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Contents

Volume 2, Issue 1 · April 2026 · published 30 April 2026 · 6 articles · pages 1–43

RESEARCH ARTICLES

1 Bioclimatic Shifts in the Tlemcen Region, Northwestern Algeria — pp. 1–8
Fatiha Barka, Mustapha Ainad Tabet

9 Measuring Algeria's Digital Transformation through an Indicator Based Assessment for Digital Algeria 2030 — pp. 9–17
Nawel Diafi, Abdelkader Magrament

18 Employing Digital Media and Artificial Intelligence in Smart Cities to Enhance Visitor Experience: A Case Study of Makkah, Saudi Arabia — pp. 18–23
Fatima Bendenia, Noha Nasser, Khulood Miliany, Mohammed Masawa, Mohammed Baali

REVIEW ARTICLES

24 Artificial Intelligence and the Internet of Things for Sustainable Waste Management — pp. 24–30
Rahma Toumi

31 Redefining Internal Audit Competencies through AI and Digital Transformation in the MENA Region — pp. 31–37
Nisrine Ouriachi, Nissrine Kamary

CONCEPTUAL PAPER

38 Smart FabLabs: The Role of Artificial Intelligence in FabLabs for Heritage Preservation — pp. 38–43
Lamia Ouahmed

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RESEARCH ARTICLE

Bioclimatic Shifts in the Tlemcen Region, Northwestern Algeria

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ABSTRACT

Research aims: This study compares the climatic conditions relevant to forests and matorrals in the Tlemcen region of northwestern Algeria. It examines spatial differences and changes between the historical, intermediate and recent configurations represented in the station summaries.

Design and approach: The study draws on precipitation and temperature summaries for nine reference stations: Tlemcen, Maghnia, Sebdou, Beni Bahdel, Zenata, Beni Saf, Ghazaouet, Nédroma and Fillaoucène. The sources are ANRH and ONM records and the historical compilation of Seltzer (1946). The descriptive comparison considers monthly and seasonal profiles, De Martonne aridity and Emberger climagram positions. Unequal records and incomplete temporal metadata limit comparisons between periods.

Findings: The profiles show low summer rainfall and marked differences between stations. Several recent configurations have lower rainfall or drier bioclimatic positions than their historical counterparts, but changes are not uniform. Temperature profiles also differ between sites and do not support a claim of warming at every station. The available summaries do not establish a regional trend rate or a causal attribution to anthropogenic forcing.

Contribution: The comparison brings together complementary climatic summaries while distinguishing bioclimatic interpretation from direct observation of vegetation change.

Management implications: The results support attention to local climatic conditions and the continuity and quality of station monitoring. Vegetation surveys and land-use observations are needed to assess ecological responses.

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1. Introduction

Temperature and precipitation influence water availability, plant growth and the distribution of vegetation. Mediterranean ecosystems experience a seasonal contrast between wetter, cooler months and a warm, dry summer. Changes in this balance can alter the climatic conditions associated with forests, shrublands and steppe formations.

Bioclimatic indicators summarise different aspects of this seasonal environment. They can help compare stations, but their interpretation depends on the observations, averaging periods and calculation conventions used. A change in an index is evidence about the climatic

conditions represented by that index; it is not a direct measurement of changes in vegetation.

The Tlemcen region includes coastal sectors, the Traras range, the Tlemcen Mountains and inland areas. This varied geography provides a setting for examining differences associated with altitude, maritime influence and continentality. Regional ecological work provides context for interpreting these contrasts (Alcaraz, 1982; Dahmani, 1984).

The study compares climatic summaries from nine reference stations across three configurations. It asks which seasonal features persist, where the summaries indicate drier conditions, and how far these patterns support ecological interpretation. The analysis is descriptive and does not quantify changes in species richness, vegetation cover or ecosystem resilience.

2. Literature review

2.1. *Mediterranean bioclimatic indicators*

Daget (1977) identifies summer dryness as a defining feature of Mediterranean bioclimate and discusses the criteria used to describe it. Bagnouls and Gaussen (1953) relate the dry season to monthly precipitation and temperature. In an ombrothermal diagram, a month is conventionally considered dry when precipitation P, in millimetres, is less than twice mean temperature T, in degrees Celsius. The precipitation and temperature scales must therefore preserve the relationship P = 2T.

Annual aridity and seasonal dryness describe different features. De Martonne's (1926) annual index relates annual precipitation to mean annual temperature, while the Emberger framework combines precipitation and thermal conditions to distinguish Mediterranean bioclimatic settings. Emberger (1936) also discusses the relationship between vegetation belts and climate in North African mountains. None of these classifications alone identifies the cause of a change in vegetation.

2.2. *Regional evidence and ecological interpretation*

Alcaraz (1982) examines vegetation in western Algeria, and Dahmani (1984) studies holm-oak communities in the Tlemcen Mountains. Aimé (1991) investigates the transition between subhumid, semi-arid and arid settings in the Oran Tell. These works provide a regional framework for relating climatic conditions to vegetation, without making a new climatic comparison equivalent to a vegetation survey.

Siba et al. (2024) combine bioclimatic analysis with GIS and Landsat observations of land use in Tlemcen. Their abstract reports a shift towards wetter bioclimatic conditions between 1985-1999 and 2004-2018, alongside forest-area losses and expansion of bare ground between 2000 and 2019. This combination illustrates why land-cover degradation cannot automatically be attributed to climatic drying. Their periods and methods differ from the station summaries considered here.

Meddi et al. (2024) examine drought in northern Algeria, while Diaf et al. (2024) use drought indices for the Wadi Lakhdar watershed over 1999-2021. The assessments of the Intergovernmental Panel on Climate Change (IPCC, 2021, 2022) provide a wider context for physical climate change and ecosystem risks. These sources establish the relevance of hydroclimatic assessment; they do not validate the observations or attribution of the present comparison.

3. Materials and methods

3.1. *Study area and stations*

The station set comprises Tlemcen, Maghnia, Sebdou, Beni Bahdel, Zenata, Beni Saf, Ghazaouet, Nédroma and Fillaoucène. It covers inland, mountain, coastal and subcoastal settings. These names identify the locations represented in the comparative material; station identifiers, coordinates and elevations are not available in the accompanying summaries.

3.2. *Climatic sources and temporal coverage*

The historical configuration is attributed to Seltzer's (1946) compilation for 1913-1938. The intermediate and recent configurations are attributed to records from the Agence nationale des ressources hydrauliques (ANRH) and Office national de la météorologie (ONM). The terms historical, intermediate and recent identify the three sets shown in the figures. Exact station-specific dates for the latter two sets are not specified in the available summaries.

Station operation was intermittent in some cases, and the observation periods may differ in length. Differences between their means therefore combine climatic variation with differences in temporal coverage and potentially in data preparation. The comparison does not treat the three configurations as equally sampled climatic normals.

The descriptive assessment uses the monthly and seasonal profiles and the reported bioclimatic diagrams. Individual annual records, missing-data treatments, station-move histories and homogenisation results are not available for independent recalculation. No rate of change per year, significance test or regional weighted average is estimated.

3.3. *Variables and bioclimatic interpretation*

Monthly precipitation profiles describe the timing of water input, and seasonal totals indicate which parts of the year contribute most rainfall. In the seasonal plots, H denotes winter, P spring, E summer and A autumn, following the French labels hiver, printemps, été and automne. A sequence such as HPAE orders those seasons from the largest to the smallest rainfall total. Seasonal ordering alone does not establish climatic continentality.

The De Martonne annual index is $I = P / (T + 10)$, where P is annual precipitation in millimetres and T is mean annual temperature in degrees Celsius (De Martonne, 1926). Lower values indicate greater aridity under this

convention. The comparison uses the plotted station positions rather than a newly calculated index series. The background runoff and irrigation labels in the De Martonne diagram are general interpretive guides, not local hydrological measurements or irrigation recommendations.

The P < 2T criterion provides a conceptual framework for discussing seasonal dryness. Applying it quantitatively requires paired monthly precipitation and mean-temperature values from the same station and period. A complete, consistent matrix is not available here, so the comparison does not estimate a common dry-season duration or precise onset and ending dates.

The Emberger diagram is read using its reported Q2 positions and the winter parameter m, the mean daily minimum temperature of the coldest month. The warm-season parameter M is the mean daily maximum temperature of the hottest month. Neither parameter is the mean annual temperature or an absolute temperature extreme. The quotient values have not been independently recalculated because the station inputs and calculation variant are not documented in full.

4. Results

4.1. *Monthly precipitation*

The rainfall profiles show a summer minimum at all nine stations. Rainfall is concentrated in the cooler part of the year, although the wettest month differs between stations and configurations. This seasonal structure is consistent with the Mediterranean climatic setting described by Daget (1977).

Several recent profiles lie below the historical profile in parts of the wet season. The contrast is clear at stations such as Maghnia and Zenata, while other stations show changes in the timing of rainfall and crossings between the curves. Thus, the figure supports station-specific comparisons rather than a uniform reduction in every month or at every location (Figure 1).

The spatial differences also matter. Mountain and coastal influence can modify precipitation, but the plotted stations do not form a single, consistently ordered rainfall gradient. The profile comparison is not used to infer a measured vegetation response.

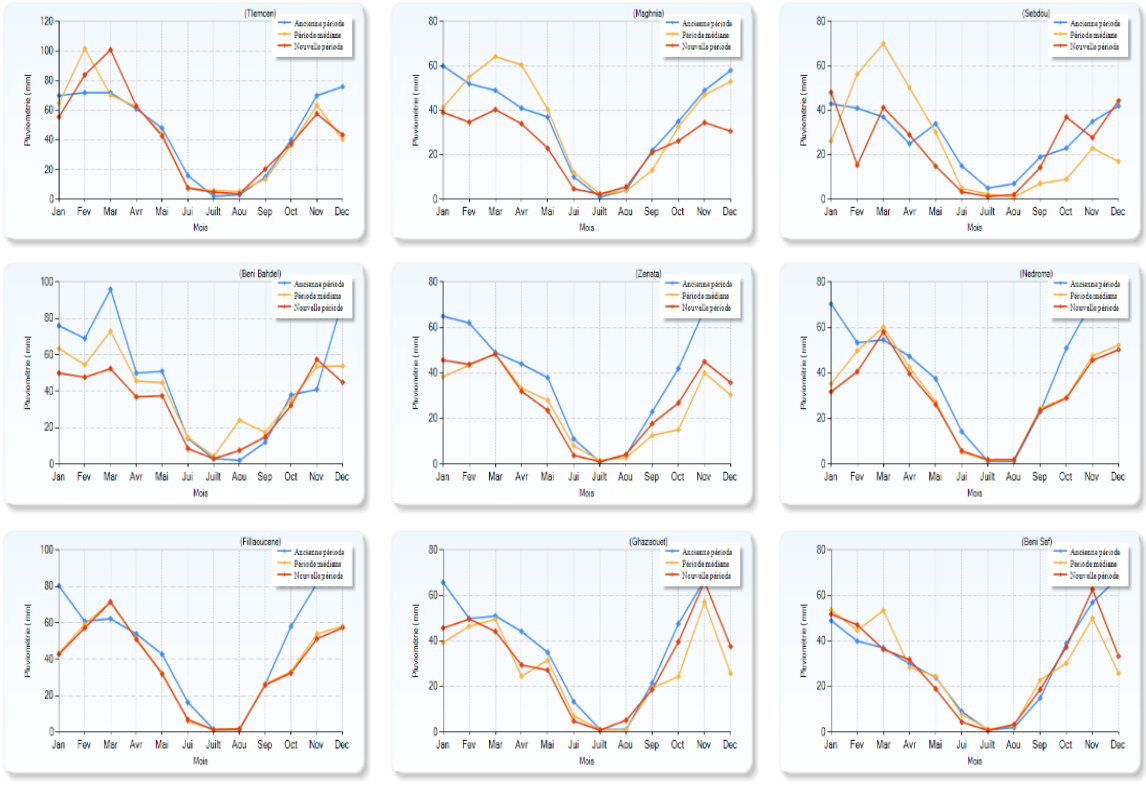

Fig. 1. Monthly precipitation profiles for the three configurations at nine stations

Source: Station summaries attributed to ANRH, ONM and Seltzer (1946). Blue: historical; orange: intermediate; red: recent.

4.2. *Seasonal rainfall distribution*

Winter or spring contributes the largest rainfall total in most station configurations, and summer contributes the smallest. Some profiles switch from winter dominance to spring dominance, as at Tlemcen or Sebdou, while autumn remains important at several coastal stations. The order varies by location and configuration (Figure 2).

This concentration of rainfall outside summer limits water input during the warm season. Ecological consequences depend on soil storage, exposure and vegetation characteristics as well as rainfall totals. The seasonal profiles do not directly measure those processes.

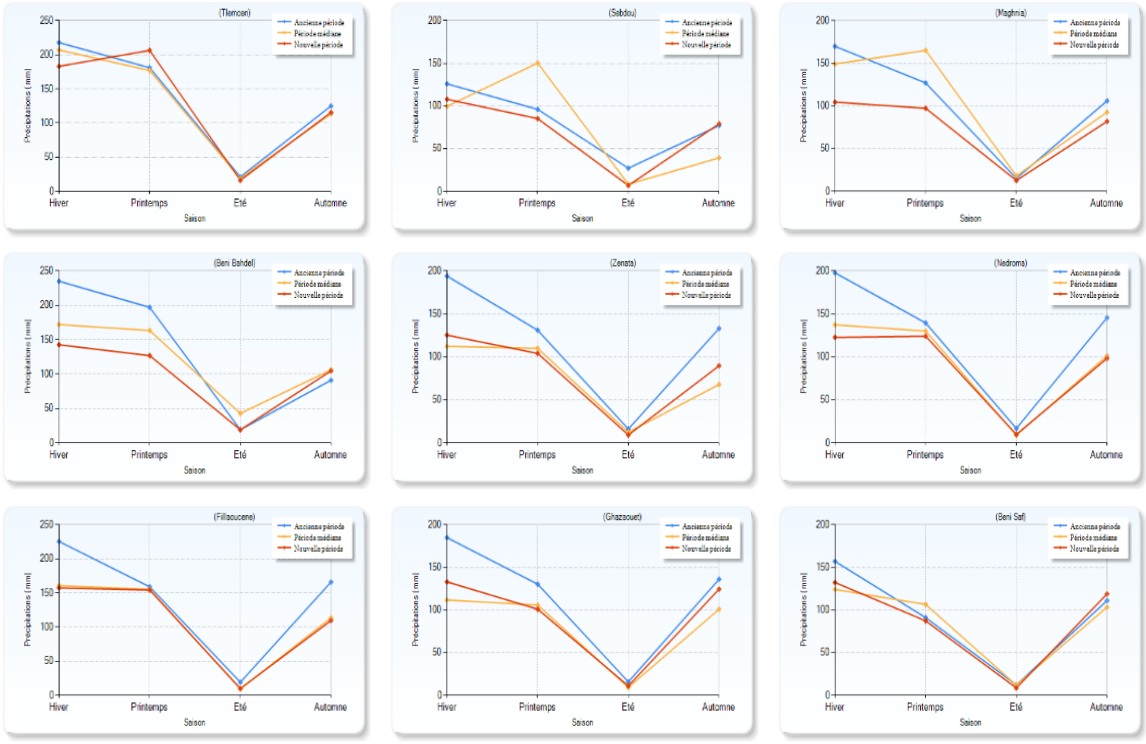

Fig. 2. Seasonal rainfall profiles for the three configurations at nine stations

Source: The same station summaries as Figure 1. Seasons follow the French labels Hiver, Printemps, Été and Automne. Blue: historical; orange: intermediate; red: recent.

4.3. *Temperature profiles*

Temperature affects atmospheric water demand and the timing of biological activity. The monthly profiles generally show a winter minimum and a summer maximum. Mean monthly temperature must be distinguished from m and M, which summarise daily minima and maxima for particular months.

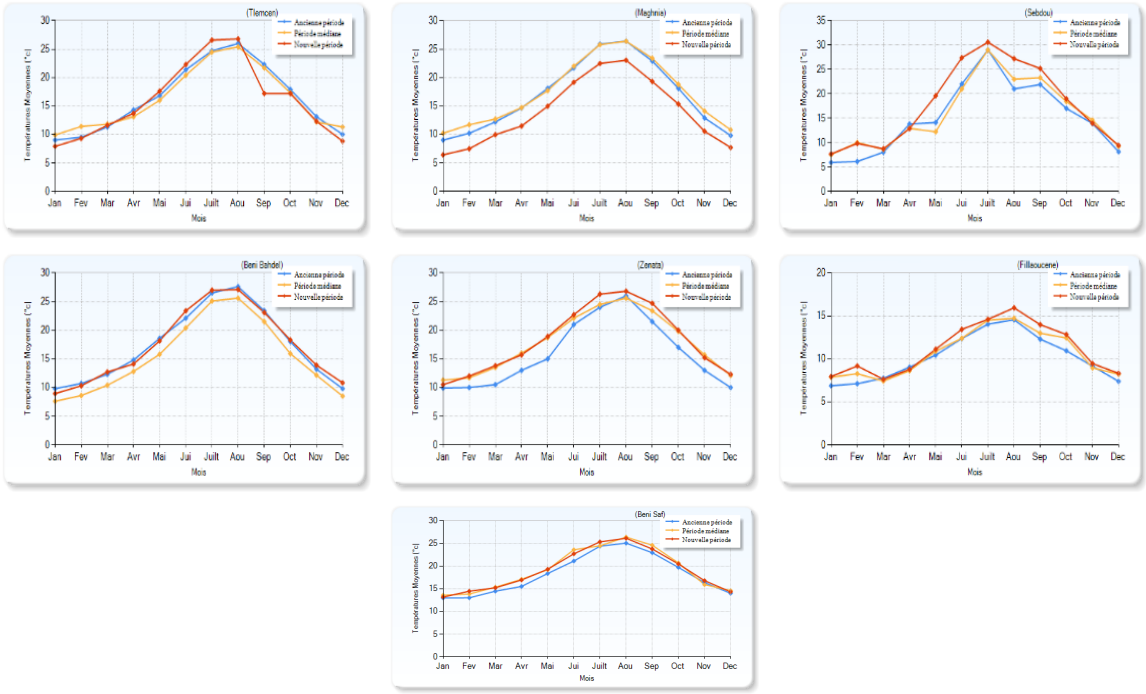

Fig. 3. Monthly mean temperature profiles for seven stations

Source: The same station summaries as Figure 1. The monthly profiles for Nédroma and Ghazaouet are excluded from this comparison. Blue: historical; orange: intermediate; red: recent.

The profiles do not show the same change at every station. The recent configuration is warmer in parts of the year at Tlemcen and Zenata, whereas the Maghnia profile is cooler than the earlier profiles in many months. Comparisons should therefore retain both the direction and the seasonal pattern of change (Figure 3).

The Nédroma and Ghazaouet monthly-temperature profiles contain isolated peaks that cannot be evaluated without the underlying observations. These two profiles are excluded from the descriptive monthly-temperature comparison. Their exclusion does not establish that the observations are erroneous and limits the coverage of Figure 3 to seven stations.

Within the Emberger framework, winter conditions depend on m rather than the lowest point on a mean-temperature curve. A diurnal temperature range, a difference between monthly means and the annual amplitude M - m are also distinct measures. They are not interchangeable indicators of dryness.

Across the retained profiles, the cooler months occur in winter and the warmest part of the year falls in summer. The differences between configurations are descriptive features of the station summaries and do not establish a statistically significant warming trend.

The coincidence of warm weather and low rainfall provides the basis for the combined bioclimatic interpretation. Temperature or rainfall alone cannot establish the duration or intensity of plant water stress.

5. Discussion

5.1. *Reading the combined indicators*

The rainfall and temperature profiles describe complementary aspects of the climatic environment. Annual aridity, seasonal dryness and Emberger classification summarise these observations in different ways. Agreement between them can help identify a pattern, but the indicators share input variables and should not be treated as independent statistical confirmations.

Regional ecological literature links vegetation distributions with climatic and site conditions (Alcaraz, 1982; Dahmani, 1984; Djebaili, 1984). These relationships support an interpretation of possible moisture constraints. The present study does not test the performance or expansion of any plant species.

5.2. *De Martonne aridity*

The De Martonne diagram places stations at different positions within the annual precipitation-temperature space. Several recent positions move towards lower aridity-index classes relative to their historical positions, while differences between the intermediate and recent configurations vary among stations (Figure 4). This indicates spatially uneven changes in the represented climatic balance.

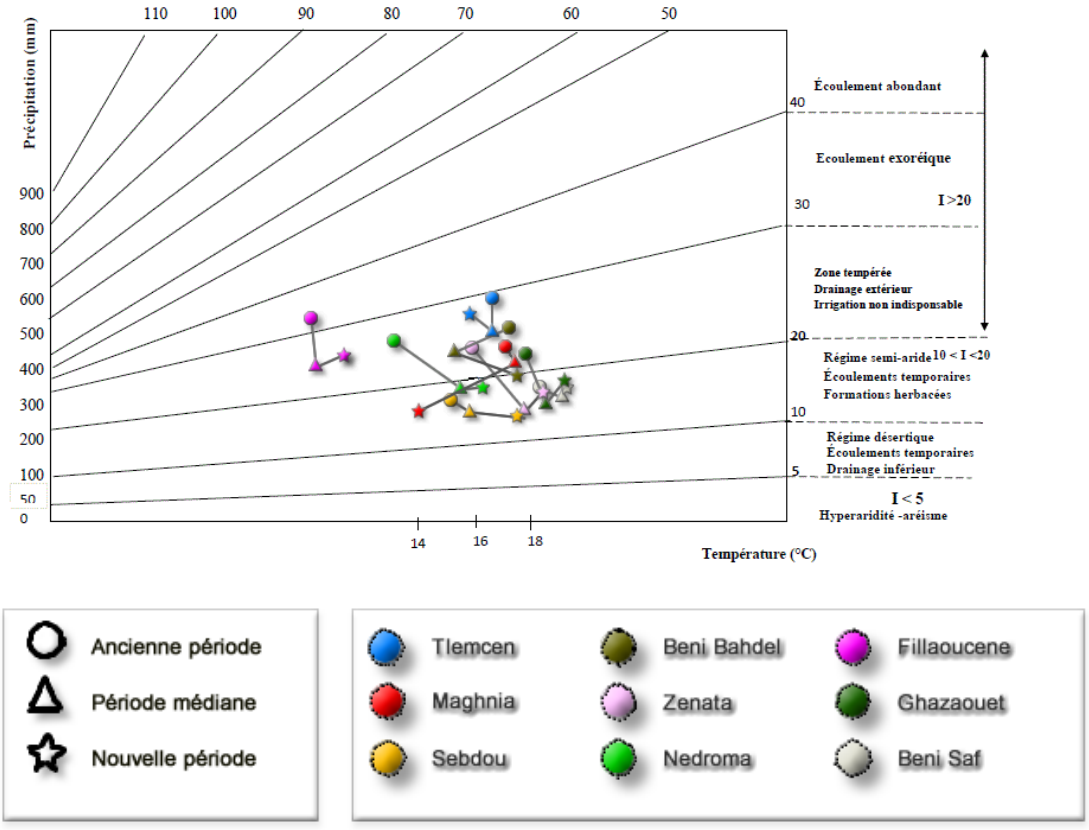

Fig. 4. De Martonne diagram for the three station configurations

Source: Reported station positions in the De Martonne diagram. The legend identifies stations and the historical, intermediate and recent configurations.

The plotted positions provide an annual summary. They do not describe rainfall intensity, soil-water storage or the occurrence of individual drought events. The descriptive pattern should therefore be considered alongside seasonal information, and the background categories should not be used as direct evidence of runoff or irrigation requirements.

5.3. *Seasonal moisture limitation*

The rainfall and retained temperature profiles indicate low rainfall during the warm season. This coincidence is consistent with the Mediterranean pattern of seasonal moisture limitation, but it does not directly measure soil moisture or plant water stress.

Variation in the timing of rainfall also makes late spring and autumn relevant to local water availability. The comparison does not assign a precise dry-season length to individual stations because a consistent set of paired monthly inputs is not available.

The ecological consequences depend on rooting depth, soils and access to stored water. These factors are not measured by the climatic summaries.

Possible effects on forest or matorral dynamics remain ecological interpretations. No new vegetation plots, floristic inventory or satellite vegetation index were analysed for this comparison.

5.4. *Emberger bioclimatic positions*

Figure 5 combines the reported Q2 positions with m to distinguish moisture conditions and winter thermal variants. The diagram includes semi-arid, subhumid and humid positions, and several recent configurations occupy drier positions than their historical counterparts. The pattern differs between stations.

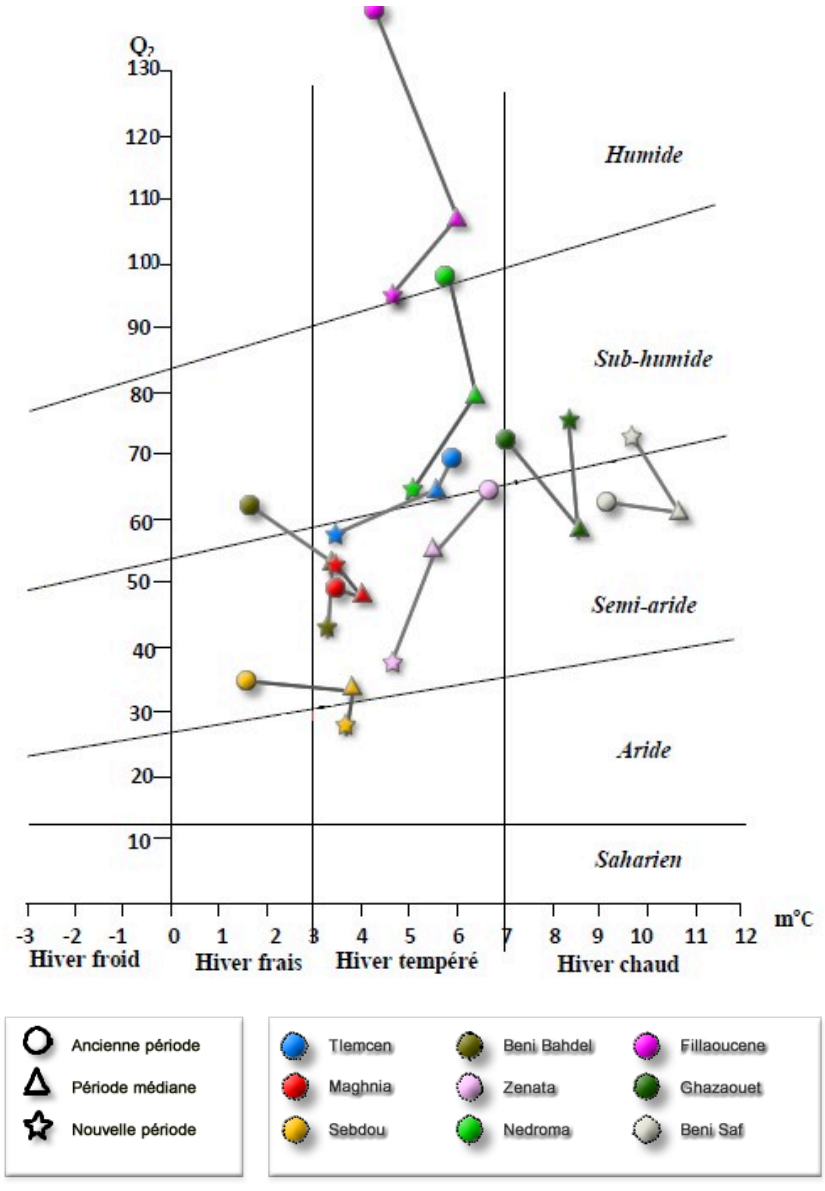

Fig. 5. Reported Emberger Q2 climagram positions of the reference stations

Source: Reported station positions in the Emberger diagram. Circle: historical; triangle: intermediate; star: recent.

The station trajectories do not support classifying the entire region in one moisture class or one winter variant. A fall in Q2 indicates a change within the chosen classification, while a change in m concerns the winter thermal component. These two dimensions should be read separately.

Some Traras stations retain relatively wet positions, particularly Fillaoucène, while several inland stations occupy semi-arid or transitional positions. Coastal influence does not produce the same classification at every station, and climatic classifications do not by themselves measure vegetation condition.

The figure provides a descriptive synthesis of the station summaries. Without complete dates, input values and quality-control records, it cannot establish a rate of climatic change, the statistical significance of a displacement or its attribution to anthropogenic forcing.

5.5. *Integrated interpretation and comparison with regional studies*

The clearest common feature is summer dryness, accompanied by differences in precipitation and thermal conditions between locations. Several configurations are consistent with increased climatic moisture limitation, but temperature changes and movements between the later configurations are not uniform. This supports a local interpretation rather than a single regional trajectory.

Restoration planning should consider these spatial differences together with soil conditions, land use and existing vegetation. A broad bioclimatic category can guide site assessment, but it is insufficient on its own to select species or predict restoration success.

The comparison with Siba et al. (2024) requires particular care. Their bioclimatic results indicate improved rainfall conditions between 1985-1999 and 2004-2018 even though their satellite analysis identifies forest loss between 2000 and 2019. The climatic periods, sampling and methods are different from those considered here. Their findings therefore support distinguishing land-use pressures from climatic signals, rather than treating every regional study as evidence of the same drying trend.

Meddi et al. (2024) and Diaf et al. (2024) provide regional drought context using approaches that differ from a comparison of bioclimatic summaries. Their findings cannot be substituted for missing station records in the present study.

For management, climatic information is most useful when combined with hydrological records and observations of vegetation and land use. This combination would help assess whether a climatic contrast corresponds to a change in ecological conditions.

The photographs in Figure 6 illustrate matorral landscapes in the study region. They do not constitute a dated before-and-after comparison or quantify a change in cover, species composition or ecosystem resilience.

A shift towards drier climatic conditions may reduce the suitability of some sites for moisture-demanding vegetation. Establishing that response requires field or remote-sensing observations and consideration of disturbance and land management. The climatic comparison alone cannot demonstrate an expansion of xerophytic formations or a loss of forest.



Fig. 6. Matorral landscapes in the Tlemcen region

Photographs: BARKA Fatiha.

6. Limitations and management implications

6.1. *Limits of the evidence*

The records differ in duration and include gaps in station operation. Exact intermediate and recent dates, station identifiers and complete quality-control procedures are not documented in the available summaries. These limitations prevent independent reproduction of the full station-by-period comparison. The exclusion of two temperature profiles further limits the thermal assessment. The retained figures are descriptive summaries, and their underlying observations have not been independently validated. Bioclimatic indices based on averages also do not resolve heatwaves or short drought events.

6.2. *Monitoring and ecosystem management*

The comparison identifies a need for continuity in station monitoring and for attention to differences between

coastal, mountain and inland sites. Climatic summaries can inform drought surveillance and the initial assessment of restoration sites, but they do not replace local hydrological, soil or vegetation evidence. The study does not quantify fire risk or assess marine ecosystems.

6.3. *Further research*

Further work could assemble station identifiers, coordinates, elevations and complete observation dates, then apply a documented procedure for missing data, station changes and homogenisation. Comparable time windows and annual records would allow formal trend analysis. Vegetation inventories, permanent plots and satellite observations would then support direct tests of ecological responses and separation of climatic and land-use effects.

7. Conclusion

The station summaries show substantial spatial variation in the Tlemcen region and a persistent Mediterranean summer rainfall minimum. Several recent profiles and bioclimatic positions are consistent with greater moisture limitation relative to historical conditions, while the direction and size of differences vary among stations.

The temperature profiles do not establish uniform warming, and the Emberger diagram includes more than one moisture class and winter variant. The available summaries support a descriptive comparison rather than a regional trend estimate or a causal attribution.

Ecological implications should be assessed against observations of vegetation, soils and land use. The present comparison does not measure a change in forest cover, biodiversity, productivity or resilience.

Maintaining long-term climatic records and combining them with standardised ecological observations would provide a stronger basis for assessing local vulnerability and planning restoration. The temporal and data-quality limits of the present summaries remain relevant to any management use.

Declarations

Author Contributions. Both authors contributed to the study concept, interpretation of the findings, and writing and revision of the manuscript.

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Conflicts of Interest. The authors declare no conflicts of interest.

Ethics Approval and Informed Consent. Not applicable.

Data Availability Statement. The climatic data were obtained from ANRH and ONM records and from the historical compilation of Seltzer (1946). Data are available from the corresponding author on reasonable request, subject to data-access requirements.

Declaration of Generative AI Use. The authors declare that the scientific content of this article was not produced using generative artificial intelligence.

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References

Aimé, S. (1991). Étude écologique de la transition entre les bioclimats subhumide, semi-aride et aride dans l'étage thermo-méditerranéen du Tell oranais (Algérie occidentale) [Doctoral thesis, Université Aix-Marseille III].

Alcaraz, C. (1982). La végétation de l'Ouest algérien [Doctoral thesis, Université de Perpignan].

Bagnouls, F., & Gaussen, H. (1953). Saison sèche et indice xérothermique. Bulletin de la Société d'Histoire Naturelle de Toulouse, 88(3–4), 193–239.

Daget, P. (1977). Le bioclimat méditerranéen: Caractères généraux, modes de caractérisation. Vegetatio, 34(1), 1–20. https://doi.org/10.1007/BF00119883

Dahmani, M. (1984). Contribution à l'étude des groupements à chêne vert (Quercus rotundifolia Lamk.) des monts de Tlemcen (Ouest algérien): Approche phytoécologique et phytosociologique [Doctoral thesis, Université des Sciences et de la Technologie Houari Boumediene].

De Martonne, E. (1926). Une nouvelle fonction climatologique: L'indice d'aridité. La Météorologie, 449–459.

Diaf, A., Djellouli, F., & Ghenim, A. N. (2024). Impact of climate change on drought in the Wadi Lakhdar watershed, North Algeria. Arabian Journal of Geosciences, 17(11), Article 299. https://doi.org/10.1007/s12517-024-12112-1

Djebaili, S. (1984). Steppe algérienne: Phytosociologie et écologie. Office des publications universitaires.

Emberger, L. (1936). Remarques critiques sur les étages de végétation dans les montagnes marocaines. Bulletin de la Société Botanique Suisse, 46, 614–631.

Intergovernmental Panel on Climate Change. (2021). Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009157896

Intergovernmental Panel on Climate Change. (2022). Climate change 2022: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009325844

Meddi, M., Bouabdelli, S., Hallouz, F., Rahmouni, A., Taibi, S., & Zeroual, A. (2024). Impacts of climate change on drought in northern Algeria. In M. M. M. Torab, M. Hereher, A. M. H. El Kenawy, & E. S. M. Robaa (Eds.), Hydroclimatic extremes in the Middle East and North Africa: Assessment, attribution and socioeconomic impacts (pp. 101–128). Elsevier. https://doi.org/10.1016/B978-0-12-824130-1.00019-9

Seltzer, P. (1946). Le climat de l'Algérie. Institut de météorologie et de physique du globe de l'Algérie, Université d'Alger. https://catalogue.bnf.fr/ark:/12148/cb326256944

Siba, A., Aboura, R., Kechairi, R., Maatouk, M., & Sebbah, B. (2024). Diachronic study (2000–2019) of bioclimate and land use in Tlemcen region, Northwest Algeria. International Journal of Environmental Studies, 81(3), 1224–1237. https://doi.org/10.1080/00207233.2022.2058761

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RESEARCH ARTICLE

Measuring Algeria's Digital Transformation through an Indicator Based Assessment for Digital Algeria 2030

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ABSTRACT

Research aims: This study describes Algeria's digital transformation using indicators relevant to the five axes of the national strategy for Digital Algeria 2030.

Design/Methodology/Approach: The analysis uses published secondary data and descriptive comparisons. The main series covers the UN E-Government Survey editions of 2020, 2022 and 2024, with national telecommunications data for 2019 to the first half of 2023. The 2025 UNCTAD assessment and Network Readiness Index provide supplementary evidence.

Research findings: Mobile and fixed internet subscriptions increased. Algeria's published EGDI score rose from 0.5173 in 2020 to 0.5956 in 2024, while its rank improved from 120 to 112 in 2022 before falling to 116 in 2024. The OSI rose in 2022 and fell in 2024. Changes to the 2024 TII and HCI methods limit direct comparisons across editions; the lower HCI score cannot establish a decline in digital skills. E-commerce indicators show expansion alongside continued use of cash on delivery. The results provide a descriptive baseline for the 2025-2030 strategy rather than an estimate of its effects.

Practitioners/Policy Implications: Policymakers should assess service usability, skills and opportunities for online participation alongside connectivity. Direct measures of service use, completion rates and user experience would strengthen monitoring of the strategy.

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1. Introduction

Governments use digital technologies to improve public-service delivery, administrative coordination and access to information. Evaluating this transformation requires evidence about the services available to users as well as the infrastructure supporting them.

Connectivity provides a foundation for digital administration, but subscription growth alone does not show whether services are accessible, usable or effective. A broader assessment should distinguish infrastructure, education, online services and economic activity.

In Algeria, Mokhtari (2024) discusses digital transformation in the context of globalisation. The National Strategy for Digital Transformation in Algeria 2025-2030 provides a policy framework for Digital Algeria 2030 (High Commission for Digitalization, 2024). Earlier initi-

atives, including the e-Algeria programme, form part of this policy background (Aggoune & Riahla, 2023).

The national strategy organises digital transformation around infrastructure, human capital, governance, the economy and society. These axes provide a useful structure for examining published indicators, although the indicators do not cover every strategic objective.

An assessment of progress must distinguish the conditions preceding the strategy from results achieved during its implementation. Most of the time-series evidence examined here comes from 2020-2024 and therefore provides a baseline for the 2025-2030 programme.

The available evidence also measures different aspects of transformation. Telecommunications subscriptions describe access, while composite indices combine several inputs or assess the features of online services. Changes in one measure need not imply equivalent changes in another.

Studies of Algerian e-government and digital learning offer evidence about particular systems and institutions. Bringing national indicators together can complement these studies, provided that the analysis respects differences in coverage, reference year and measurement method.

This paper asks: What do published indicators show about Algeria's digital transformation, and which issues do they identify for monitoring Digital Algeria 2030?

The study maps selected indicators to the five strategic axes and examines their published scores, rankings and underlying definitions. It identifies areas for further investigation without constructing a new composite score or estimating the proportion of strategic targets achieved.

The assessment uses national telecommunications statistics and reports from the United Nations, the International Telecommunication Union, UNCTAD, the Portulans Institute and the World Bank. Global rankings provide comparative context, rather than a controlled comparison with matched countries.

The evidence shows increasing subscriptions and variation in online-service and participation measures. The interpretation of these patterns requires attention to changes in index design and to the distinction between a published score and the outcome it is intended to represent.

The resulting overview can support the selection of monitoring priorities. It also indicates where direct observations of service use, accessibility, skills and institutional performance would be needed to assess implementation.

2. Literature Review

2.1. *Digital Algeria 2030 and the analytical framework*

2.1.1. Overview of the strategy

The National Strategy for Digital Transformation in Algeria covers 2025-2030. Its English version is dated 2 August 2024 and sets out the direction for Digital Algeria 2030 (High Commission for Digitalization, 2024).

The strategy links connectivity and digital public services with the development of the digital economy and wider social inclusion. Digital security and the regulatory framework support its strategic axes.

2.1.2. The five strategic axes

The five axes are basic ICT infrastructure; human capital, training, research and development; digital governance; the digital economy; and digital society (High Commission for Digitalization, 2024).

Infrastructure concerns the technical foundation for digital connectivity and services. The human-capital axis covers training and research, while digital governance concerns the use of digital systems in public administration.

The digital-economy and digital-society axes extend the agenda to economic activity and social participation. Together, the five axes provide the organising framework for this study.

2.1.3. Mapping indicators to the strategic axes

The following indicators provide partial evidence relevant to each axis. This mapping is an analytical choice by the study and is not an official scorecard for the national strategy.

Infrastructure: telecommunications subscriptions, internet use and the UN Telecommunication Infrastructure Index (TII).

Human capital: the Human Capital Index (HCI) used in the UN E-Government Survey. This index differs from the World Bank Human Capital Index and is not a direct test of digital skills.

Governance: the UN E-Government Development Index (EGDI), with separate attention to its Online Service Index (OSI) component.

Society: the UN E-Participation Index (EPI), which assesses government provision of opportunities for online participation rather than actual citizen participation.

Economy: e-commerce and digital-payment indicators, supplemented by the broader Network Readiness Index (NRI). The NRI also covers dimensions outside the digital economy.

Institutional and security context: the ITU Global Cybersecurity Index (GCI) and selected Worldwide Governance Indicators (WGI). These measures provide indirect context for trust rather than a direct measure of users' confidence in digital services.

The measures overlap. The EGDI is the arithmetic mean of the OSI, TII and HCI, and the EPI also contributes to the OSI. They are therefore interpreted as related measures rather than independent confirmations of the same finding (United Nations Department of Economic and Social Affairs [UNDESA], 2024).

2.2. *Key E-Governance Initiatives in Algeria*

Earlier national programmes and sectoral studies help explain the setting in which digital services developed.

Their findings concern specific systems and should not be treated as evidence of nationwide effects.

Aggoune and Riahla (2023) discuss the e-Algeria programme in a preprint on information agility in e-government systems. Their study provides background on the programme and proposes a method for evaluating systems.

The same preprint presents TAWASSOL as a proposed platform for integrating access to government services. The proposal illustrates an approach to coordination; it does not establish a nationwide rollout or a measured improvement in Algeria's OSI (Aggoune & Riahla, 2023).

Belhocine et al. (2019) evaluate the National Housing File in the Algerian housing sector. Their case study examines e-governance within housing administration and provides sector-specific evidence rather than a national measure of public-service performance.

Aouissi (2024) studies e-learning at Ghardaia University and identifies a need for staff training and institutional support. Benaida (2023) compares the usability of Algerian and UK e-government websites. These studies draw attention to skills and usability, but their findings cannot be generalised to all Algerian public institutions.

3. Methodology

The study uses a descriptive review of published quantitative indicators. It compares scores across available editions and reports international rankings where supplied by the publisher. It does not estimate causal effects, test hypotheses or produce a harmonised annual panel.

The five strategic axes organise the analysis. Indicator selection reflects relevance and public availability, with the limitations of each proxy made explicit. No common weighting scheme combines the measures, and no quantified national-target attainment score is calculated.

The principal sources are the 2020, 2022 and 2024 UN E-Government Surveys. Additional sources include the Algerian Ministry of Post and Telecommunications report for the first half of 2023, World Development Indicators, UNCTAD's 2025 assessment, the NRI 2025 country profile, the ITU GCI 2024 report and the archived 2025 WGI revision. The WGI series uses one release for all selected years to avoid mixing revisions.

The UN comparison covers 2020-2024. Telecommunications subscriptions cover 2019 to mid-2023; annual internet-use estimates cover 2019-2023. UNCTAD reports several reference periods, and the NRI 2025 is a supplementary observation outside the main period. Publication years do not necessarily equal the years of the underlying observations. Because the national strategy covers 2025-2030, the earlier indicators are interpreted as baseline conditions. Changes to UN index methods in 2024 limit direct trend comparisons (UNDESA, 2024).

4. Findings

The findings describe published values and their implications within the coverage and methodological limits of each source.

4.1. *Infrastructure*

Subscriptions and internet-use estimates describe different aspects of connectivity. One person may hold several subscriptions, so subscription counts cannot be read as counts of unique users.

Table 1 reports growth in mobile and fixed internet subscriptions. The final subscription observation is for the first half of 2023. The internet-use column gives annual population estimates from the World Bank's current World Development Indicators series (World Bank, 2026).

Table 1 Internet subscriptions and annual internet use

Year	Mobile internet subscriptions (3G and 4G)	Fixed internet subscriptions	Individuals using the internet (% of population)
2019	36,911,428	3,580,456	55.8
2020	38,772,562	3,789,128	63.5
2021	41,780,199	4,175,372	72.2
2022	44,757,505	4,705,846	74.8
2023*	45,144,609	5,095,712	76.2

*Sources: Ministry of Post and Telecommunications (2023); World Bank (2026). *The 2023 subscription counts refer to the first half of the year; the internet-use estimate refers to the calendar year. Population estimates are rounded to one decimal place.*

Table 2 Selected fixed internet technologies and total subscriptions

Year	ADSL	FTTH	Fixed 4G LTE	Total fixed internet*
2019	2,334,005	43,115	1,191,612	3,580,456
2020	2,500,080	72,314	1,204,931	3,789,128
2021	2,656,942	165,244	1,340,957	4,175,372
2022	2,792,695	478,172	1,423,425	4,705,846
First half 2023	2,771,460	740,109	1,571,912	5,095,712

*Source: Ministry of Post and Telecommunications (2023), French-language report. *The total also includes WiMAX and leased lines, which are not displayed as separate columns. These categories account for the difference between the three displayed technologies and the total.*

Table 2 shows the composition of fixed internet subscriptions. FTTH subscriptions increased from 43,115 in 2019 to 740,109 in the first half of 2023. ADSL remained the largest category. These counts describe technology adoption and do not directly measure connection speed, reliability or service quality.

Figure 1 and Table 3 present the TII values reported in the three UN survey editions. The index scores range from 0 to 1.

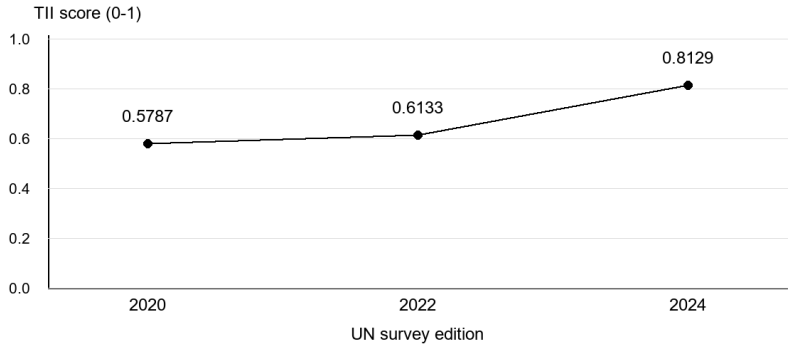

Fig. 1. Reported TII scores in the 2020, 2022 and 2024 editions

Table 3 Reported Telecommunication Infrastructure Index scores

TII	2024	2022	2020
Algeria (Value)	0.8129	0.6133	0.5787

Sources: UNDESA (2020, 2022, 2024).

The published TII score rose from 0.5787 in 2020 to 0.8129 in 2024. However, the 2024 methodology replaced the fixed-broadband subscription component with an affordability component. The difference therefore combines changes in the measured conditions with a change in index construction (UNDESA, 2024).

The national subscription figures independently document expanded access. Together, these observations provide relevant baseline information for the infrastructure axis, but they do not identify the effect of particular investments or demonstrate achievement of the strategy's targets.

4.2. *Human Capital*

The UN HCI combines education-related measures with an e-government literacy component introduced in 2024. It provides a proxy for conditions relevant to the use of digital services rather than a direct assessment of individual digital competence.

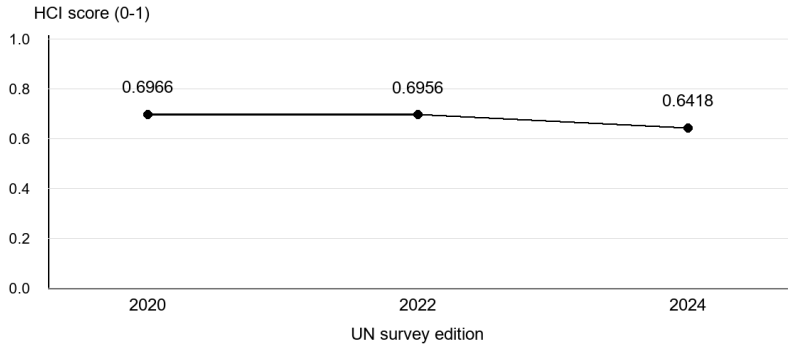

Fig. 2. Reported HCI scores in the 2020, 2022 and 2024 editions

Table 4 Reported UN Human Capital Index scores

HCI	2024	2022	2020
Algeria (Value)	0.6418	0.6956	0.6966

Sources: UNDESA (2020, 2022, 2024).

The published HCI was 0.6966 in 2020, 0.6956 in 2022 and 0.6418 in 2024. In 2024, UNDESA added e-government literacy and changed the weighting to five equally weighted components. The resulting discontinuity prevents the lower score from establishing a comparable decline in education or digital skills.

Monitoring the human-capital axis therefore requires consistent measures of skills and training in addition to the HCI. The present series cannot establish a failure of strategy implementation or quantify a growing skills gap.

4.3. *Governance*

The EGDI summarises infrastructure, human capital and online-service provision. The OSI is examined separately

to clarify the service dimension; it is already included in the EGDI.

4.3.1. Performance in the E-Government Development Index (EGDI)

Table 5 reports the published EGDI scores and global ranks. Ranks describe relative position among countries and need not move in the same direction as scores.

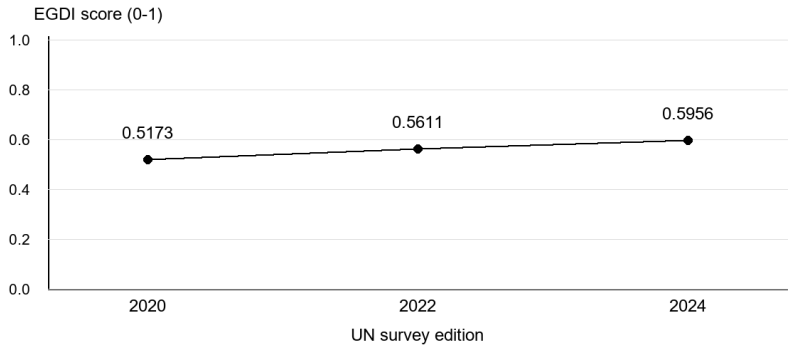

Fig. 3. Reported EGDI scores in the 2020, 2022 and 2024 editions

Table 5 E-Government Development Index scores and ranks

EGDI	2024	2022	2020
Algeria (Rank)	116	112	120
Algeria (Value)	0.5956	0.5611	0.5173

Sources: UNDESA (2020, 2022, 2024).

The published EGDI score increased across the three editions. Algeria's rank improved from 120 in 2020 to 112 in 2022, then fell to 116 in 2024 despite the higher score. A country can gain points while losing places if other countries improve their relative position.

Changes to the component indices limit interpretation of the score increase. The EGDI describes broad conditions for e-government and does not by itself show the integration or effectiveness of every public service.

4.3.2. Online Service Index (OSI)

The OSI assesses features of government online services. Its score concerns the assessed online provision and should not be treated as a direct measure of user satisfaction or successful completion of services.

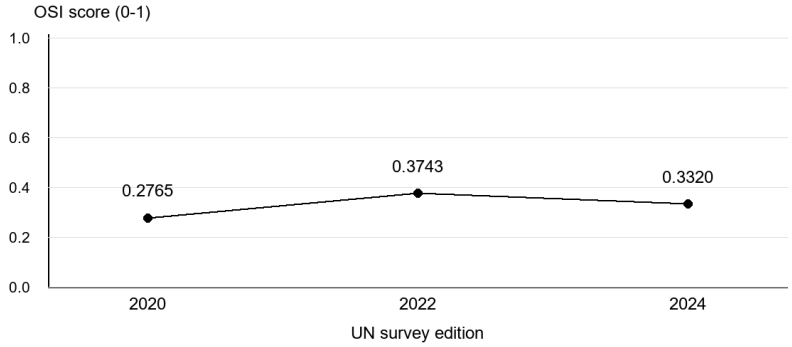

Fig. 4. Reported OSI scores in the 2020, 2022 and 2024 editions

Table 6 Online Service Index scores

OSI	2024	2022	2020
Algeria (Value)	0.3320	0.3743	0.2765

Sources: UNDESA (2020, 2022, 2024).

The OSI rose from 0.2765 in 2020 to 0.3743 in 2022, then fell to 0.3320 in 2024. The 2024 score remained above the 2020 score. Changes in the survey assessment also warrant caution when interpreting differences across editions.

These results support closer examination of online-service provision. Service-level evidence on accessibility, usability and completed transactions would help identify the practical priorities for digital governance.

4.4. *Digital Economy*

This section considers e-commerce and online payments, followed by the broader NRI. These measures cover selected aspects of digital economic activity and readiness rather than the total value added by the digital economy.

4.4.1. E-Commerce Development

UNCTAD's 2025 assessment brings together indicators of registered e-commerce businesses, online payments and connectivity. Table 7 retains the reference periods and approximations reported in that assessment.

Table 7 E-commerce indicators reported in the 2025 UNCTAD assessment

Indicator	Value	Interpretation
Growth in registered e-commerce businesses	Average annual growth of 92% since 2020	Expansion of registered businesses
Online payments for goods and services	Tripled between 2020 and 2024	Growth in recorded online payments
Estimated B2C e-commerce sales relative to GDP	0.8% in 2023	Sales-to-GDP ratio; not a value-added contribution
Individuals using the internet	76.9% in 2023	Estimate published in the assessment
Mobile internet subscriptions per 100 inhabitants	104, as reported in the assessment	Subscription density; not unique users
Cash on delivery	Approximately 90%	Continued predominance in e-commerce payments

Source: United Nations Conference on Trade and Development (UNCTAD, 2025). Reference periods vary across indicators. The internet-use estimate is the value published by UNCTAD; Table 1 uses the subsequently revised World Bank series.

The assessment reports expanding registered e-commerce activity and online payments alongside continued use of cash on delivery. Subscription density above 100 indicates more subscriptions than inhabitants and does not mean that every person uses mobile internet.

The estimated B2C sales-to-GDP ratio describes market sales relative to GDP. It is not the value-added contribution of e-commerce and cannot establish the contribution of the entire digital economy. The figures identify topics for further analysis of payment adoption and business activity without measuring the effects of the 2025-2030 strategy.

4.4.2. Network Readiness Index (NRI)

The NRI covers Technology, People, Governance and Impact. The 2025 country profile supplements the earlier series and is not treated as a 2024 observation (Portulans Institute, 2025). Table 8 reports pillar and sub-pillar scores on a 0-100 scale, with ranks among 127 economies.

Table 8 Algeria in the Network Readiness Index 2025

Pillar/Sub-pillar		Rank	Score
Technology Pillar		84	37.23
Sub-Pillar	Access	79	63.09
	Content	79	20.60
	Future technologies	92	28.01
People Pillar		99	31.06
Sub-Pillar	Individuals	57	53.08
	Businesses	116	17.33
	Governments	109	22.76
Governance Pillar		119	32.93
Sub-Pillar	Trust	109	34.70
	Regulation	111	41.31
	Inclusion	122	22.76
Impact Pillar		110	39.85
Sub-Pillar	Economy	101	23.35
	Quality of life	97	49.55
	SDG Contribution	113	46.66

Algeria ranked 109th of 127 economies in the NRI 2025, with an overall score of 35.27. Within the Technology pillar, Access scored 63.09, while Content and Future technologies scored 20.60 and 28.01. The Businesses sub-pillar scored 17.33. These results describe the profile's distribution of readiness measures; they do not establish the cause of differences between pillars.

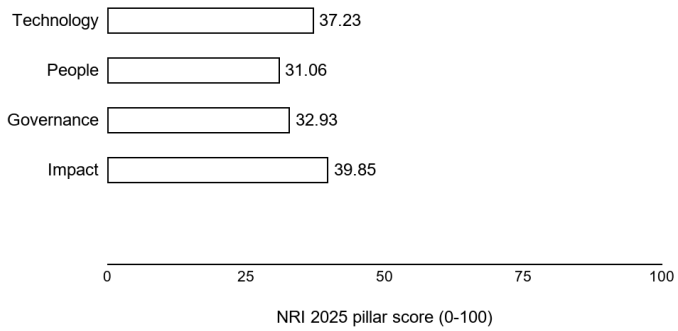

Fig. 5. Algeria's NRI 2025 pillar scores

Source: Portulans Institute (2025), Algeria country profile. Scores range from 0 to 100; a lower rank number indicates a higher position.

4.5. *Digital Society*

The EPI assesses the online information, consultation and decision-making opportunities offered by governments. It does not count actual participants or directly measure social inclusion.

Table 9 E-Participation Index scores and global ranks

EPI	2024	2022	2020
Algeria (Rank)	187	148	183
Algeria (Value)	0.0548	0.2273	0.1548

Sources: UNDESA (2020, 2022, 2024).

Algeria's EPI rose from 0.1548 in 2020 to 0.2273 in 2022, then fell to 0.0548 in the published 2024 edition. Its rank moved from 183 to 148 and then to 187. The 2024 value is an observed survey-edition result, not a projection. The pattern concerns assessed opportunities for participation and does not establish a decline in actual citizen engagement.

4.6. *Institutional quality and cybersecurity*

Cybersecurity commitments and institutional quality provide context for digital services. Neither measure directly tests public trust, the security of a particular platform or citizens' reasons for using a service.

4.6.1. Cybersecurity commitments

The ITU Global Cybersecurity Index assesses commitments across legal, technical, organisational, capacity-development and cooperation measures. The 2024 report classifies Algeria in Tier 3, Establishing (International Telecommunication Union [ITU], 2024).

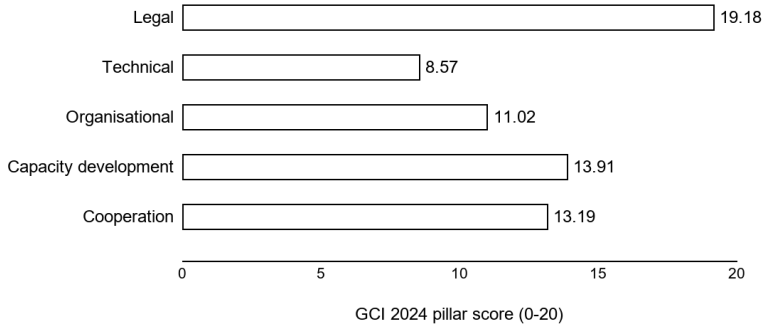

Fig. 6. Algeria's GCI 2024 pillar scores out of 20

Source: ITU (2024), Algeria country profile, p. 70.

The country profile reports 19.18 for legal measures, 8.57 for technical measures, 11.02 for organisational measures, 13.91 for capacity development and 13.19 for cooperation. ITU identifies legal measures as a relative strength and the other pillars as areas for potential growth. These scores concern commitments and do not measure cyberattack incidence, operational security or public confidence.

4.6.2. Worldwide Governance Indicators

The WGI Government Effectiveness and Control of Corruption dimensions describe broader institutional conditions. Table 10 uses the archived 2025 revision for 2020, 2022 and 2024. The values are governance scores on the 0-100 scale, not percentile ranks (World Bank, 2025).

Table 10 Selected WGI governance scores on the 0-100 scale

Indicators	2024	2022	2020
Government effectiveness	46.46	46.15	46.10
Control of Corruption	35.84	34.84	34.99

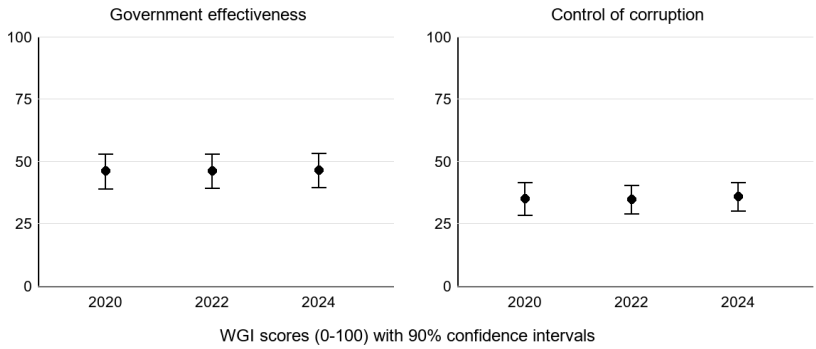

Fig. 7. WGI scores with 90% confidence intervals

Source: World Bank (2025), archived WGI dataset, 2025 revision. Higher scores indicate better assessed governance. Figure 7 shows the associated 90% confidence intervals.

Government Effectiveness changed from 46.10 in 2020 to 46.46 in 2024. Control of Corruption changed from 34.99 to 35.84, with a lower value in 2022. The 90% confidence intervals overlap across the selected years. These small point-estimate differences do not support a clear conclusion of institutional deterioration or improvement.

The WGI provides institutional context, but this descriptive comparison does not estimate how governance affects digital-service use or public trust. Direct evidence would be required to examine those relationships.

5. Discussion

The indicators show expanded telecommunications subscriptions alongside variation in assessed online services and participation opportunities. The differences between dimensions are relevant to monitoring, but measurement changes and overlapping indices limit any claim that one dimension has advanced faster than all others.

The national subscription series provides evidence of broader connectivity. The TII score increase points in the same general direction, although the introduction of affordability in 2024 prevents a direct interpretation of the full score difference as infrastructure growth.

The higher published EGDI score coexists with a fall in the OSI between 2022 and 2024. Because the EGDI averages three components, its overall score can rise while the online-service component falls. These results warrant service-level investigation rather than a conclusion about the success of all administrative reforms.

The lower 2024 HCI requires particular caution. The new e-government literacy component and changed weights alter the measure. The comparison cannot establish a decline in national educational attainment or digital skills.

UNCTAD's evidence documents e-commerce expansion and a continuing reliance on cash on delivery. It does not quantify the entire digital economy's contribution to GDP or identify the cause of payment preferences. Surveys of businesses and consumers could help explain these patterns.

The low EPI score in 2024 concerns assessed online participation opportunities. Evidence about actual participation, accessibility and users' experiences would be needed before drawing conclusions about the extent of citizen involvement.

The ITU and WGI measures add security and institutional context. The GCI assesses commitments, and the WGI scores are estimates with uncertainty. Neither provides direct evidence that public trust has increased or decreased.

The combined evidence supports monitoring connectivity together with service usability, training and participation. Since most observations precede the strategy's implementation period, they identify baseline conditions and questions for evaluation rather than verified effects of Digital Algeria 2030.

6. Limitations and policy implications

6.1. *Limitations*

The sources differ in reference year, coverage and method, so the analysis is not a balanced annual panel. The 2024 HCI and TII changes interrupt direct comparability, and the EGDI, its components and the EPI overlap. The NRI 2025 falls outside the main UN comparison period. WGI revisions alter historical estimates, while confidence

intervals limit interpretation of small changes. Several measures concern reported commitments or assessed online provision rather than experienced outcomes. The descriptive design cannot establish causation, and it does not control for income, population or regional differences.

6.2. *Policy implications*

Monitoring should combine the published indices with direct measures of service completion, accessibility and user satisfaction. Comparable skills assessments and training outcomes would provide stronger evidence for the human-capital axis. Payment and e-commerce data should distinguish registered activity, transactions, sales and value added.

A monitoring framework for Digital Algeria 2030 should record the source, release, reference period and definition of each measure. Consistent observations during 2025-2030 would support an assessment of progress against explicit national targets.

6.3. *Future Research Agenda*

Future research could compare Algeria with selected North African economies using harmonised definitions and consistent data releases. Longitudinal and service-level evidence could help distinguish changes in access from changes in use and outcomes. Any causal analysis would require an appropriate identification strategy beyond the descriptive comparisons presented here.

7. Conclusion

This study examines published indicators relevant to the five axes of Digital Algeria 2030. National statistics document growing internet subscriptions, while UN survey editions show higher published EGDI scores and variable online-service and participation measures.

Methodological changes prevent the 2024 HCI decrease and the full TII increase from being read as directly comparable changes in skills and infrastructure. The e-commerce, NRI, GCI and WGI evidence adds context, with different reference periods and measurement limits.

The findings provide a baseline for monitoring the 2025-2030 strategy. They support further investigation of service quality, skills, online participation and payment adoption, but they do not establish the strategy's effects or quantify achievement of its targets.

Declarations

Author Contributions. Conceptualisation, methodology, validation, formal analysis, investigation and data curation: N.D. and A.M. Writing of the original draft: N.D. and A.M. Supervision and review and editing: N.D. All authors have read and agreed to the manuscript.

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Ethics Approval and Informed Consent. Not applicable.

Data Availability Statement. The analysis uses publicly available secondary data. The reports, country profiles and data releases are identified in the references.

Declaration of Generative AI Use. The authors used Grammarly for language refinement. They reviewed the content and take responsibility for the manuscript.

References

Aggoune, S., & Riahla, M. A. (2023). A method for evaluation of e-Government systems information agility: Case of e-Algeria [Preprint]. Research Square. https://doi.org/10.21203/rs.3.rs-2564949/v1

Aouissi, K. (2024). E-learning realities and challenges: A case of Ghardaia University in Algeria. Filosofija. Sociologija, 35(2), 227–236. https://doi.org/10.6001/fil-soc.2024.35.2.9

Belhocine, O., Djiar, K. A., & Lagati, M. (2019). Performance evaluation of the National Housing File (FNL) for the development of e-governance in the housing sector in Algeria. International Journal of E-Planning Research, 8(4), 60–73. https://doi.org/10.4018/IJEPR.2019100104

Benaida, M. (2023). e-Government usability evaluation: A comparison between Algeria and the UK. International Journal of Advanced Computer Science and Applications, 14(1), 680–690. https://doi.org/10.14569/IJACSA.2023.0140175

High Commission for Digitalization. (2024). National strategy for digital transformation in Algeria 2025–2030: For Digital Algeria 2030 (2 August 2024 version). https://hcn.dz/SNTN-En.pdf

International Telecommunication Union. (2024). Global cybersecurity index 2024 (5th ed.). https://www.itu.int/dms_pub/itu-d/opb/hdb/d-hdb-gci.01-2024-pdf-e.pdf

Ministry of Post and Telecommunications, Algeria. (2023). Rapport sur le développement des indicateurs des services des télécommunications: Premier semestre 2023 [Report on the development of telecommunications service indicators: First half of 2023]. https://www.mpt.gov.dz/wp-content/uploads/2024/03/rapport_TIC-S1-2023-FR.pdf

Mokhtari, A. (2024). Digital transformation in Algeria as an inevitable necessity in light of globalization. Journal of Law and Sustainable Development, 12(8), e3926. https://doi.org/10.55908/sdgs.v12i8.3926

Portulans Institute. (2025). Network readiness index 2025: Algeria. https://download.networkreadinessindex.org/reports/countries/2025/algeria.pdf

United Nations Conference on Trade and Development. (2025). Algérie: Évaluation de l'état de préparation au commerce électronique [Algeria eTrade readiness assessment] (UNCTAD/DTL/ECDE/2025/3). https://unctad.org/publication/algeria-etrade-readiness-assessment

United Nations Department of Economic and Social Affairs. (2020). United Nations e-government survey 2020: Digital government in the decade of action for sustainable development. https://desapublications.un.org/file/781/download

United Nations Department of Economic and Social Affairs. (2022). United Nations e-government survey 2022: The future of digital government (Annexes). https://desapublications.un.org/sites/default/files/publications/2022-11/Annexes%2BCover.pdf

United Nations Department of Economic and Social Affairs. (2024). United Nations e-government survey 2024: Accelerating digital transformation for sustainable development. https://desapublications.un.org/publications/un-e-government-survey-2024

World Bank. (2025). Worldwide governance indicators: 2025 revision [Data set]. https://www.worldbank.org/content/dam/sites/govindicators/doc/wgidataset_with_sourcedata-2025.xlsx

World Bank. (2026). Individuals using the Internet (% of population), Algeria, 2019–2023 (IT.NET.USER.ZS). World Development Indicators. https://api.worldbank.org/v2/country/DZA/indicator/IT.NET.USER.ZS?date=2019:2023&format=json

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RESEARCH ARTICLE

Employing Digital Media and Artificial Intelligence in Smart Cities to Enhance Visitor Experience: A Case Study of Makkah, Saudi Arabia

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ABSTRACT

Research aims: This study examines Umrah pilgrims' use of digital media, AI-related applications and smart services in Makkah.

Design/Methodology/Approach: A descriptive questionnaire survey collected responses from 400 pilgrims during Ramadan 1447 AH (2026). The analysis presents self-reported use, proficiency and perceptions of visitor services.

Research findings: All respondents reported using the digital services covered by the survey, and 48.5% rated their proficiency as high. Smart applications received a mean score of 4.09 out of 5; the equivalent relative score of 81.8% describes the rating, not the proportion of users. Respondents also reported benefits for guidance, awareness of landmarks and completion of procedures. Information overload, account access and the timeliness of information remained concerns.

Theoretical Contribution/Originality: The study provides descriptive evidence about pilgrims' experiences of digital services in a Saudi smart-city setting.

Practitioners/Policy Implications: Service providers should consider multilingual guidance, accessible interfaces and practical support alongside technological development. The survey describes participants' perceptions and does not establish causal effects or distinguish the contribution of AI from other digital services.

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1. Introduction

Smart-city development uses information and communication technologies to support urban services and address residents' needs. Kotarba and Zawiła-Niedźwiedzki (2025) propose a functional model linking city activities with digital intelligence. Research on user adoption also considers perceived usefulness, ease of use and trust

(Wang, 2025). These perspectives suggest that assessments of digital urban services should examine how people use them, as well as the infrastructure available.

Digital tools can support transport, energy management and public services, but their value depends on organisational capacity and users' experiences. Pivar (2025) identifies technological readiness and management support among the factors associated with big-data adoption in EU cities. Brown and Patten (2024) discuss potential uses of generative AI alongside the commitments and risks involved in smart-city development.

In Saudi Arabia, smart-city initiatives form part of the development agenda associated with Vision 2030 (Al Jaafreh & Allouzi, 2023). Urbanisation creates demands for coordinated planning and sustainable services (Almulhim & Cobbinah, 2023). Makkah presents a particular setting because services must accommodate pilgrims with different languages, travel needs and levels of digital proficiency. Balbaid and Al-Dahwi (2024) examine the city's readiness for smart-city development, including governance and implementation challenges.

Research on citizen participation shows why user perspectives matter when evaluating digital urban services (Allen et al., 2020). This study therefore examines how 400 Umrah pilgrims in Makkah reported using digital media, AI-related applications and smart services. It describes their proficiency, perceptions of guidance and service quality, intentions to continue using the services, and practical difficulties. The focus is the experience of this sample, rather than a citywide measure of technological performance.

2. Literature review

2.1. *Studies in Saudi Arabia*

Doheim et al. (2019) review smart-city visions and practices in Saudi Arabia. Alotaibi et al. (2022) also discuss the Saudi smart-city context, while Al Jaafreh and Allouzi (2023) review adoption drivers and challenges. Aldegheishem (2023) assesses Riyadh, Makkah, Jeddah and Madinah using 57 indicators across six dimensions; smart mobility shows the least progress among the dimensions examined.

Almulhim and Aina (2025) combine literature, expert consultation and cases to examine human-centred development, identifying participation and institutional challenges. Alwafi (2025) analyses climate-responsive design in The Line as a planning proposal. Bahreldin et al. (2025) examine digital twins, infrastructure readiness and governance. These studies discuss conditions for development rather than measured benefits for the pilgrims in this survey.

Alotaibi et al. (2025) examine urban sustainability and smart-city variables in Najran. Alhazmi et al. (2025) model battery-swapping infrastructure for electric vehicles, while Mohanty et al. (2025) review smart-grid communication and measurement technologies. These infrastructure studies provide wider context but do not establish outcomes for visitor services in Makkah.

Belaïd and Arora's (2024) edited volume considers social and environmental challenges in smart cities. Bennoui (2021) reviews international and Arab experiences. Together with the Makkah readiness study by Balbaid and Al-Dahwi (2024), this literature places digital-service development within a wider discussion of governance and local needs.

2.2. *International studies*

International research examines how governance and user participation shape digital urban services. Kummitha (2025) identifies embedded, blended and networked models of citizen engagement in smart-city governance. Smalec (2025) considers communication and social participation, including the risk of excluding groups with limited digital access. Szymańska (2025) uses focus groups to examine Generation C's views of AI; participants describe potential benefits as well as privacy, transparency and employment concerns.

Studies of digital infrastructure provide related context. Tong and Amalia Rivai (2025) review 976 articles on IoT and smart-city governance. Shao and Min (2025) develop a framework for sustainable smart-city development through bibliometric research. Aliyari (2025) reviews digital technologies in smart cities and sustainable logistics, while Okonta and Vukovic (2024) examine software applications and case studies concerning urban sustainability and resilience.

Ben Rjab and Mellouli (2019) review AI applications and challenges across smart-city sectors. Chipriyanov (2025) discusses how public-private partnerships need management capacity and attention to the technology life cycle. In Baghdad, Al-Bari et al. (2025) examine digital urban services, including electronic payments, alongside infrastructure and access difficulties. These findings concern their respective settings and cannot be assumed to describe Makkah.

2.3. *Research focus*

The reviewed literature addresses infrastructure, governance and citizen engagement through different methods. Almulhim and Aina (2025), for example, combine a literature review, expert consultation and case analysis; Alotaibi et al. (2025) use quantitative methods in Najran. These studies provide context for examining visitors' experiences, but their findings concern populations and services different from the pilgrims surveyed here.

This study focuses on self-reported digital-service use and perceptions among Umrah pilgrims in Makkah during Ramadan 1447 AH. It adds a visitor perspective to the wider smart-city literature.

3. Methodology

The study uses a descriptive quantitative questionnaire survey. It examines how respondents use digital media and smart services, how they rate their own proficiency,

and how they perceive guidance, service quality and practical difficulties. The analysis is descriptive and does not estimate the independent effect of AI on the visitor experience.

3.1. *Population and sample*

The study population was Umrah pilgrims visiting Makkah during Ramadan 1447 AH (2026). The survey included 400 respondents. Their gender, age and reported residence or origin are summarised in Table 1. The results describe these respondents and are not presented as population estimates.

4. Findings

4.1. *Measures and interpretation*

The questionnaire covered use of digital media and smart services, interaction with AI-related applications, guidance and navigation, perceived benefits for the visitor experience, intentions to continue using the services, and technical and human difficulties. Proficiency and experiences were self-reported.

The results below present frequencies and percentages for participant characteristics and reported use, together with the reported item means. Where a relative percentage accompanies an item mean, it equals the mean divided by 5 and multiplied by 100. Such percentages describe the item score and are distinct from the percentage of respondents using a service.

All 400 respondents reported using the digital services covered by the questionnaire. Of the sample, 48.5% described their proficiency as high. These responses concern a combined set of digital and AI-related services; they do not establish that every respondent used a separate AI system.

4.2. *Participant characteristics*

The sample comprised 250 men (62.5%) and 150 women (37.5%). The largest age group was under 25 years (30.5%), followed by 35 to under 45 years (28.0%). Pilgrims from South and East Asia formed 35.3% of the sample, while domestic pilgrims formed 33.5%.

Table 1 Participant characteristics (n = 400)

		Respondents	
Variables	Categories	n	%
Gender	Male	250	62.5
	Female	150	37.5
Age	Under 25 years old	122	30.5
	25 to under 35 years old	106	26.5
	35 to under 45 years old	112	28.0
	45 to under 55 years old	52	13.0
	55 years and over	8	2.0
Reported residence or origin	Domestic pilgrims from within the Kingdom	134	33.5
	Pilgrims from Arab countries	73	18.3
	Pilgrims from non-Arab African countries	30	7.5
	Pilgrims from European countries, America, and Australia	22	5.5
	Pilgrims from South and East Asia	141	35.3

5. Discussion

5.1. *Digital-service use and visitor perceptions*

Participants reported using the digital services included in the survey, although their self-rated proficiency varied. The 48.5% who rated their proficiency as high should not be taken to represent all pilgrims or to demonstrate proficiency through an independent test. The findings support providing practical assistance alongside digital services.

For current use of digital media and smart services, reported item means ranged from 2.96 to 3.51, with an overall mean of 3.15.

Smart applications received a mean score of 4.09, equivalent to 81.8% of the maximum score of 5. Chatbot services on Nusuk or other platforms received 3.93 (78.6%), followed by phone voice assistants at 3.88 (77.6%). These are ratings of the survey items, not the proportions of respondents who used each application. The term smart application also covers digital functions that may not rely on AI.

Items concerning guidance and navigation had means ranging from 3.68 to 4.21, with an overall mean of 3.95.

Participants therefore rated these functions more highly than the current-use dimension, whose reported overall mean was 3.15. The comparison concerns the reported scores and does not show that one technology caused a better experience.

Awareness of religious and historical landmarks received a mean score of 4.13 (82.6% of the maximum score), followed by perceived reductions in the time needed to complete procedures at 4.07 (81.4%) and perceived service-quality improvements at 3.97 (79.4%). The item on the spiritual and religious experience received 3.91 (78.2%). These results describe perceived benefits; they do not measure actual time savings or changes in service performance.

Intentions to continue using smart services had item means ranging from 3.73 to 4.05, with an overall mean of 3.86. Intentions reported in a survey may differ from later behaviour and should not be interpreted as evidence of long-term use.

The most highly rated challenge was information overload or distraction from frequent digital notifications, with a mean of 3.87 (77.4% of the maximum score). Login and password-recovery difficulties ranked second in the reported results. Concerns about the timeliness of digital information followed, with a mean of 3.79 (75.8%). These findings suggest that reducing friction in routine use deserves attention alongside adding new functions.

5.2. *Recommendations*

The following recommendations are proposed improvements to visitor services. They require assessment of accessibility, feasibility and privacy before implementation.

Simplify interfaces and provide multilingual help. Clear icons, adjustable text size and voice guidance can support visitors who have difficulty with text-heavy applications. Service providers should test these options with pilgrims from different language and age groups.

Provide support at points where visitors need it. Trained staff or volunteers at transport hubs, accommodation and visitor-service locations could help with registration, login and navigation. Assistance should remain available to visitors who cannot use digital tools independently.

Reduce information overload and improve the timeliness of guidance. Service providers could prioritise essential notifications and distinguish verified current information from general advice. Offline maps and clear signs could complement mobile applications when connectivity is limited.

Evaluate proposed navigation and AI functions before wider use. Voice assistance, translation and augmented-reality navigation may be useful, but trials should examine accuracy, usability and the needs of visitors with limited digital proficiency. The present survey does not establish the performance of these proposed functions.

Offer optional digital guidance before arrival. Travel operators and visitor-service providers could distribute short multilingual instructions and audio guides for essential services. Visitors should also have access to personal assistance.

Monitor service problems through user feedback. Analysis of complaints and routine service interactions could help identify login problems, confusing guidance and excessive notifications. Such monitoring should limit the collection of personal information and use appropriate privacy safeguards.

6. Limitations and implications

6.1. *Limitations*

This cross-sectional survey describes self-reported use and perceptions at one point in time. It cannot establish causal effects of digital media or AI on the visitor experience. The combined treatment of digital platforms and AI-related services also prevents a separate estimate of AI's contribution.

The sample consists of 400 Umrah pilgrims in Makkah during Ramadan 1447 AH. Visitors in other seasons or settings may face different crowd conditions, services and connectivity. The demographic distribution of the sample does not establish that it represents all pilgrims.

Self-reported proficiency and perceived benefits are subject to differences in experience and interpretation. The survey does not independently test digital skills, application accuracy, actual time savings or service performance. It also provides no basis here for reliable comparisons between age or nationality groups.

The reported item means describe the selected questionnaire dimensions. Without a common validated measurement framework, differences between those dimensions should be interpreted cautiously. These results provide descriptive evidence for service improvement rather than a causal model of smart-city performance.

6.2. *Policy implications and contribution*

The findings draw attention to the practical conditions under which visitors use digital services. Participants reported benefits for guidance and awareness, while also identifying information overload, account access and the timeliness of information as concerns. Service development should address these routine difficulties as well as introducing new features.

Accessible interfaces, multilingual instructions and personal assistance are relevant priorities for pilgrim-service providers. The survey supports considering these options, but it does not determine which specific intervention would be most effective. Pilot evaluations could compare proposed improvements before wider deployment.

The study contributes a descriptive account of visitor experiences in Makkah. Its focus on use, self-rated proficiency and practical difficulties complements research concerned with smart-city infrastructure and governance. The findings relate to this sample of 400 pilgrims and should be assessed within that scope.

6.3. *Future research*

Longitudinal research could examine how pilgrims' use and perceptions change across visits and seasons. Such work could distinguish continued use from intentions expressed during a single survey.

Mixed-method studies could combine questionnaires with interviews or observed service tasks. These approaches would help explain difficulties with accounts, language, navigation and notifications.

Comparative studies could use consistent measures across Makkah, Madinah and other visitor settings. Researchers should define the sampling frame and record the digital services used, distinguishing AI functions from other application features.

Further research could examine visitors with lower digital proficiency and those who need language or accessibility support. Validated measures and clearly reported sampling procedures would support more reliable comparisons between groups.

Trials of translation, voice assistance and augmented-reality navigation could assess task completion, accuracy and visitor satisfaction. Evaluations should also consider privacy and the availability of non-digital assistance.

7. Conclusion

This survey examined digital media, AI-related applications and smart services through the self-reported experiences of 400 Umrah pilgrims in Makkah during Ramadan 1447 AH. All respondents reported using the digital services covered by the questionnaire, and 48.5% rated their proficiency as high.

Participants reported benefits for guidance, awareness of landmarks and completion of procedures. Smart applications received a mean score of 4.09 out of 5, while the guidance and navigation dimension had an overall mean of 3.95. Information overload, account access and the timeliness of information remained practical concerns.

These findings describe the views of the surveyed pilgrims. They do not establish causal effects, demographic differences or an independent contribution of AI. The practical implication is to consider accessible digital services and personal support together, and to evaluate proposed improvements through further research.

Declarations

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References

Al Jaafreh, M. B., & Allouzi, M. A. (2023). Smart cities adoption in Saudi Arabia: A comprehensive review and future drivers. British Journal of Multidisciplinary and Advanced Studies, 4(5), 20–39. https://doi.org/10.37745/bjmas.2022.0300

Al-Bari, E. S. A., Alrikabi, N. K., Alwan, K. H., & Saadoon, R. A. (2025). Digitization of cities and its impact on city sustainability. International Journal of Sustainable Development and Planning, 20(3), 1317–1325. https://doi.org/10.18280/ijsdp.200337

Aldegheishem, A. (2023). Assessing the progress of smart cities in Saudi Arabia. Smart Cities, 6(4), 1958–1972. https://doi.org/10.3390/smartcities6040091

Alhazmi, Y., Turkistani, Y., Alharbi, S., Almalki, A., Alotaibi, A., Alotaibi, N., & Alotibi, M. (2025). Optimal design of electric vehicle battery swap charging station for smart cities in Saudi Arabia. In 2025 2nd International Conference on Advanced Innovations in Smart Cities (ICAISC) (pp. 1–7). IEEE. https://doi.org/10.1109/ICAISC64594.2025.10959629

Aliyari, M. (2025). The role of digital technologies (Internet of Things and artificial intelligence) in the development of smart cities and sustainable logistics. International Journal of Modern Achievement in Science, Engineering and Technology, 2(4), 77–89. https://doi.org/10.63053/ijset.115

Allen, B., Tamindael, L. E., Bickerton, S. H., & Cho, W. (2020). Does citizen coproduction lead to better urban services in smart cities projects? An empirical study on e-participation in a mobile big data platform. Government Information Quarterly, 37(1), 101412. https://doi.org/10.1016/j.giq.2019.101412

Almulhim, A. I., & Aina, Y. A. (2025). Achieving human-centered smart city development in Saudi Arabia. Urban Science, 9(10), 393. https://doi.org/10.3390/urbansci9100393

Almulhim, A. I., & Cobbinah, P. B. (2023). Can rapid urbanization be sustainable? The case of Saudi Arabian cities. Habitat International, 139, 102884. https://doi.org/10.1016/j.habitatint.2023.102884

Alotaibi, A., Alsubaie, D., Alaskar, H., Alhumaid, L., Thuwayni, R. B., Alkhalifah, R., & Alhumoud, S. (2022). Kingdom of Saudi Arabia: Era of smart cities. In 2022 2nd International Conference on Computing and Information Technology (ICCIT) (pp. 285–292). IEEE. https://doi.org/10.1109/ICCIT52419.2022.9711548

Alotaibi, B. S., Elnaklah, R., Agboola, O. P., Abuhussain, M. A., Tunay, M., Dodo, Y. A., Maghrabi, A., & Alyami, M. (2025). Enhancing Najran's sustainable smart city development in the face of urbanization challenges in Saudi-Arabia. Journal of Asian Architecture and Building Engineering, 24(4), 2905–2935. https://doi.org/10.1080/13467581.2024.2358203

Alwafi, A. A. M. (2025). Climate change as an influential factor in designing future cities (case study the NEOM Project "The line city" in Saudi Arabia). Journal of Umm Al-Qura University for Engineering and Architecture, 16(2), 237–251. https://doi.org/10.1007/s43995-025-00103-6

Bahreldin, I., Samir, H., Maddah, R., Hammad, H., & Hegazy, I. (2025). Leveraging advanced digital technologies for smart city development in Saudi Arabia: Opportunities, challenges, and strategic pathways. International Journal of Low-Carbon Technologies, 20, 834–847. https://doi.org/10.1093/ijlct/ctaf044

Balbaid, M. S., & Al-Dahwi, H. A. (2024). The readiness of Makkah Al-Mukarramah to transform into a smart city [in Arabic]. Arab Journal for Scientific Publishing, 7(74), 451–504.

Belaïd, F., & Arora, A. (Eds.). (2024). Smart cities: Social and environmental challenges and opportunities for local authorities. Springer. https://doi.org/10.1007/978-3-031-35664-3

Ben Rjab, A., & Mellouli, S. (2019). Artificial intelligence in smart cities: Systematic literature network analysis. In Proceedings of the 12th International Conference on Theory and Practice of Electronic Governance (pp. 259–269). ACM. https://doi.org/10.1145/3326365.3326400

Bennoui, A. (2021). Smart cities: International and Arab achievements and experiences [in Arabic]. Journal of Social Empowerment, 3(4), 16–33. https://www.asjp.cerist.dz/en/article/170713

Brown, P. D., & Patten, L. (2024). Smart cities: Characteristics, impact, and future with generative artificial intelligence. Journal of International Business Disciplines, 19(2), 21–35. https://faculty.utrgv.edu/louis.falk/jibd/JIBDnov24.pdf

Chipriyanov, M. (2025). Management of public-private partnerships for smart city projects. Economic Archive, 78(4). https://doi.org/10.58861/tae.ea-nsa.2025.4.01.en

Doheim, R. M., Farag, A. A., & Badawi, S. (2019). Smart city vision and practices across the Kingdom of Saudi Arabia: A review. In A. Visvizi & M. D. Lytras (Eds.), Smart cities: Issues and challenges (pp. 309–332). Elsevier. https://doi.org/10.1016/B978-0-12-816639-0.00017-X

Kotarba, M., & Zawiła-Niedźwiedzki, J. (2025). The "Smart City": A functional model and digital intelligence in Europe's Digital Decade 2030. Politeja, 22(5[99]), 95–130. https://doi.org/10.12797/Politeja.22.2025.99.04

Kummitha, R. K. R. (2025). Smart city governance: Assessing modes of active citizen engagement. Regional Studies, 59(1), 2399262. https://doi.org/10.1080/00343404.2024.2399262

Mohanty, A., Mohanty, S., Satapathy, A. S., Soudagar, M. E. M., Shahapurkar, K., & Cuce, E. (2025). Empowering smart city through smart grid communication and measurement technology. International Journal of Low-Carbon Technologies, 20, 404–420. https://doi.org/10.1093/ijlct/ctae224

Okonta, D. E., & Vukovic, V. (2024). Smart cities software applications for sustainability and resilience. Heliyon, 10(12), e32654. https://doi.org/10.1016/j.heliyon.2024.e32654

Pivar, J. (2025). Determinants of big data technology adoption in smart cities of European Union. Interdisciplinary Description of Complex Systems, 23(6), 732–759. https://doi.org/10.7906/indecs.23.6.9

Shao, J., & Min, B. (2025). Sustainable development strategies for smart cities: Review and development framework. Cities, 158, 105663. https://doi.org/10.1016/j.cities.2024.105663

Smalec, A. (2025). Smart cities, smart governance: The role of communication and social participation in building cities of the future. Scientific Papers of Silesian University of Technology. Organization and Management Series, 227, 355–365. https://doi.org/10.29119/1641-3466.2025.227.27

Szymańska, A. I. (2025). Using artificial intelligence in the development of sharing smart cities: The Generation C perspective. Scientific Papers of Silesian University of Technology. Organization and Management Series, 229, 503–519. https://doi.org/10.29119/1641-3466.2025.229.29

Tong, L., & Amalia Rivai, F. (2025). The applications of the internet of things in smart cities governance: A bibliometric study. Innovation: The European Journal of Social Science Research, 38(3), 1294–1310. https://doi.org/10.1080/13511610.2024.2387594

Wang, H.-J. (2025). Factors that influence adoption intentions toward smart city services among users. Information Technology and Management, 26(4), 609–623. https://doi.org/10.1007/s10799-024-00429-y

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REVIEW ARTICLE

Artificial Intelligence and the Internet of Things for Sustainable Waste Management

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ABSTRACT

Urbanisation and rising consumption increase the demands placed on waste services in the Middle East and North Africa (MENA). This study examines how artificial intelligence (AI) and the Internet of Things (IoT) can support waste collection and material recovery within a circular economy. It uses a qualitative narrative review of selected academic and institutional sources, with regional examples and comparative evidence from outside MENA. The analysis distinguishes sensor-based monitoring, route optimisation and image classification from wider claims about environmental performance. Published studies report potential operational gains, but their results depend on the system, setting and evaluation method. In particular, the TUHR system for Makkah is a proposed and developed system with limited testing under actual operating conditions, rather than evidence of citywide deployment. The review also considers the energy and material requirements of digital equipment, privacy and the role of workers. AI and IoT can support more responsive waste services, but their net contribution to sustainability requires local evaluation, reliable data and accountable governance.

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1. Introduction

Urbanisation and changing consumption patterns increase the volume and complexity of waste that municipalities must manage. Waste services need to protect public health while supporting waste prevention and material recovery. Kaza et al. (2018) describe the global scale of this challenge and the differences between waste systems across countries.

The World Bank (2026) estimates that MENA generates about 155 million tonnes of municipal solid waste annually, with volume projected to reach 294 million tonnes by 2050 without further action. It reports less than 10% recycling, substantial mismanagement and annual environmental damage of about USD 7.2 billion. These figures concern municipal solid waste and should be distinguished from national accounts covering waste from all economic activities.

The central question is: How can AI and IoT support waste-management services relevant to the circular economy in MENA, and what conditions limit their environmental and social benefits?

Three analytical propositions guide the review:

P1: IoT monitoring can reduce gaps in information about waste volumes and collection needs when actors share accurate, timely data.

P2: Combining sensor data with prediction and optimisation can improve collection and sorting, with benefits that depend on local operating conditions.

P3: The environmental and social value of digital waste systems depends on governance that addresses equip-

ment, energy, data and worker impacts.

The review pursues the following objectives:

To examine how AI and IoT can support information sharing and coordination across waste collection and recovery activities.

To assess reported operational gains while distinguishing proposals, simulations and field evaluations, and separating regional evidence from examples outside MENA.

To consider technical constraints, material and energy requirements, and questions of privacy and inclusion when proposing governance priorities.

The discussion links these objectives to the circular economy, responsible digital practice and the twin transition, understood here as the coordination of digital development with environmental goals.

2. Review approach and conceptual framework

This study uses a qualitative narrative review of selected research papers, institutional reports and documented regional initiatives. The sources span 2016-2026. The synthesis compares the functions, reported outcomes and limitations of digital waste systems; it does not pool effect sizes or present an exhaustive systematic review. Regional statistics provide context, while the technical examples illustrate different levels of evidence. The three propositions organise the discussion and are not statistically tested hypotheses.

2.1. *From the linear economy to circular resource use*

The circular economy seeks to retain the value of products and materials through prevention, reuse, repair and recycling. Ghisellini et al. (2016) review its principles and implementation across different scales. Digital tools may assist coordination, but circular practices also require appropriate product design, collection arrangements and markets for recovered materials.

Özsoy (2023) reviews potential AI applications in resource management and circular business models. Prediction and classification may support decisions about maintenance, recovery and material flows. These are possible applications rather than proof that AI adoption automatically produces circular outcomes.

2.2. *Responsible digital practice and organisational accountability*

Corporate social responsibility provides a framework for considering stakeholder interests alongside organisational performance. Grünfelder and Delalieux (2023) discuss responsible practices, including the digital context. For waste operators, this perspective includes the effects of sensors, software and automation on workers, service users and the environment.

Traceable records can support sustainability reporting, but their value depends on data quality and clear responsibility for collection and verification. Cigref (2026) discusses these governance issues in its report on digital departments and sustainability reporting. Digital records alone do not establish regulatory compliance or the accuracy of an environmental claim.

2.3. *The twin transition*

The twin transition concerns the relationship between digital development and environmental objectives. The OECD (2024) identifies opportunities for digital technologies to support environmental performance while recognising their own environmental footprint.

For waste management, the relevant question is whether operational gains outweigh the impacts of equipment manufacture, communications, computation and disposal. A useful assessment therefore considers the whole service and its life cycle rather than treating digitalisation as an environmental benefit in itself.

Table 1 maps selected circular-economy objectives to possible digital functions. It presents conceptual links rather than measured effects or guaranteed performance thresholds.

Table 1 Circular economy objectives and possible digital functions

Circular economy objective	Digital function	Potential contribution
Product and service design	Digital twins and simulation	Compare options for resource use before implementation
Longer equipment life	Condition monitoring and predictive maintenance	Identify maintenance needs and avoid preventable replacement
Collection planning	Fill-level sensors and route optimisation	Reduce unnecessary visits where local evaluation supports a change
Material sorting	Computer vision and validated sensing	Assist identification and separation; output quality requires measurement
Material-flow traceability	Shared digital records, including blockchain where appropriate	Improve records for verification; accuracy depends on physical checks and data quality

Source: Author synthesis based on Ghisellini et al. (2016), Özsoy (2023) and Kannan et al. (2024). The contributions are potential benefits that require evaluation in the intended setting.

3. Technological architecture of smart waste management

3.1. *Sensing and connectivity*

IoT devices can provide operators with observations about bins and collection vehicles. Systems described in the literature combine sensors, communication links and a platform for storing or displaying data (Abdullah et al., 2022; Al Qurashi et al., 2026). Their practical value depends on calibration, maintenance and reliable communication.

Ultrasonic sensors estimate fill level from the distance between the sensor and the waste surface. Irregular contents can affect the reading, so a volume estimate should not be treated as a direct measurement of waste mass.

Cameras and other sensors may support material identification or contamination checks. Performance depends on the materials, lighting and sensing method, and the classification requires validation against labelled observations.

Location devices can support the tracking of vehicles and bins. Operators can combine these observations with collection records when planning routes.

Communication options include low-power wide-area networks and cellular connections. Addas et al. (2024) describe a LoRaWAN and cellular architecture. Network choice should reflect coverage, battery requirements and cost. Billing by weight or volume would also require suitable measurement and service rules; a digital bin identifier alone does not make charging more equitable.

3.2. *Analysis and optimisation*

Sensor data can support two related tasks: planning collection and identifying materials. Prediction estimates future conditions, while route optimisation selects collection plans subject to constraints such as vehicle capacity and service priorities. These functions need not all use the same form of AI.

Algorithms can use current fill levels and collection histories to prioritise bins and calculate routes. Kannan et al. (2024) review Industry 4.0 applications across waste-management activities and propose a framework connecting technologies, processes and circular strategies.

Computer vision can assist image-based classification for sorting. A high image-classification score, however, is distinct from the purity or recovery rate of a physical output stream. Evaluation should examine the actual materials, contamination and sorting equipment rather than transfer a model score to an entire facility (Kannan et al., 2024).

3.3. *Digital twins and traceability*

Digital twins can represent parts of a waste system for scenario analysis, such as changes in collection frequency or facility use. Their usefulness depends on whether the underlying model and data represent operating conditions. A simulation cannot establish the outcome of an investment before that outcome is observed.

Digital records, including blockchain-based systems, may help actors share a history of material movements. Their integrity still depends on accurate entries and verification of physical flows. A ledger cannot by itself guarantee the origin of materials, prevent false reporting or prove that recycling has occurred (Kannan et al., 2024).

4. Regional examples and waste-sector context

4.1. *Saudi Arabia and the Makkah examples*

Saudi Arabia's General Authority for Statistics (GASTAT, 2025) reports 135.1 million tonnes of recorded waste in 2024, covering economic activities and households. This total is broader than municipal waste. Separately, the national waste-management plan includes a target to divert 90% of waste from landfill by 2040 (Saudi Press Agency, 2025). Diversion is a wider objective than material recycling, and the target describes a policy ambition.

Table 2 Selected categories in Saudi recorded waste accounts for 2024

Classification	Selected category	Quantity (million tonnes)	Share of recorded total (%)
Economic activity / households	Agriculture, forestry and fishing	46.9	34.7
Economic activity / households	Construction	32.2	23.8
Economic activity / households	Households	20.5	15.2
Economic activity / households	Manufacturing	18.3	13.5
Waste type	Organic waste	61.7	45.7
Waste type	Plastic waste	7.8*	5.8

*Source: GASTAT (2025), Waste Statistics in Saudi Arabia 2024. Shares use the recorded total of 135.1 million tonnes; values are rounded. The selected categories are not exhaustive. Classification by economic activity and classification by waste type describe the same overall total from different perspectives and must not be added together. *The plastic-waste quantity is calculated from 135.1 million tonnes multiplied by the reported 5.8% share and rounded to one decimal place.*

Al Qurashi et al. (2026) present TUHR, a smart waste-management system designed for Makkah. It combines sensor observations with a cloud platform and interfaces for collection staff and administrators. The authors describe difficulties obtaining real-world data and identify testing in actual operating conditions as further work. TUHR therefore illustrates system development and feasibility rather than a demonstrated citywide operational effect.

Abdullah et al. (2022) evaluate collection scenarios through C++ and MATLAB simulation with randomly assigned bin conditions. Their abstract reports a 46% reduction in locations and bins requiring visits under the simulated conditions. The paper also describes a separate infrastructure approach in Makkah: pneumatic transport through a 30 km underground network with capacity to move 600 tonnes per day. This background example illustrates transport capacity, while the simulation examines collection decisions. Table 2 presents the national statistical context.

4.2. *Other regional examples*

In Abu Dhabi, TWMA (2025) reports the start of operations at its Habshan drill-cuttings treatment facility. The operator describes a design capacity of up to 300 tonnes per day and real-time tracking and analytics through its Xlink platform. This is an industrial-waste example. Design capacity is not the same as measured daily throughput, and the operator announcement does not establish a separate causal effect of AI.

Qatar News Agency (2023) describes government initiatives for sorting at source and the recovery of waste through recycling, energy production and composting. These pathways have different outputs and environmental implications. Their treatment together in policy statements should not be interpreted as a material-recycling rate or as evidence that AI caused the reported progress.

5. Economic and environmental implications

5.1. *Reported operational gains and their interpretation*

Addas et al. (2024) report a pilot involving 10 locations in Lahore, Pakistan. Their published results include a 32% reduction in route distance, 29% lower fuel consumption and 18% lower vehicle-maintenance costs relative to conventional practices. The study combines sensor monitoring with route simulation. These source-reported results provide comparative evidence from outside MENA, with transferability requiring evaluation in the intended setting. Separately, the World Bank (2026) estimates that a 1% reduction in MENA waste generation could save up to USD 150 million annually. This regional scenario concerns waste prevention rather than the effect of a particular digital system.

Material recovery may create revenue when operators can supply suitable materials to buyers. The size of the market provides context rather than a return-on-investment estimate for a particular technology. Grand View Research (2025) estimates the Middle East waste-management market at USD 58.06 billion in 2024 and forecasts USD 104.05 billion by 2033. This is a commercial forecast for the market defined in that report, not an observed outcome or evidence that AI alone drives growth.

5.2. *Work and inclusion*

The World Bank (2026) reports around 400,000 formal workers in the regional solid-waste sector and at least as many informal workers. Digital systems may change the skills and tasks required, including equipment maintenance and data management. The review does not estimate net job creation or displacement.

Planning should consider how informal waste workers can participate in collection and recovery arrangements. Training, access to information and consultation can support this process, but digital registration alone does not secure income or remove exclusion. The effects on different worker groups require local evidence.

5.3. *Environmental performance*

Fewer vehicle kilometres may reduce fuel use, while improved sorting may support material recovery. Net environmental performance also depends on treatment choices, equipment and electricity use. The different measures should be assessed separately; a reduction in fuel consumption does not by itself establish the same percentage reduction in the life-cycle footprint of the waste service (OECD, 2024).

6. Environmental and ethical constraints

6.1. *Materials and equipment*

Digital waste systems require physical devices, communications equipment and computing infrastructure. Izoard (2024) examines the material demands of technologies associated with the transition and the impacts of mineral extraction. Assessing a digital waste service therefore requires attention to the equipment supply chain as well as operations.

Equipment life, repairability and end-of-life management affect the material demands of a system. Reuse and recycling of devices may reduce some impacts, but they do not create a fully closed material loop. Operators should consider whether a proposed function justifies additional hardware.

6.2. *Energy use and the footprint of computation*

The energy requirements of computing vary with the model, workload and infrastructure. The Shift Project (2025) examines AI, data and computing infrastructure in relation to decarbonisation. For a waste-management service, evaluation should identify the workload attributable to the application and the infrastructure supporting it.

Possible design choices include simpler models, reduced data transfers and processing near the sensor. These choices require evaluation: moving computation to the edge does not automatically reduce the total environ-

mental footprint. Comparisons should include the relevant equipment, communication and processing requirements.

6.3. *Privacy and algorithmic accountability*

Cameras, location records and identifiable service data can affect privacy. Operators should define the purpose of collection, limit access and retention, and apply the requirements of the relevant jurisdiction.

Route-planning systems can also reproduce inequalities if their objectives or input data favour some districts. Evaluation should check service coverage and waiting times across neighbourhoods. Human oversight and a way to challenge errors are relevant safeguards when algorithmic recommendations affect public services.

7. Governance and public policy

7.1. *Coordination across stakeholders*

Implementing digital waste services requires agreement on service goals, responsibilities and the handling of data. The following roles provide a basis for coordination:

Public authorities can define service obligations, reporting requirements and procurement conditions, with attention to the capabilities of local operators.

Private providers can supply equipment, software and operational services. Contracts should make maintenance, interoperability and performance responsibilities clear.

Universities and research organisations can assist with skills development and independent evaluation, including life-cycle assessment.

Workers, service users and community organisations can help identify access problems, practical constraints and priorities for service improvement.

7.2. *Digital records and regulatory capacity*

Digital tracking can improve the availability of records for inspections and service planning. Authorities still need procedures for checking data, investigating discrepancies and acting on findings. An electronic record should support oversight rather than substitute for verification of physical waste movements.

Regional cooperation can assist the exchange of experience and the development of compatible data definitions. Any cross-border waste arrangements also require attention to the applicable national and international requirements. The review does not propose a single regulatory model for all MENA countries.

8. Discussion

8.1. *Interpretation of the evidence*

The reviewed sources show several ways to connect waste observations with operational decisions. They cover different activities and levels of development, so their findings should not be combined into a single estimate of AI and IoT performance across MENA.

The distinction between system design and measured outcomes is central. A prototype can demonstrate communication between components; a simulation can examine a routing rule under stated assumptions. Evidence of service performance requires observations under actual operating conditions.

For collection, the Lahore pilot provides a reported operational example, while the Makkah simulation examines a proposed collection strategy (Addas et al., 2024; Abdullah et al., 2022). Their percentages refer to different outcomes and settings. A reduction in stops, a shorter route and lower fuel use are related possibilities, but they are not interchangeable measures and cannot be multiplied or pooled without a common design.

For recovery, image classification is one part of the sorting process. Feedstock quality, physical separation and markets for recovered materials also matter. The review provides no common basis for claiming a universal classification accuracy or recycled-material purity.

The regional examples underline the need to distinguish treatment capacity from demonstrated improvements in collection and recovery. Operational trials in high-density settings would strengthen the evidence on scalability and service performance.

8.2. *Implications for the analytical propositions*

The sources provide grounds for considering the three propositions, with different strengths of evidence for each. The review does not conduct a statistical or experimental test.

The following interpretations follow from the synthesis:

P1 identifies a plausible information mechanism: sensors can make collection needs more visible. Reliability and data sharing remain conditions for that mechanism to work. The simulation reported by Abdullah et al. (2022) illustrates this approach under assigned bin conditions; field observations would help assess its practical effect.

P2 concerns potential operational improvements. Source-reported gains in a particular setting support further evaluation, but they do not establish a common regional effect or prove the independent contribution of AI within a combined system.

P3 directs attention to governance and the digital system's own impacts. The energy, equipment and stakeholder issues discussed here justify including these dimensions in evaluation, without treating the proposition as empirically validated.

The practical implication is to assess whether a digital system improves the intended waste service at an acceptable environmental and social cost. The appropriate balance may differ between municipalities and waste streams.

9. Limitations and directions for research

9.1. *Limitations*

This narrative review brings together selected sources and examples. It does not provide an exhaustive search protocol, a formal risk-of-bias assessment or a pooled effect estimate. Selection and publication bias may therefore affect the evidence presented.

The regional examples concern particular national or urban settings, while the Lahore study provides comparative evidence outside MENA. These examples cannot represent the conditions of every municipality, especially rural or lower-resource services.

The quantitative claims are secondary, source-reported results. The underlying methods differ, including simulation, pilot monitoring and operator reporting. The review does not independently reproduce those studies, and their figures cannot establish an average regional benefit. National all-waste accounts, regional municipal-waste estimates and commercial market forecasts also have different scopes.

The study does not calculate a complete life-cycle assessment of sensors, communications and computing. It therefore cannot quantify the net environmental benefit of a particular deployment. Long-term evidence on equipment failure, service coverage and worker outcomes is also needed.

9.2. *Policy implications*

The review links information gaps in waste services with circular-economy aims and responsible digital practice. Its contribution is a conceptual synthesis and an account of the limits of the available examples rather than a newly validated performance model.

The following priorities follow from that analysis:

Interoperability and maintenance: Specify data formats, interfaces and maintenance responsibilities before procurement. Select communication technologies according to local coverage and service needs rather than assuming that one protocol fits all settings.

Environmental procurement: Consider equipment life, repairability, electricity demand and end-of-life treatment when comparing bids. Require suppliers to document the assumptions behind environmental claims.

Worker and community participation: Combine technical trials with consultation and support for source separation. Evaluate participation and access without assuming that awareness campaigns will produce a particular sorting-accuracy percentage.

Performance monitoring: Compare the system with a documented baseline and report route distance, fuel, recovery and service coverage as separate measures. Include the relevant digital infrastructure when evaluating net environmental effects.

9.3. *Future research*

Further work should address the following areas:

Long-term field evaluation: Compare service performance before and after deployment, or use suitable comparison areas. Record waste volumes, route conditions, equipment downtime and costs to support an assessment of operational resilience and return on investment.

Life-cycle assessment: Compare operational savings with equipment manufacture, energy use, communications and end-of-life treatment. Use local data rather than importing a percentage from an unrelated pilot.

Governance and distribution: Examine data ownership, privacy, service coverage and effects on formal and informal workers. Test how consultation and contract arrangements influence outcomes.

10. Conclusion

AI and IoT can support the monitoring, planning and analysis of waste services, but sustainability depends on how they are used. This review distinguishes source-reported pilot results, simulations and proposed systems from regional waste statistics and policy ambitions. The evidence supports targeted evaluation of collection and recovery functions; it does not establish a universal percentage benefit or confirm the three analytical propositions. For MENA, deployment decisions should consider local service needs, reliable data, equipment and energy demands, and the people who operate and use the system.

Declarations

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References

Abdullah, N., Al-wesabi, O. A., Mohammed, B. A., Al-Mekhlafi, Z. G., Alazmi, M., Alsaffar, M., Baklizi, M., & Sumari, P. (2022). IoT-based waste management system in formal and informal public areas in Mecca. International Journal of Environmental Research and Public Health, 19(20), 13066. https://doi.org/10.3390/ijerph192013066

Addas, A., Khan, M. N., & Naseer, F. (2024). Waste management 2.0 leveraging internet of things for an efficient and eco-friendly smart city solution. PLOS ONE, 19(7), e0307608. https://doi.org/10.1371/journal.pone.0307608

Al Qurashi, R. S., Almanjumi, M. M., Alghamdi, T. L., Almalki, A. H., Alharthi, S. S., Althobuti, S. M., Alharthi, A. S., & Thafar, M. A. (2026). Smart waste management system for Makkah City using artificial intelligence and Internet of Things. In D. Berkouk, U. Chatterjee, T. A. Bouzir, I. B. Dhaou, & S. Altarteer (Eds.), Proceedings of the 2nd International Conference on Creativity, Technology, and Sustainability (pp. 56–65). Springer. https://doi.org/10.1007/978-981-95-7607-4_7

Cigref. (2026). Mise en œuvre de la Corporate Sustainability Reporting Directive (CSRD): Enjeux et perspectives pour les directions numériques. https://www.cigref.fr/wp/wp-content/uploads/2026/01/Rapport-Mise-en-oeuvre-de-la-Corporate-Sustainability-Reporting-Directive-CSRD-janvier-2026-Cigref.pdf

General Authority for Statistics. (2025, December 30). GASTAT publishes Waste Statistics in Saudi Arabia 2024. https://stats.gov.sa/en/w/news/148

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. Journal of Cleaner Production, 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Grand View Research. (2025). Middle East waste management market size, share & trends analysis report, 2025–2033. https://www.grandviewresearch.com/industry-analysis/middle-east-waste-management-market-report

Grünfelder, S., & Delalieux, G. (Eds.). (2023). RSE: Responsabilité sociale des entreprises: Parties prenantes et outils. Dunod. https://www.dunod.com/entreprise-et-economie/rse-responsabilite-sociale-entreprises-parties-prenantes-et-outils

Izoard, C. (2024). La ruée minière au XXIe siècle: Enquête sur les métaux à l'ère de la transition. Seuil.

Kannan, D., Khademolqorani, S., Janatyan, N., & Alavi, S. (2024). Smart waste management 4.0: The transition from a systematic review to an integrated framework. Waste Management, 174, 1–14. https://doi.org/10.1016/j.wasman.2023.08.041

Kaza, S., Yao, L., Bhada-Tata, P., & Van Woerden, F. (2018). What a waste 2.0: A global snapshot of solid waste management to 2050. World Bank. https://doi.org/10.1596/978-1-4648-1329-0

OECD. (2024). Digital technologies and the environment. In OECD digital economy outlook 2024 (Volume 2). OECD Publishing. https://www.oecd.org/en/publications/oecd-digital-economy-outlook-2024-volume-2_3adf705b-en/full-report/digital-technologies-and-the-environment_c0701b0b.html

Özsoy, T. (2023). The role of artificial intelligence in facilitating the transition to a circular economy. İstanbul Nişantaşı Üniversitesi Sosyal Bilimler Dergisi, 11(2), 369–389. https://doi.org/10.52122/nisantasisbd.1345828

Qatar News Agency. (2023, May 10). Ministers of municipality, environment outline Qatar's efforts in establishing culture of sustainability and waste recycling. https://qna.org.qa/en/news/news-details?date=10%2F05%2F2023&id=0082-ministers-of-municipality%2C-environment-outline-qatar%27s-efforts-in-establishing-culture-of-sustainability-and-waste-recycling

Saudi Press Agency. (2025, November 13). MWAN completes the comprehensive strategic plan covering all regions of the Kingdom [In Arabic]. https://www.spa.gov.sa/N2443168

The Shift Project. (2025). IA, données, calcul: Quelles infrastructures dans un monde décarboné? (October 2025 report). https://theshiftproject.org/app/uploads/2025/09/RF-PIA.pdf

TWMA. (2025, December 16). Introducing a new era of drill cuttings treatment in the UAE. https://twma.com/news/twma-introduces-a-new-era-of-drill-cuttings-treatment-in-the-uae

World Bank. (2026). Waste management in the Middle East and North Africa. https://www.worldbank.org/en/region/mena/publication/waste-management-in-the-middle-east-and-north-africa

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REVIEW ARTICLE

Redefining Internal Audit Competencies through AI and Digital Transformation in the MENA Region

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ABSTRACT

Research aims: This study examines how artificial intelligence (AI) and digital transformation are changing internal audit competencies in the MENA region.

Design/Methodology/Approach: The study uses an exploratory qualitative approach based on thematic analysis of 13 selected empirical journal articles published between 2021 and 2025. The studies were reviewed to identify recurring competency requirements and challenges, which were grouped into four domains and interpreted through the resource-based view (RBV).

Research findings: The synthesis identifies digital competencies, cybersecurity and IT risk management, communication and reporting, and organisational adaptability as recurring competency domains. The reviewed studies describe opportunities associated with AI, robotic process automation and data analytics, alongside gaps in the human and organisational capabilities required to use them effectively. They also point to the importance of regulatory and organisational conditions.

Theoretical Contribution/Originality: The study interprets emerging competency requirements as organisational resources that may support technology-enabled internal auditing.

Practitioners/Policy Implications: Organisations should develop audit competencies alongside technological investment, with attention to training, cybersecurity, change management and governance. The findings describe the included studies and should not be read as national rankings or comparable estimates of effect size.

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1. Introduction

Artificial intelligence (AI), digital platforms, advanced analytics and interconnected information systems are reshaping organisational structures and working practices. In both public and private organisations, digital technologies influence strategy, resource allocation, risk management, communication and value creation. Digital transformation involves changes to how individuals and institutions operate and coordinate their activities. These changes draw on technologies such as machine learning, cloud computing, big data analytics, robotic process automation and blockchain. Together, these technologies contribute to an increasingly connected organisational environment (Fenton et al., 2019).

Digital transformation affects functions throughout an organisation. Managers use real-time data to monitor performance, identify operational weaknesses and inform decisions. Employees work with integrated systems, while organisations need arrangements for data quality, cybersecurity, privacy and algorithmic transparency. Organisations must also demonstrate that their systems are reliable, that they manage data responsibly and that technology-assisted decisions can be explained. These requirements create new expectations for assurance functions, including internal audit.

Internal auditing supports assurance, consulting, risk management and governance (Pickett, 2003). In MENA organisations, growing data volumes have encouraged interest in AI and audit analytics for control and oversight (Taşdöken, 2024). Auditors can use these tools to analyse transactions, automate routine procedures and detect unusual patterns (Ghafar et al., 2024).

Digital technologies also change the skills required of internal auditors. Auditors need to understand analytical tools, assess their outputs and adapt their procedures as systems change (Kruskopf et al., 2020; Ghafar et al., 2024). The selected MENA studies address these requirements in different organisational settings. This review asks: How are AI and digital transformation changing internal audit competencies in the MENA region?

The study examines the competencies that internal auditors need to work with digital technologies and the gaps described in the selected studies. It considers how technical knowledge, professional judgement and organisational support affect auditors' use of these tools.

This exploratory qualitative review compares 13 empirical journal articles published between 2021 and 2025. The thematic synthesis examines internal auditing and related audit work in selected MENA settings.

2. Theoretical and Conceptual Framework

Barney's (1991) resource-based view (RBV) links sustained competitive advantage to resources that are valuable, rare, difficult to imitate and non-substitutable. Human capital, including professional competencies, constitutes a potential strategic resource within this framework. For internal auditors, technical knowledge and analytical skills may help translate investment in digital tools into better audit work. This review uses the RBV to interpret competency requirements; it does not test whether those competencies satisfy all four conditions.

Digital transformation involves changes to organisational processes and business models as well as the adoption of technology (Daim, 2020; Gilchrist, 2018). Managers need infrastructure and operating arrangements that allow staff to use new systems (Maheshwari, 2019; Kale, 2019). Fenton et al. (2019) discuss changes in working practices and user experiences, while Schallmo and Williams (2018) and Saldanha (2019) examine how organisations manage digital transformation. In internal auditing, AI can support data analysis, automation and anomaly detection, but its use also raises questions about data privacy, skills and system integration (Ghafar et al., 2024). Public-sector audit teams face similar requirements for appropriate technical and organisational arrangements (Taşdöken, 2024).

Internal auditors therefore need to understand the tools they use and assess the evidence those tools produce. The RBV offers one way to examine how organisations develop and retain these capabilities alongside other professional skills.

3. Methodology

This study uses an exploratory qualitative approach to compare empirical research on digital technologies and audit work in selected MENA settings. The reviewed articles cover publications from 2021 to 2025 and examine AI, robotic process automation, information technology, ERP systems, cybersecurity and remote auditing.

The synthesis draws on the 13 studies listed in Table 1. For each study, the comparison records its country setting, method, participants and main findings. Most studies address internal auditing. Al Shbail et al. (2025) and Al-Hajaya et al. (2025) examine external or remote auditing and provide related evidence on skills and implementation conditions. Their findings are treated as indirect evidence for internal audit competencies.

The thematic analysis groups recurring findings into digital competencies, cybersecurity and IT risk management, communication and reporting, and organisational adaptability. The RBV provides the interpretive framework. Differences in study design and measurement limit the synthesis to a qualitative comparison of the selected settings.

Table 1 The 13 selected studies

No.	Study	Country	Methodology	Sample	Principal finding
1	Ali & Dammak (2025)	Iraq	Quantitative	145 respondents; study conducted across five private banks	Digital transformation is associated with internal audit quality and financial performance. In the final mediation model, the indirect effect through internal audit quality is significant, while the direct effect on financial performance is not significant.
2	Jaradat et al. (2025)	Saudi Arabia	Quantitative	138 certified internal auditors	RPA adoption is positively associated with internal audit efficiency, particularly when regulatory, data-security and organisational conditions are favourable.

No.	Study	Country	Methodology	Sample	Principal finding
3	Alassuli (2025)	Jordan	Quantitative	390 valid responses from 480 questionnaires	AI-enabled RPA is positively associated with internal audit efficiency, including planning and audit activity management. The study also considers execution and communication.
4	Al Shbail et al. (2025)	Jordan	Quantitative	Audit professionals in non-Big 4 firms	In non-Big 4 external audit firms, remote auditing is associated with audit quality, with staff capabilities relevant to this relationship.
5	Al-Hajaya et al. (2025)	Jordan	Mixed methods (questionnaire + semi-structured interviews)	208 external audit professionals and 11 IT audit professionals	AI-enabled remote auditing faces technological, organisational and environmental barriers, especially inadequate infrastructure, data-quality problems and shortages of AI-related skills.
6	Puthukulam et al. (2021)	Oman	Quantitative	169 internal auditors	AI and machine learning are perceived to improve professional scepticism, professional judgement and audit effectiveness, although implementation costs and training requirements remain challenges.
7	Alqaraleh et al. (2022)	Jordan	Quantitative	153 internal auditors	IT use positively affects internal audit effectiveness, with organisational culture playing a significant mediating role.
8	Elbardan et al. (2025)	Egypt	Qualitative (multiple-case study; interviews, observation and document analysis)	Two companies; interviews, observation and documents	Active internal auditor involvement in ERP implementation strengthens auditors' legitimacy, technical expertise and strategic role, whereas limited involvement and managerial distrust weaken their position.
9	Al-Khasawneh & Baniata (2024)	Jordan	Quantitative	64 respondents from 16 banks	IT use in internal auditing is moderate to high, particularly in analytical procedures and documentation; technological maturity and IT-specialist auditors significantly influence its use.
10	Alhawtmeh (2025)	Jordan	Quantitative	84 valid responses	Internal auditing is positively associated with cybersecurity effectiveness in the surveyed Jordanian government agencies.
11	Bouziane (2025)	Morocco	Quantitative	23 internal auditors	Perceived usefulness of ChatGPT is positively associated with internal audit quality, particularly by improving analysis, understanding of technical documents and audit reporting.
12	Jouiet & Ghaleb (2025)	Morocco	Qualitative exploratory study	14 public-sector internal auditors	AI adoption is constrained by fragmented infrastructure, insufficient technical skills, high costs, AI complexity, regulatory uncertainty and limited technical support.
13	Musa (2024)	Saudi Arabia	Quantitative	150 internal auditors and accountants	Augmented AI has a significant positive effect on internal audit performance, whereas assistive and autonomous AI show no statistically significant effects.

Source: Prepared by the authors.

4. Analysis and discussion of results

4.1. *Distribution of the Included Studies by Year and Country*

The selected studies include one article published in 2021, one in 2022, two in 2024 and nine in 2025. No article in this sample is dated 2023. Figure 1 uses the final issue year for Al Shbail et al. and the journal's online publication year for Ali and Dammak. These counts describe the sample and provide no measure of technology adoption over time.

Six studies examine Jordan, two Saudi Arabia, two Morocco, and one each Iraq, Egypt and Oman. The sample contains unequal numbers of studies from these settings, so the country counts cannot be used to compare national research capacity or readiness for digital auditing.

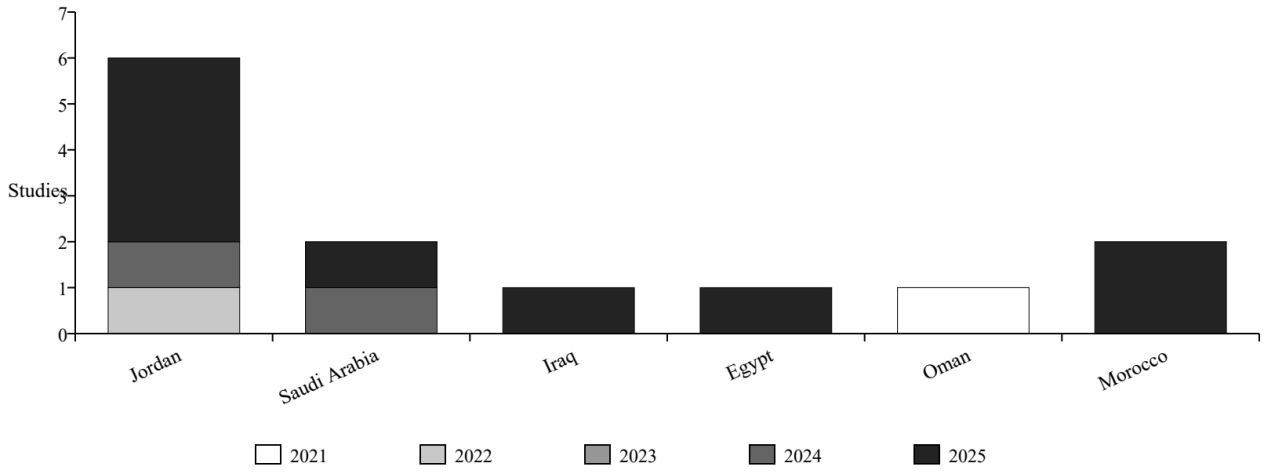

Fig. 1. Distribution of the included studies by year and country

Source: Prepared by the authors.

4.2. *Competency Requirements and Gaps in the Reviewed Studies*

The studies describe the value of digital skills for audit analysis and interpretation in particular organisations (Alassuli, 2025; Bouziane, 2025; Musa, 2024; Elbardan et al., 2025). The findings concern different tools and measures. They therefore support a discussion of competency requirements within those settings rather than a comparison of national effect sizes.

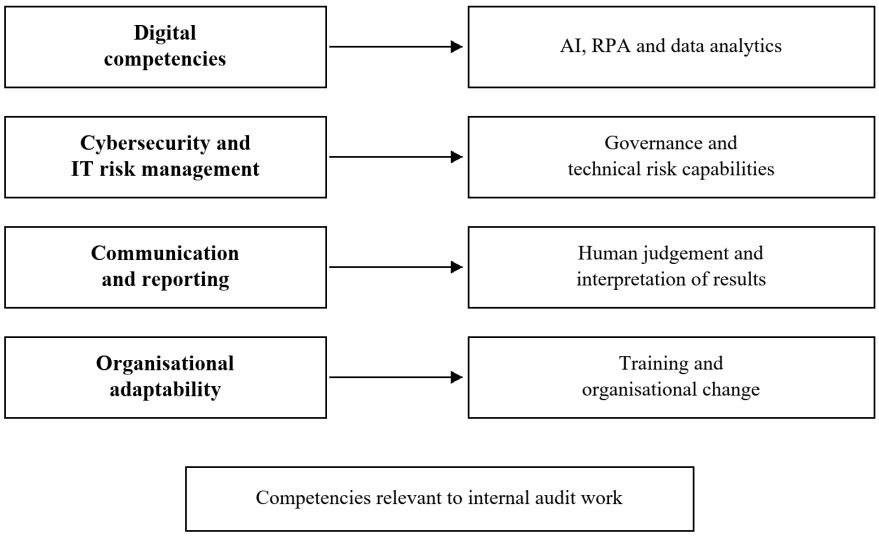

Fig. 2. Competency domains identified in the reviewed studies

Source: Authors' synthesis of the reviewed studies.

Cybersecurity and IT risk management recur in the reviewed evidence. Alhawtmeh (2025) reports an association between internal auditing and cybersecurity effectiveness in Jordanian government agencies. Jaradat et al. (2025) examine regulatory and data-security conditions associated with RPA adoption and audit efficiency in Saudi Arabia. Moroccan public-sector auditors describe regulatory uncertainty and limited support as barriers to AI adoption (Jouiet & Ghaleb, 2025). These studies point to the need for technical knowledge alongside governance arrangements that support its use.

For communication and reporting, auditors need to interpret technology-assisted analysis and explain its implications (Elbardan et al., 2025; Puthukulam et al., 2021). Alassuli (2025) reports a communication score of 3.75 out of 5, classified as high in that study, although lower than the other audit dimensions. The findings support continued attention to professional judgement when auditors use automated outputs.

Organisational adaptability concerns how audit teams change their working practices as they adopt new tools. The studies describe training needs and organisational

conditions that affect this process (Alassuli, 2025; Musa, 2024; Bouziane, 2025). Ali and Dammak (2025) report an indirect association between digital transformation and financial performance through internal audit quality. Across these settings, auditors' capabilities and organisational support matter to the use of technology.

Table 2 Gaps between traditional and emerging competencies

General Competency	Identified gaps	Findings by study setting	Critical observation
Digital competencies	**Traditional:** basic Excel, manual processes **Emerging:** AI, RPA, advanced analytics, ERP	• **Morocco:** Lack of data science skills (Jouiet & Ghaleb, 2025) • **Jordan:** Communication rated high, but lower than the other audit dimensions (3.75/5) (Alassuli, 2025) • **KSA:** No statistically significant effect of autonomous AI in the reported model (Musa, 2024)	The reviewed studies identify needs for advanced digital skills and continued training; they do not establish a universal gap.
Cybersecurity / IT risks	**Traditional:** paper-based control **Emerging:** IT audit, network security, digital compliance	• **Jordan:** Internal audit is positively and significantly associated with cybersecurity effectiveness, explaining 77.6% of its variance (Alhawtmeh, 2025) • **Morocco:** Regulatory gaps hinder AI adoption (Jouiet & Ghaleb, 2025)	Technical and governance capabilities require attention; the studies do not provide comparable national measures.
Communication and reporting	**Traditional:** basic reporting **Emerging:** automated insights, data visualization	• **Oman:** AI improves rapid data synthesis (Puthukulam et al., 2021) • **Jordan:** Communication rated high (3.75/5), although lower than the other dimensions (Alassuli, 2025)	Automation supports but does not replace human interpretation.
Adaptability	**Traditional:** rigid methods **Emerging:** continuous auditing, AI-driven processes, lifelong learning	• **Iraq:** Digitalization improves performance but requires adaptation (Ali & Dammak, 2025) • **KSA:** Effects differ by type of AI system (Musa, 2024)	Resistance to change and sector disparities remain key barriers.

Source: Prepared by the authors.

The gaps identified in the reviewed studies can be interpreted through the RBV (Barney, 1991). Traditional audit skills, including control knowledge and professional judgement, remain relevant alongside AI literacy, data analytics and RPA-related capabilities. Digital competencies may function as organisational resources, but the included studies do not establish that they are rare, inimitable and non-substitutable in every setting.

The studies describe different organisational constraints. Jouiet and Ghaleb (2025) identify skills and infrastructure barriers in interviews with Moroccan public-sector auditors. Musa (2024) reports different effects for assistive, augmented and autonomous AI in a Saudi sample. Alassuli (2025) reports a high communication score that remains lower than the other audit dimensions. These findings suggest that organisations need to develop professional capabilities alongside their digital tools; the studies do not test sustained competitive advantage.

Table 3 Implications for auditors and organisations in the reviewed settings

General Competency	Key insights	Findings by study setting	Critical observation
Digital competencies	Invest in AI and RPA training, standardise data analytics tools	Jordan and Oman: Studies report benefits associated with RPA or AI-assisted auditing Morocco and KSA: Studies describe context-specific opportunities and constraints	Infrastructure disparities and small samples affect comparability of results
Cybersecurity / IT risks	Develop regulatory frameworks and strengthen IT audit capabilities	Jordan and KSA: **Evidence on cybersecurity or adoption conditions;** Morocco: reported public-sector barriers	Governance and IT capabilities need attention; national adoption levels were not measured consistently.
Communication and reporting	Train auditors in AI-assisted interpretation and reporting	Different patterns of communication and reporting across countries	Need to balance automation with human judgement
Adaptability	Promote adaptive culture, continuous auditing	Iraq and Jordan: Studies report benefits linked to digital processes Morocco and KSA: Studies describe different organisational conditions and barriers	Training, resistance to change and organisational differences warrant further investigation.

Source: Prepared by the authors.

Table 3 sets out practical implications of the reviewed evidence for digital skills, cybersecurity governance, communication and organisational adaptability. The recommendations concern the settings examined in the studies.

Organisations can support digital competencies through training in AI, RPA and data analytics. The studies in Jordan and Oman report benefits from technology-assisted auditing, while those in Morocco and Saudi Arabia describe opportunities and constraints associated with particular tools and working conditions.

For cybersecurity and IT risk management, audit teams need technical knowledge and clear governance arrangements. The studies of cybersecurity effectiveness in Jordan and RPA adoption in Saudi Arabia provide examples of these needs within specific organisations.

For communication and reporting, auditors need to explain how they assessed technology-assisted outputs and what those outputs mean for an audit. Training can address the interpretation of analytical results and the presentation of findings to decision-makers.

For organisational adaptability, training and change management can help audit teams revise their procedures as they introduce digital tools. The reviewed evidence concerns particular organisations and sectors, so these recommendations need to be considered within each organisation's working conditions.

5. Conclusion

This review identifies digital competencies, cybersecurity and IT risk management, communication and reporting, and organisational adaptability as recurring themes in 13 empirical studies. The findings describe how auditors use AI, RPA and other digital tools in selected MENA settings. They suggest that organisations need to develop auditors' technical and professional capabilities alongside investment in technology.

The review draws on a small set of studies with different methods, samples and measures. Two studies concern external or remote auditing and provide indirect evidence for internal auditing. These differences limit comparison across countries and prevent regional estimates of effect size or national rankings of adoption.

Future research should examine competency requirements using primary data from internal auditors in different countries and sectors. Common measures and transparent reporting of samples, coding procedures and study quality would improve the basis for comparison.

Declarations

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References

Al Shbail, M. O., Jaradat, Z., Al-Hawamleh, A., Hamdan, A., & Alsartawi, A. M. A. M. (2025). Enhancing audit quality in non-Big 4 firms: The role of remote auditing and audit staff capabilities. Journal of Financial Reporting and Accounting, 23(2), 700–720. https://doi.org/10.1108/JFRA-11-2023-0653

Alassuli, A. (2025). Impact of artificial intelligence using the robotic process automation system on the efficiency of internal audit operations at Jordanian commercial banks. Banks and Bank Systems, 20(1), 122–135. https://doi.org/10.21511/bbs.20(1).2025.11

Al-Hajaya, K., Alma'aitah, R. T., Salem, R. I. A., & Hutaibat, K. (2025). Understanding challenges of conventional remote auditing and AI-enabled remote IT auditing: Audit professionals' perspectives from an emerging economy. Journal of Accounting & Organizational Change. Advance online publication. https://doi.org/10.1108/JAOC-12-2024-0395

Alhawtmeh, O. M. (2025). The role of internal audit as a tool for enhancing cybersecurity effectiveness in Jordanian government agencies. Heritage and Sustainable Development, 7(1), 317–328. https://doi.org/10.37868/hsd.v7i1.1130

Ali, A. H., & Dammak, S. (2025). The impact of digital transformation on internal auditing and financial performance of Iraqi banks. Journal of Ecohumanism, 3(8), 12080–12103. https://doi.org/10.62754/joe.v3i8.5804

Al-Khasawneh, R. O., & Baniata, J. A. S. (2024). The extent of using information technology in internal auditing and the differences in its use in Jordanian banks. Journal of System and Management Sciences, 14(1), 418–435. https://doi.org/10.33168/JSMS.2024.0124

Alqaraleh, M. H., Almari, M. O. S., Ali, B. J. A., & Oudat, M. S. (2022). The mediating role of organizational culture on the relationship between information technology and internal audit effectiveness. Corporate Governance and Organizational Behavior Review, 6(1), 8–18. https://doi.org/10.22495/cgobrv6i1p1

Barney, J. B. (1991). Firm resources and sustained competitive advantage. Journal of Management, 17(1), 99–120. https://doi.org/10.1177/014920639101700108

Bouziane, A. (2025). The impact of using ChatGPT on internal audit quality: A case study of a subsidiary of an oil group in Morocco. EDPACS, 70(3), 42–54. https://doi.org/10.1080/07366981.2025.2450876

Daim, T. U. (Ed.). (2020). Digital transformation: Evaluating emerging technologies. World Scientific Publishing Company. https://doi.org/10.1142/11675

Elbardan, H., Nordberg, D., & Sinha, V. K. (2025). Reconstructing legitimacy of internal auditing during ERP implementations: Two contrasting cases. Journal of Accounting Literature, 47(5), 184–210. https://doi.org/10.1108/JAL-01-2023-0001

Fenton, A., Fletcher, G., & Griffiths, M. (Eds.). (2019). Strategic digital transformation: A results-driven approach. Routledge.

Ghafar, I., Perwitasari, W., & Kurnia, R. (2024). The role of artificial intelligence in enhancing global internal audit efficiency: An analysis. Asian Journal of Logistics and Management, 3(2), 64–89. https://doi.org/10.14710/ajlm.2024.24652

Gilchrist, A. (2018). Digital success: A holistic approach to digital transformation for enterprises and manufacturers. Independently published.

Jaradat, Z., Al-Hawamleh, A. M., Al Shbail, M., & Hamdan, A. (2025). Innovative practices: Assessing the impact of robotic process automation adoption on internal audit efficiency in KSA. Journal of Science and Technology Policy Management. Advance online publication. https://doi.org/10.1108/JSTPM-06-2024-0230

Jouiet, I., & Ghaleb, N. E. A. E. (2025). Barriers to the integration of artificial intelligence in public sector internal audit in Morocco: An exploratory study. Edelweiss Applied Science and Technology, 9(5), 1291–1302. https://doi.org/10.55214/25768484.v9i5.7139

Kale, V. (2019). Digital transformation of enterprise architecture. CRC Press. https://doi.org/10.1201/9781351029148

Kruskopf, S., Lobbas, C., Meinander, H., Söderling, K., Martikainen, M., & Lehner, O. M. (2020). Digital accounting and the human factor: Theory and practice. ACRN Journal of Finance and Risk Perspectives, 9(1), 78–89. https://doi.org/10.35944/jofrp.2020.9.1.006

Maheshwari, A. (2019). Digital transformation: Building intelligent enterprises. Wiley.

Musa, A. M. H. (2024). Detecting the effect of artificial intelligence on internal audit performance: Empirical study in Saudia Arabia. Decision Science Letters, 13(4), 967–976. https://doi.org/10.5267/j.dsl.2024.7.003

Pickett, K. H. S. (2003). The internal auditing handbook (2nd ed.). John Wiley & Sons.

Puthukulam, G., Ravikumar, A., Sharma, R. V. K., & Meesaala, K. M. (2021). Auditors' perception on the impact of artificial intelligence on professional skepticism and judgment in Oman. Universal Journal of Accounting and Finance, 9(5), 1184–1190. https://doi.org/10.13189/ujaf.2021.090527

Saldanha, T. (2019). Why digital transformations fail: The surprising disciplines of how to take off and stay ahead. Berrett-Koehler Publishers.

Schallmo, D. R. A., & Williams, C. A. (2018). Digital transformation now!: Guiding the successful digitalization of your business model. Springer. https://doi.org/10.1007/978-3-319-72844-5

Taşdöken, Ö. (2024). Use of artificial intelligence and audit analytics in internal audit processes in the public sector. EDPACS, 69(9), 1–15. https://doi.org/10.1080/07366981.2024.2376790

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CONCEPTUAL PAPER

Smart FabLabs: The Role of Artificial Intelligence in FabLabs for Heritage Preservation

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ABSTRACT

This article examines how artificial intelligence (AI) and digital fabrication could support the safeguarding of tangible and intangible cultural heritage through FabLabs. It presents a conceptual discussion based on selected publications and institutional project descriptions, rather than an empirical evaluation of integrated AI-FabLab systems. The analysis considers laboratory organisation, possible technical workflows and public participation. HeritageWatch.AI illustrates the use of digital information for monitoring heritage risks; the Aromatic FabLab and Odeuropa provide distinct examples of craft transmission and AI-supported olfactory heritage research. The Notre-Dame restoration illustrates the value of 3D documentation and multidisciplinary data sharing. These examples inform a proposed workflow linking documentation, expert interpretation and the fabrication of educational objects. Potential benefits depend on reliable evidence, specialist oversight, community participation and sustained funding. Digital models and physical facsimiles can support interpretation, but generated reconstructions require clear provenance and validation. The discussion identifies conditions for responsible implementation without claiming universal accessibility or demonstrated conservation gains from AI-FabLab integration.

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1. Introduction

Digital fabrication connects computer-based design with the production of physical objects. The FabLab movement developed from work on personal and digital fabrication at the Massachusetts Institute of Technology (MIT), particularly its Center for Bits and Atoms. Gershenfeld (2007) describes how access to fabrication tools can help people develop practical responses to local needs. Anderson (2012) situates desktop manufacturing and shared design within the broader maker movement.

FabLabs offer a setting in which researchers, craftspeople, students and other participants can design and make objects together. In this article, a smart FabLab means a fabrication laboratory that uses AI for a defined task within such work. This is a proposed direction for practice, rather than a claim that all FabLabs already operate integrated AI systems. In heritage projects, relevant tasks could include organising documentation, assisting interpretation and producing educational models.

The central question is how AI could contribute to heritage work in FabLabs while respecting the evidence, the physical integrity of objects and the communities associated with them. Technical possibilities must be considered alongside funding, staff expertise, data quality and the long-term maintenance of project outputs.

Four questions organise the discussion:

Q1: How can researchers, craftspeople and community contributors participate in defining a heritage project and assessing its outputs?

Q2: Under what conditions could AI-assisted interpretation and fabricated objects improve access to heritage information?

Q3: How might shared laboratory networks support the continuity of projects, skills and documentation?

Q4: What data practices and forms of oversight are needed for community participation in digital heritage work?

The article first examines FabLab organisation, then considers AI applications in heritage documentation and interpretation. It uses selected examples to develop a possible workflow for FabLabs and discusses its technical, financial and ethical limits.

1.1. *Scope and approach*

The article is a conceptual narrative discussion of selected publications, institutional accounts and project websites. It examines the purposes, technical functions and organisational requirements described by these sources, then proposes a workflow for FabLabs. It does not report fieldwork, a systematic search, a tested prototype or measurements of conservation outcomes. The four questions guide interpretation; they are not hypotheses tested on a common dataset. Project websites document how initiatives describe their activities and are considered separately from research evaluations.

2. FabLab organisation and practice

2.1. *Definition and origins*

A FabLab is a workshop for digital fabrication and learning that connects local activity with a wider network. Its users may include entrepreneurs developing prototypes, artists exploring materials, students learning design and electronics, and community groups addressing practical needs. The Fab Foundation (n.d.) describes shared tools, processes and knowledge exchange as features of the network. The equipment and services available at individual sites vary.

Common equipment includes laser cutters, vinyl cutters, computer-controlled milling machines, 3D printers and tools for electronics and microcontroller programming (Fab Foundation, n.d.). These serve different purposes: cutting sheet material, machining parts, building objects layer by layer and assembling electronic prototypes. A heritage project must select equipment according to the required material, size and level of detail, as well as the laboratory's capabilities.

Staffing depends on the host organisation, resources and activities. Responsibilities may be divided among the following roles:

A director or project lead develops the laboratory's strategy, seeks funding and maintains relationships with partner organisations.

A FabManager coordinates daily activities, supports users, organises workshops and arranges equipment maintenance and safe operation.

Technicians, interns, students or volunteers may assist with projects and public activities according to their training. Specialist heritage work also requires access to conservators, curators or relevant craft practitioners; general machine competence does not establish conservation expertise.

The FabLab movement grew out of MIT's work on digital fabrication and its educational outreach. Its emphasis on practical experimentation links learning with the design and production of objects (Gershenfeld, 2007; Fab Foundation, n.d.).

The educational aim is to make design and fabrication more accessible, allowing users to explore how technologies work and how they can be adapted to local needs.

Gershenfeld's (2007) account of personal fabrication provides a basis for considering several possible contributions of FabLabs:

Helping users develop practical skills through the design and fabrication of their own projects.

Supporting learning through prototypes, testing, revision and collaboration across disciplines.

Connecting local problems with knowledge and experience shared through the wider network.

Providing space for ideas initiated by users and community groups.

Helping prospective enterprises explore designs before committing to larger production. These are possible functions; their achievement depends on each laboratory's activities and resources.

2.2. *Establishing a FabLab*

An institution-led laboratory may be hosted by a university, public authority or business that provides premises, equipment or staff. Funding can combine host support, grants, partnerships and income from services. A founding institution need not provide all of the laboratory's continuing resources.

A community-led laboratory may develop from a group of makers, artists, electronics enthusiasts or other participants who pool skills and equipment. Institution-led and community-led arrangements can also be combined. These are useful ways of considering project organisation, rather than mutually exclusive categories (Eychenne, 2012).

2.3. *Organisational models and public access*

The host organisation and funding arrangements influence whom a laboratory serves and how it operates. Drawing on Eychenne's (2012) discussion of FabLab organisation, three broad orientations can be distinguished for this analysis. Actual laboratories may combine them, and access conditions differ between sites.

Educational laboratories primarily support teaching, student projects and research. They may also offer activit-

ies for external participants. Fees, opening hours and staffing depend on the institution and its partners.

Business-oriented laboratories focus on prototyping for companies, start-ups and independent practitioners. Paid services may help fund their activities. Participation in the FabLab network involves more than adopting a name: the Fab Foundation (n.d.) identifies public access for free or in-kind exchange during part of each week, support for the Fab Charter, shared tools and processes, and engagement with the network.

Public and community-oriented laboratories place greater emphasis on workshops, training and locally defined projects. Their viability may depend on public support, partnerships, memberships or paid activities. The number of projects and public sessions must be planned around staffing, safety and available equipment.

3. AI in heritage documentation and interpretation

AI can assist selected tasks in heritage research and interpretation, including the analysis of digital collections and the development of virtual experiences. Münster et al. (2024) review opportunities, challenges and research priorities in this field. Their discussion supports examining particular applications and their requirements, rather than assuming that AI improves every conservation activity.

A useful distinction is between documenting observed features and proposing an interpretation of missing or uncertain features. Both may contribute to a heritage project, but their evidential status differs. A digital file also needs information about its source, processing history and uncertainty if it is to support subsequent research.

3.1. *Analysis and diagnosis*

For condition assessment, a trained image-analysis system could help identify patterns associated with visible damage or changes between surveys. Its usefulness depends on the observations available, the quality of the training data and validation for the intended setting. Alerts require specialist review before they guide an intervention.

Materials analysis requires appropriate observations and measurements. AI may assist the interpretation of analytical data, but an ordinary photograph alone does not establish an object's chemical composition. Any proposed conservation treatment must take account of material properties and the judgement of qualified specialists.

Generative models require particular caution. Altaweel et al. (2024) examine GAN-based enhancement of 2D images of Roman coins and report both improvements in appearance and limitations, including distortions and weaker results for severe damage. The study concerns image visualisation; it does not show that generated details recover the exact original appearance. In a FabLab, such output could be used for a labelled interpretive model after expert review, while the source record is retained.

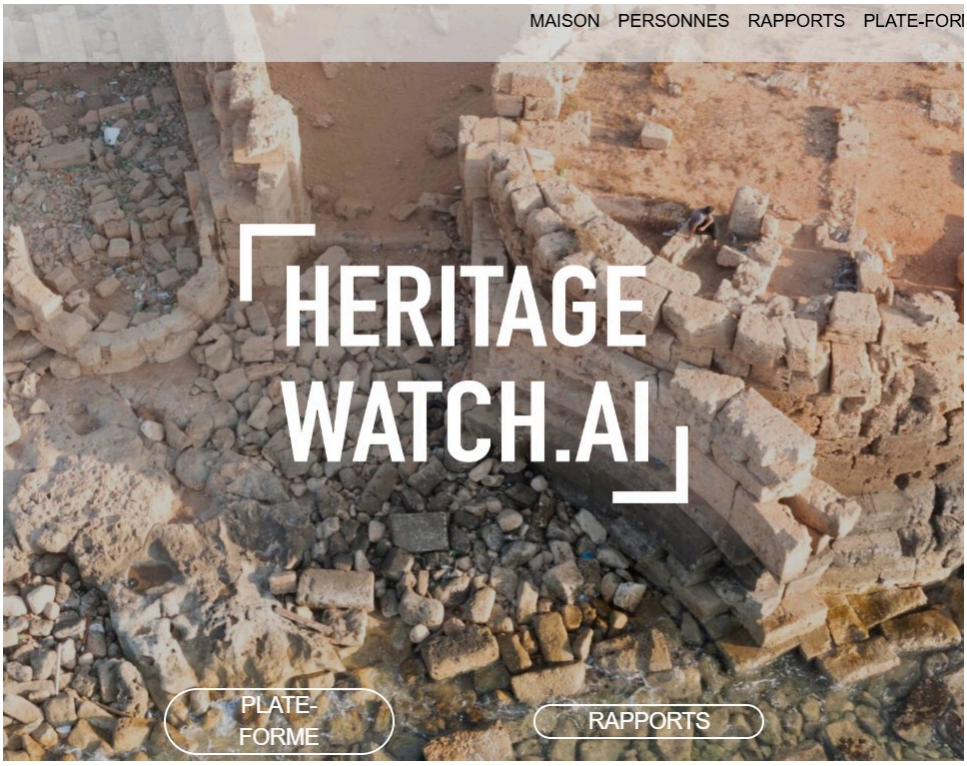

Fig. 1. The HeritageWatch.AI website

Source: HeritageWatch.AI (n.d.), https://heritagewatch.ai/

HeritageWatch.AI (n.d.) describes the use of automated change detection and pattern recognition to assess threats to heritage. Its website identifies sources such as satellite observations, 3D documentation, geospatial data, image

archives and crowdsourced contributions. The project illustrates an approach to information collection and risk monitoring. Its public description is not a comparative evaluation of conservation outcomes or evidence of a FabLab implementation. Figure 1 shows its website.

4. Possible applications in FabLabs

FabLabs could connect digital heritage information with the design of physical objects and public activities. A possible collaboration would bring together heritage specialists, machine operators and community participants, with clearly defined responsibility for the accuracy of information and the purpose of the object being made. The applications below are proposals informed by the selected examples.

4.1. *Workshops and public interpretation*

Collaborative workshops could involve participants in documenting objects, preparing 3D models or designing educational games based on historical sources. Tasks should match participants' skills and the permissions attached to the material. The value of participation would need to be assessed through the quality of the work and participants' experience, rather than inferred from attendance alone.

Tactile models and interactive exhibits could provide additional ways to explore heritage. For example, a fabricated model might help visitors examine a form that cannot be handled in the original collection. An AI-generated conversation with a historical figure would be an interpretive device whose content requires source checking and clear labelling. Accessibility also depends on the interface, language and needs of the intended audience.

4.2. *Perfume skills and olfactory heritage*

The Aromatic FabLab illustrates a local initiative for the cultivation of perfume plants, experimentation and the transmission of related skills. Grasse Expertise (2020) describes a nursery and training activities associated with Les Fleurs d'Exception du Pays de Grasse. The UNESCO inscription concerns the skills related to perfume in Pays de Grasse, including cultivation, processing and perfume composition (UNESCO, 2018). The laboratory supports this field of practice; the cited account does not establish the use of AI in its activities.



Fig. 2. Grasse Expertise page about the Aromatic FabLab

Source: Grasse Expertise (2020), https://grasse-expertise.com/plantes-a-parfum-et-savoir-faire-rendez-vous-a-laromatic-fablab/

Odeuropa is a separate research project. Europa Nostra (2025) describes its use of AI to identify and analyse references to smells in European historical texts and images dating from 1600 to 1920. Its resources support the study and presentation of olfactory heritage, including work with perfumers and heritage specialists. Historically informed scent recreations are interpretations based on evidence and expertise, rather than the recovery of every original smell. The project offers ideas for collaboration, but its achievements do not establish that the Aromatic FabLab uses its methods.

4.3. *A proposed workflow for heritage projects*

The following workflow brings together the article's organisational and technical discussion. It is a proposal for implementation and evaluation in a FabLab.

The first stage is to define the heritage question with the relevant institution and community, establish permissions and document the available evidence. Photogrammetry or laser scanning may then be used where appropriate to record an object or site. AI-assisted analysis should address a specified task, with results checked against observations and expert interpretation. Selected models can subsequently be prepared for educational fabrication or digital presentation.

Workshops and demonstrations could involve participants in reviewing models, testing exhibits and explaining the local significance of objects. A project should record who contributed, what decisions were made and which outputs are suitable for public release.

Before an output is published or fabricated, the team should distinguish measured features from inferred ones and record the sources of any reconstruction. The project

also needs a plan for storage, maintenance and reuse, including access arrangements for the community and the institution responsible for the collection.

4.4. *Digital models and the Notre-Dame example*

A 3D model records selected features of an object or site at a particular time. A digital twin links a digital representation with observations of its physical counterpart and may be updated as new data become available. The scope and frequency of those updates depend on the sensors, surveys and processes in place. A model does not capture every material property or become a digital twin simply because it was produced by laser scanning.

Simulation can help explore possible interventions or structural behaviour, but its conclusions depend on the model's assumptions, input data and validation. Changes in a monument must first be observed reliably before they can inform an update. Recording interventions and preserving earlier model versions can make a digital archive more useful for later conservation work.

Notre-Dame de Paris illustrates the importance of documentation before and after a major loss.

Tallon (2012) describes the use of laser scanning to investigate the cathedral's geometry before the April 2019 fire. Hertz (2024) reports that Tallon's scans contained more than a billion data points and contributed to the restoration. These records provided valuable evidence about parts of the building before the damage.

Dargemont and Heidmann's (2025) CNRS report describes the collection of pre-fire records, including Tallon's data, and new post-fire surveys using laser scanning, photogrammetry and drones. The Aïoli platform helped centralise and annotate documentation for multidisciplinary work. This example demonstrates the contribution of geometric records, shared data and specialist analysis. Laser scanning, photogrammetry and building information modelling (BIM) are distinct from AI, even though AI can be incorporated into some workflows. The Notre-Dame case is therefore informative for planning documentation and collaboration, while the performance of an integrated AI-FabLab process remains a separate question.

4.5. *Governance resources and limits*

The safeguarding of intangible heritage includes the continued practice and transmission of knowledge within communities (UNESCO, 2003). A digital archive can assist this work, but it cannot by itself sustain the relationships, learning and settings through which a practice is passed on. Project priorities and public interpretations should therefore be developed with the people concerned.

For FabLabs, a workable budget needs to include skilled staff, maintenance, consumables, storage and the preservation of digital files. Open sharing can facilitate reuse, while permissions may limit the publication of sensitive cultural information or identifiable contributions. Responsibility for access, corrections and long-term stewardship should be agreed before the project begins.

The environmental costs of digital equipment also belong in project planning. Flipo et al. (2012) examine the environmental implications of information and communication technologies. For a heritage laboratory, the relevant assessment includes equipment manufacture and lifetime, energy use and material consumption, alongside any benefits from reuse or reduced travel.

The analysis is limited by the variety of the sources and the absence of a common evaluation framework. It does not estimate the prevalence of AI adoption in FabLabs, establish causal effects on preservation or compare the full costs of alternative methods. Claims about improved accuracy, engagement or accessibility require evaluation in the intended setting.

5. Conclusion

FabLabs offer a possible setting for connecting heritage documentation, digital interpretation and the fabrication of educational objects. AI could assist defined tasks within these activities, provided that its outputs can be checked and that the laboratory has the necessary technical and heritage expertise.

The selected examples have different purposes. HeritageWatch.AI describes digital monitoring of heritage risks; the Aromatic FabLab supports plant cultivation and skill transmission; Odeuropa uses AI in historical olfactory research; and the Notre-Dame restoration illustrates the value of detailed documentation and data sharing. Together they suggest useful components for future collaborations, rather than a demonstrated model of integrated AI-FabLab conservation.

Public participation can contribute local knowledge and help shape the design of educational objects. Its value depends on meaningful involvement, accessible activities and respect for the communities whose heritage is represented. Digital access and physical replicas can extend opportunities for interpretation without replacing the original object or the practice of a living tradition.

Sustained implementation requires funding for staff, equipment, data stewardship and training. It also requires a record of the evidence underlying reconstructions and a clear distinction between observed features and generated interpretations.

The proposed workflow provides a basis for practical evaluation. Further work could examine costs, the accuracy and usefulness of outputs, accessibility and community experience in specific laboratory settings. Such evidence would be needed to assess whether AI adds value to a heritage activity compared with the alternatives available.

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References

Altaweel, M., Khelifi, A., & Zafar, M. H. (2024). Using generative AI for reconstructing cultural artifacts: Examples using Roman coins. Journal of Computer Applications in Archaeology, 7(1), 301–315. https://doi.org/10.5334/jcaa.146

Anderson, C. (2012). Makers: The new industrial revolution. Crown Business.

Dargemont, C., & Heidmann, A. (2025). Étude d'impact sociétal: Chantier scientifique de Notre-Dame. CNRS. https://www.cnrs.fr/sites/default/files/news/2025-09/cnrs-etude-impact-societal-notre-dame.Tl8JljaC.pdf

Europa Nostra. (2025, June 12). Odeuropa. European Heritage Awards / Europa Nostra Awards. https://www.europeanheritageawards.eu/winners/odeuropa/

Eychenne, F. (2012). Fab Lab: L'avant-garde de la nouvelle révolution industrielle. FYP Éditions.

Fab Foundation. (n.d.). Getting started. https://fabfoundation.org/getting-started/

Flipo, F., Deltour, F., Dobré, M., & Michot, M. (2012). Peut-on croire aux TIC vertes? Technologies numériques et crise environnementale. Presses des Mines. https://www.pressesdesmines.com/produit/peut-on-croire-aux-tic-vertes/

Gershenfeld, N. (2007). Fab: The coming revolution on your desktop, from personal computers to personal fabrication. Basic Books.

Grasse Expertise. (2020, August 20). Plantes a parfum et savoir-faire: rendez-vous à l'Aromatic FABLAB. https://grasse-expertise.com/plantes-a-parfum-et-savoir-faire-rendez-vous-a-laromatic-fablab/

HeritageWatch.AI. (n.d.). HeritageWatch.AI. https://heritagewatch.ai/

Hertz, L. (2024, December 9). Cathedral of Notre-Dame of Paris reopens with help from Vassar professor. Vassar College. https://www.vassar.edu/news/cathedral-notre-dame-paris-reopens-help-vassar-professor

Münster, S., Maiwald, F., di Lenardo, I., Henriksson, J., Isaac, A., Graf, M. M., Beck, C., & Oomen, J. (2024). Artificial intelligence for digital heritage innovation: Setting up a R&D agenda for Europe. Heritage, 7(2), 794–816. https://doi.org/10.3390/heritage7020038

Tallon, A. (2012). La technologie 3D au service de Notre-Dame. In A. Vingt-Trois (Ed.), Notre-Dame de Paris: La grâce d'une cathédrale (pp. 159–160). La Nuée Bleue. https://facultysites.vassar.edu/antallon/pdfs/tallon-notre-dame-2012.pdf

UNESCO. (2003). Convention for the safeguarding of the intangible cultural heritage. https://ich.unesco.org/en/convention

UNESCO. (2018). Decision 13.COM 10.b.14. https://ich.unesco.org/en/Decisions/13.COM/10.b.14

Appendices

Appendix A Glossary of AI and FabLabs

BIM (building information modelling): A process for organising digital information about a building, including geometry and associated attributes. A BIM model may support coordination and analysis without using AI.

CAD/CAM (computer-aided design and computer-aided manufacturing): Tools and processes used to design objects digitally and prepare instructions for fabrication. CFAO is the corresponding French abbreviation.

GANs (generative adversarial networks): Generative models trained through the interaction of a generator and a discriminator. In heritage applications they may produce plausible visual reconstructions, which require validation and must be distinguished from documentary evidence.

LiDAR (light detection and ranging): A measurement technique using laser light to estimate distances and produce spatial data such as 3D point clouds. A point cloud is a record of measured geometry, rather than an automatically updating digital twin.

3D printing: Additive manufacture of a physical object from a digital model. The detail and dimensional accuracy of a facsimile depend on the source data, preparation, equipment and material.

Appendix B Illustrative heritage initiatives

These initiatives illustrate different aspects of documentation, interpretation and skill transmission. They are not presented as equivalent implementations of AI in FabLabs.

HeritageWatch.AI: A project describing automated analysis and multiple data sources for monitoring changes and risks affecting heritage sites (HeritageWatch.AI, n.d.).

Aromatic FabLab: A plant-cultivation and training initiative associated with perfume skills in Pays de Grasse. The UNESCO inscription concerns the skills themselves (Grasse Expertise, 2020; UNESCO, 2018).

Odeuropa: A research project using AI to identify smell-related evidence in European historical texts and images from 1600 to 1920, with resources for olfactory interpretation (Europa Nostra, 2025).

Notre-Dame documentation: Pre-fire laser records and post-fire surveys supported multidisciplinary analysis and restoration documentation. The example concerns digital heritage work beyond the FabLab setting (Tallon, 2012; Hertz, 2024; Dargemont & Heidmann, 2025).