest that the value of PACS is multidimensional[9]. Efficiency gains arise not solely because an analog medium is replaced by a digital one, but because digital infrastructure can reorganize relationships among technological processes, administrative tasks, information exchange, and clinical work[10].

This distinction is important from a health-service and policy perspective. Evaluating PACS solely according to technical functionality or image storage capacity risks overlooking its broader implications for healthcare delivery. A technologically functional PACS may not necessarily generate optimal service outcomes when integration with other hospital systems is weak, network reliability is inadequate, users lack appropriate competencies, or organizational governance does not support digital workflows[11]. Conversely, an integrated PACS environment may contribute to faster access to diagnostic information and more coordinated care. The effectiveness of digital transformation therefore depends on interactions among technology, organizational readiness, human resources, information governance, and clinical processes[12]. The original study similarly identifies storage capacity, network stability, data security, system integration, staff competency, organizational readiness, governance, and user training as important conditions for sustaining PACS benefits.

These issues are particularly relevant in hospital settings undergoing a transition from conventional to digitally integrated services. The financial dimension is also significant. Film-based radiology requires recurring expenditure for radiographic film and related administrative materials, in addition to physical space for long-term archiving[13],[14]. PACS can eliminate or substantially reduce several of these components, although implementation introduces new expenditures associated with system operation, storage infrastructure, networking, maintenance, and information technology support[1]. Therefore, economic efficiency should not be interpreted simply as the elimination of film costs[15]. It should instead be assessed as a restructuring of operational resources in which conventional physical expenditure is exchanged for digital infrastructure and system-management requirements[16]. The study setting illustrates this complexity: approximately IDR 1 billion was spent on radiographic

films during 2021–2023, whereas PACS was subsequently operated through a cooperation scheme costing approximately IDR 30 million per month.

Another important dimension concerns the relationship between digital radiology and patient care. Faster image availability can facilitate earlier interpretation by radiologists and more timely access to diagnostic information by referring clinicians[17]. Digital storage also enables previous examinations to be retrieved for follow-up assessment and comparison, reducing dependence on patients or healthcare personnel retaining and transporting physical films. This capability is relevant to continuity of care because radiological information can remain accessible across successive encounters within an integrated hospital environment[18]. In this sense, PACS can function as part of the broader clinical information ecosystem rather than as an isolated radiology technology[19]. The potential policy relevance lies in understanding how digital infrastructure can simultaneously contribute to operational efficiency, information continuity, and service quality[20],[21].

Despite these potential advantages, important empirical and methodological gaps remain. Much of the existing discussion reflected in the literature used by this study concentrates on specific dimensions of PACS, such as waiting time, workflow, implementation benefits and challenges, or internal user satisfaction[22]. Such evidence is valuable but can fragment understanding of PACS implementation by treating operational, economic, and patient-care consequences separately. Evidence is particularly limited regarding how these dimensions interact during an actual hospital transition from film-based radiology to an integrated digital workflow. Moreover, technology-centered evaluations may inadequately capture the experiences of the multiple actors involved in implementation, including radiologists, radiographers, administrative personnel, information technology staff, referring physicians, managers, and patients[23],[24].

The present study addresses this gap by examining PACS implementation as a multidimensional transformation of hospital radiology services. Its novelty lies in integrating operational efficiency, waiting time, cost implications, digital information accessibility, patient experience, and continuity of care within a single qualitative evaluation involving multiple stakeholder perspectives[25]. Rather than conceptualizing PACS exclusively as an image-archiving technology, the study evaluates its role within an integrated clinical and organizational workflow[26]. This perspective is important for health policy and hospital management because decisions concerning digital health investment require evidence not only that a technology functions technically, but also that its implementation produces meaningful changes in service processes and supports sustainable integration across clinical units[27].

The study was conducted in the Radiology Department of Dr. La Palaloi Regional Hospital, Maros, Indonesia, where PACS implementation began in 2024 as part of the transition toward filmless and increasingly paperless radiology services. The system was connected to multiple imaging modalities and integrated with the hospital information system, providing an appropriate setting for examining the organizational and clinical implications of digital radiology transformation[28]. Preliminary service evidence documented in the study indicates substantial workflow changes, including a reduction in chest radiography waiting time from approximately three hours to 30–40 minutes and the transition from physical film distribution to real-time digital access. These changes warrant analysis beyond their numerical magnitude to understand how PACS alters service delivery and contributes to integrated care. Accordingly, this study aimed to evaluate the implementation of PACS and its implications for radiology service efficiency, digital integration, and continuity of patient care. Specifically, it addressed the following research question: How does PACS implementation influence radiology workflow efficiency, operational resource use, access to clinical information, patient care, and continuity of care within an integrated hospital environment? By addressing these interconnected dimensions, the study seeks to provide contextually grounded evidence that can inform hospital management and health-policy decisions concerning the implementation, optimization, and sustainability of digitally integrated radiology services.

RESEARCH METHODOLOGY

Study Design

This study employed a descriptive qualitative design to evaluate the implementation of the Picture Archiving and Communication System (PACS) and its implications for radiology service efficiency, digital integration, and continuity of care. The qualitative approach was selected to explore changes in workflow, information accessibility, resource utilization, and service delivery from multiple stakeholder perspectives.

Setting and participants

The study was conducted in the Radiology Department of Dr. La Palaloi Regional Hospital, Maros, Indonesia, during 2024–2025. PACS was introduced in 2024 and integrated with several imaging modalities and the hospital information system. Participants were recruited using purposive sampling based on their direct involvement in or experience with PACS-supported radiology services. Informants included radiologists, radiographers, radiology managers and administrative staff, information technology personnel, referring physicians, and patients. Individuals without direct involvement in PACS-related services were excluded. The final number of participants should be reported according to the original study records.

Data collection

Data were collected through direct observation, semi-structured in-depth interviews, and document review. Observations focused on radiology workflows, waiting times, image distribution, and PACS use. Interviews explored workflow changes, service efficiency, accessibility of results, resource use, patient care, and implementation challenges. Secondary data included waiting-time records, radiographic film expenditures for 2021–2023, PACS operational information, and patient satisfaction data. Research procedures maintained participant confidentiality and informed consent. The ethics committee name and approval number should be added from the original ethical documentation.

Evaluation domains

The evaluation focused on five domains: radiology workflow efficiency, operational resource use, digital and clinical integration, patient care and service experience, and continuity of care. Sustainability issues, including network stability, storage capacity, data security, system integration, and user competency, were also considered.

Data analysis

Data were analyzed through data reduction, descriptive data display, and conclusion drawing. Information from interviews, observations, and documents was compared to identify consistent and contrasting patterns related to PACS implementation. Trustworthiness was strengthened through source and method triangulation and member checking. Numerical indicators obtained from hospital records were used descriptively to contextualize the qualitative findings rather than as a separate quantitative analysis. No inferential statistical analysis was performed.

Ethical Considerations

Participation was voluntary, and confidentiality was maintained throughout data collection and reporting. Informed consent was obtained before interviews.

RESULT

Transformation of radiology workflow

PACS implementation substantially changed radiology service delivery from a film-based workflow to an integrated digital system. PACS was connected to several imaging modalities, including 128-slice computed tomography, ultrasonography, digital radiography, mobile digital radiography, and digital panoramic radiography. Images generated by these modalities were electronically transmitted to PACS, centrally stored, and accessible through the hospital network. Integration with the hospital information system further enabled patient and clinical information to be incorporated into radiology

workflows. The most apparent operational change concerned image processing and distribution. Before PACS implementation, radiographic images required printing and physical distribution before interpretation and clinical use. Following implementation, images became digitally available to radiologists and referring physicians, reducing dependence on physical media and manual transportation.

Table 1. Changes in Radiology Services Following PACS Implementation

Service indicator	Before PACS	After PACS
Image workflow	Physical film printing and distribution	Digital transmission and storage
Chest radiography waiting time	Approximately 3 hours	Approximately 30–40 minutes
Result distribution	Manual/physical	Digital and real-time access
Radiographic film	Routinely used	Filmless workflow
Clinical access	Dependent on physical results	Accessible through hospital system
Archiving	Physical storage	Long-term digital storage

Reduced waiting time and improved information access

A major finding was the reduction in waiting time for chest radiography results. Under the conventional workflow, approximately three hours were required to complete the process, including examination, film printing, physical distribution, and radiological interpretation. After PACS implementation, images could be transmitted directly from the imaging modality to the radiologist's workstation without printing or physical transportation. Waiting time was subsequently reported at approximately 30–40 minutes. Digital distribution also improved accessibility of radiological information. Once reports were finalized, images and results could be accessed through the hospital system by referring physicians in outpatient clinics, the emergency department, and inpatient units. This change reduced reliance on patients or hospital personnel physically transporting radiology results between service units.

Operational resource efficiency and filmless transformation

PACS implementation supported the transition toward filmless and increasingly paperless radiology services. Hospital documentation indicated that radiographic film procurement expenditure during 2021–2023 was approximately IDR 1 billion, corresponding to an average of approximately IDR 330 million annually. Following PACS implementation, routine film printing was progressively discontinued. The use of paper reports, film envelopes, and related administrative materials was also reduced, while digital archiving decreased dependence on physical storage space. PACS itself generated operational expenditure. The system was implemented through an operational cooperation arrangement costing approximately IDR 30 million per month. Therefore, the observed change represents a restructuring of radiology operating resources rather than the complete elimination of service expenditure.

Table 2. Descriptive Indicators of PACS-Related Service Changes

Indicator	Finding
Film expenditure, 2021–2023	± IDR 1 billion
Average annual film expenditure	± IDR 330 million
PACS operational cost	± IDR 30 million/month
Reported patient satisfaction	± 82%
Service model	Filmless and increasingly paperless

Clinical Integration and Continuity of Care

PACS integration with the hospital information system enabled radiological images and relevant clinical information to be accessed within an integrated digital environment. Radiologists could access patient information and previous examinations to support image interpretation, while referring physicians obtained radiological results more rapidly for diagnosis and treatment planning. Digital

storage also strengthened the availability of longitudinal radiological information. Previous images and reports could be retrieved when patients underwent follow-up examinations, disease monitoring, referral, or subsequent care in other hospital units. PACS therefore functioned not only as an image archive but also as part of the hospital's broader clinical information infrastructure. From the patient-service perspective, faster processing and easier access to results were associated with improvements in service experience. Hospital documentation reported patient satisfaction of approximately 82%. However, because this figure originated from a routine hospital survey rather than a PACS-specific outcome instrument, it was treated as supporting contextual evidence and not as a direct measure of PACS effectiveness.

Implementation and Sustainability Issues

Despite the observed benefits, PACS implementation introduced several requirements for sustainable digital service delivery. These included adequate storage capacity, stable network infrastructure, data security, interoperability with other hospital information systems, and sufficient user competency. The findings indicate that PACS implementation should therefore be understood as an organizational and clinical transformation rather than solely as the installation of an image-storage technology. Maintaining its benefits requires continued system management, user training, organizational readiness, and governance mechanisms capable of supporting integrated digital workflows. Overall, evidence from observations, interviews, and hospital documentation converged on three principal areas of change: (1) faster and more digitally integrated radiology workflows, (2) reduced dependence on film and physical administrative resources, and (3) improved accessibility and continuity of radiological information for clinical care.

DISCUSSION

The findings of this study indicate that the implementation of the Picture Archiving and Communication System (PACS) was associated with substantial changes in radiology service delivery, particularly in workflow efficiency, information accessibility, resource utilization, and continuity of care. The most prominent operational change was the reduction in waiting time for chest radiography results from approximately three hours to 30–40 minutes. At the same time, PACS facilitated the transition from a conventional film-based process toward filmless and increasingly paperless radiology services. Integration with the hospital information system also enabled radiological images and relevant clinical information to be accessed more rapidly across clinical units. Taken together, these findings suggest that PACS should not be viewed merely as a digital image storage system but as part of a broader transformation in how radiology information is generated, distributed, accessed, and incorporated into clinical care.

The reduction in waiting time is particularly important because it demonstrates how digital technology can alter the structure of radiology workflows. Previous studies cited in the current research have similarly reported that PACS can improve image distribution and reduce waiting time in radiology services. However, the present findings suggest that the benefit is not simply attributable to faster technology. Before PACS implementation, the workflow involved several sequential physical activities, including image production, film printing, transportation, availability for radiological interpretation, and subsequent distribution to the requesting clinical unit. Each additional step represented a potential source of delay. By allowing images to move electronically from imaging modalities directly to PACS and radiologists' workstations, several physical handoffs were removed. The observed improvement can therefore be interpreted as the consequence of workflow simplification and improved information flow rather than merely the replacement of analog images with digital ones.

This interpretation broadens the understanding of PACS implementation. Earlier studies referenced in the manuscript have emphasized its role in image storage, retrieval, distribution, and workflow efficiency. The current findings show that these technological capabilities have organizational consequences because they change how professionals interact with radiological information. Once a radiological image becomes available electronically, the radiologist no longer needs to wait for physical film delivery, while the referring physician can access finalized information through the integrated hospital system. PACS consequently reduces the dependence of clinical

communication on physical media and supports a more interconnected model of hospital service delivery.

The transition toward filmless radiology also had important implications for resource utilization. Hospital documentation showed that radiographic film procurement during 2021–2023 amounted to approximately IDR 1 billion, or an average of around IDR 330 million annually. Following PACS implementation, routine film printing was progressively discontinued, accompanied by reductions in paper, film envelopes, physical archiving, and related administrative materials. These changes illustrate how digital transformation can alter the structure of operational resource consumption. Nevertheless, the financial implications require cautious interpretation. PACS itself was operated through a cooperation arrangement costing approximately IDR 30 million per month. The findings should therefore not be interpreted as demonstrating that PACS eliminated radiology expenditure. Instead, expenditure shifted from recurring physical consumables and storage requirements toward digital infrastructure and system operation.

This distinction has practical importance for assessing the economic value of digital health investments. Comparing historical film expenditure directly with PACS operational costs would provide only a partial assessment because PACS implementation involves other cost components, including storage infrastructure, network maintenance, technical support, cybersecurity, training, and system upgrades. Conversely, its potential economic benefits may extend beyond reduced film expenditure to include lower administrative workload, reduced physical storage requirements, faster information distribution, and productivity gains. A formal cost-effectiveness or cost-benefit analysis would therefore be necessary before definitive conclusions about economic efficiency could be drawn. The current study provides descriptive evidence of changing resource use rather than a comprehensive economic evaluation.

Another important finding concerns the integration of PACS with the hospital information system. This integration enabled radiologists to access relevant patient and clinical information while allowing referring physicians to retrieve radiological results more efficiently. The significance of this finding extends beyond technological interoperability. Radiology is closely connected to clinical decision-making, and delays in accessing imaging information may affect subsequent diagnostic and therapeutic processes. By reducing the time and physical effort required to distribute images and reports, an integrated digital system may strengthen communication between radiology and other clinical services. The mechanism underlying this benefit is therefore information availability: clinical information becomes accessible to authorized professionals when and where it is required rather than remaining dependent on the movement of physical records.

Digital storage further contributed to continuity of care by allowing previous radiological images and reports to be retrieved during follow-up examinations, disease monitoring, referrals, or subsequent clinical encounters. Compared with physical film archives, which require storage space and manual retrieval and may be vulnerable to loss or damage, centralized digital archiving provides greater flexibility in preserving longitudinal imaging information. In this context, PACS contributes primarily to information continuity, ensuring that radiological information generated during one episode of care remains potentially available during subsequent episodes. This function is particularly relevant in integrated hospital services, where patients may move between outpatient departments, emergency services, inpatient units, and other clinical specialties.

The reported patient satisfaction level of approximately 82% provides additional contextual evidence that the overall service experience was perceived positively. However, this finding should be interpreted carefully because the satisfaction figure originated from routine hospital survey data rather than from a PACS-specific validated instrument. It cannot therefore be assumed that the reported satisfaction level resulted directly from PACS implementation. Patient satisfaction is influenced by multiple factors, including waiting time, communication, staff responsiveness, facility conditions, and overall service quality. Nevertheless, the reduction in waiting time and easier access to radiological results provide plausible pathways through which digital workflow improvement could contribute to a more favorable patient experience.

From a theoretical perspective, these findings support a socio-technical understanding of digital transformation in healthcare. The benefits of PACS cannot be explained solely by the technical

characteristics of the system. They emerge through interactions among technology, healthcare professionals, organizational processes, infrastructure, information systems, and clinical workflows. A technically functional PACS may produce limited-service improvement if the network is unstable, integration with other systems is incomplete, users lack appropriate competencies, or organizational governance does not support digital workflows. Conversely, when technology is effectively integrated into organizational and clinical processes, it can facilitate broader changes in efficiency, information exchange, and care coordination. PACS implementation should therefore be understood as an organizational transformation supported by technology rather than as a technology installation alone.

This perspective also distinguishes digitization from digital transformation. Converting radiographic films into digital images represents digitization, whereas redesigning how images are transmitted, interpreted, stored, retrieved, and integrated into clinical decision-making represents digital transformation. The findings of this study are more consistent with the latter process. PACS altered not only the medium through which radiological images were stored but also the workflow through which information moved between radiology and other clinical services. This distinction is important because it suggests that evaluating digital health interventions requires attention to organizational processes and service outcomes rather than focusing exclusively on whether a technology has been installed.

The findings consequently have several implications for hospital management and health policy. PACS should be implemented as part of an integrated digital-health strategy, with interoperability between imaging modalities, PACS, and hospital information systems treated as a central requirement. Investment decisions should consider not only hardware and software acquisition but also network reliability, long-term storage capacity, technical maintenance, data governance, cybersecurity, and workforce competency. The sustainability of digital radiology depends on all of these components functioning together. Hospitals should also establish contingency mechanisms to maintain clinical services during network interruptions or system failures because increasing dependence on digital infrastructure creates new forms of operational vulnerability.

Human-resource capacity is equally important. Radiologists, radiographers, administrative personnel, referring physicians, and information technology staff interact with different elements of the PACS ecosystem. Continuous training should therefore accompany technological development to ensure that users can operate the system effectively, understand appropriate information-access procedures, and adapt to evolving digital workflows. From a policy perspective, implementation evaluation should consequently move beyond indicators of technology availability and incorporate measures of workflow performance, interoperability, system reliability, user competency, information security, and clinical integration.

Waiting time could serve as one practical performance indicator for such evaluations. The substantial change observed in this study demonstrates the usefulness of monitoring service indicators before and after digital implementation. Future hospital evaluations could systematically monitor radiology turnaround time, system uptime, image accessibility, user experience, operating costs, and service interruptions. Such monitoring would provide stronger evidence regarding whether improvements are sustained over time and could inform decisions about system expansion or modification.

This study has several strengths. It examined PACS implementation across multiple dimensions rather than restricting evaluation to technical system performance. Workflow efficiency, operational resources, information accessibility, patient care, and continuity of care were considered within the same service environment. The inclusion of different stakeholder groups also allowed implementation to be considered from technical, managerial, clinical, and patient perspectives. In addition, the combination of interviews, direct observations, and hospital documentation enabled triangulation across different sources of evidence, strengthening the contextual interpretation of the findings.

Several limitations should nevertheless be acknowledged. The study was conducted in a single hospital, which limits the transferability of its findings to institutions with different organizational structures, technological capacity, patient volumes, or levels of digital maturity. The descriptive qualitative design also does not permit causal attribution; therefore, changes observed after PACS implementation cannot be assumed to have resulted exclusively from PACS. Other concurrent organizational or workflow changes may have contributed. Furthermore, numerical indicators such as

waiting time, expenditure, and patient satisfaction were derived from routine institutional documentation rather than a prospectively designed quantitative evaluation. The financial findings do not constitute a formal economic evaluation, and the patient satisfaction measure cannot isolate the specific contribution of PACS. Future research should therefore employ multicenter and longitudinal designs to determine whether the observed benefits are sustained across different hospital environments. Prospective pre–post studies could provide more robust estimates of changes in turnaround time and workflow performance, while formal economic

CONCLUSION

This study demonstrates that the implementation of the Picture Archiving and Communication System (PACS) was associated with meaningful improvements in radiology service delivery at Dr. La Palaloi Regional Hospital. The transition from film-based to digitally integrated workflows substantially reduced chest radiography waiting time from approximately three hours to 30–40 minutes, minimized dependence on radiographic film and physical administrative resources, and enabled more rapid access to radiological images and clinical information. Integration between PACS and the hospital information system further supported information continuity by facilitating the retrieval of previous examinations and improving the availability of radiological information across clinical services. The principal contribution of this study is its multidimensional evaluation of PACS as more than an image-archiving technology. The findings position PACS as an organizational and clinical infrastructure that can support workflow efficiency, digital integration, resource optimization, and continuity of care. Hospitals implementing PACS should therefore prioritize interoperability, network reliability, storage capacity, data security, digital governance, and continuous workforce training to ensure sustainable implementation. Hospital and health-service policies should incorporate PACS within broader digital transformation and quality-improvement strategies rather than treating it as an isolated technological investment. Future research should employ multicenter, longitudinal, and prospective pre–post designs, complemented by formal economic evaluations, to assess the sustainability, cost-effectiveness, clinical impact, and scalability of PACS across diverse healthcare settings.

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Conflict of Interest

The authors declare that they have no competing interests or conflicts of interest related to the conduct, authorship, or publication of this study.

Authors' Contributions

Suherman Hadi Saputro: Conceptualization, Methodology, Investigation, Data Curation, Writing – Original Draft.

Nurwahyu Tajuddin: Conceptualization, Methodology, Supervision, Validation, Writing – Review & Editing, Project Administration.

Muh Nur Syihab: Investigation, Data Curation, Formal Analysis, Writing – Review & Editing.

Muh. Saifur Rohmad: Investigation, Resources, Data Curation, Writing – Review & Editing.

Purwanto: Methodology, Validation, Formal Analysis, Writing – Review & Editing.

Fajar Meilinda Omega Sutandi: Investigation, Visualization, Writing – Original Draft, Writing – Review & Editing.

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Declaration of Generative AI Use

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist with language editing, academic writing refinement, and improving the clarity and organization of the manuscript. The authors critically reviewed and edited all AI-assisted content and take full

responsibility for the accuracy, integrity, and final content of the manuscript. Generative AI was not used to generate, alter, or fabricate research data or findings.

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